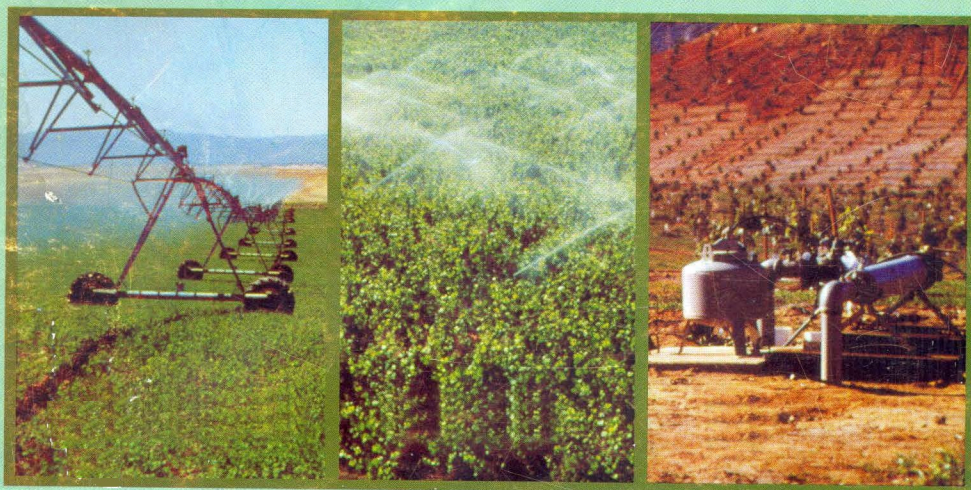


Plant Nutrient Management under Pressurized Irrigation Systems in the Mediterranean Region

John Ryan
Editor



World Phosphate Institute



**International Center for Agricultural
Research in the Dry Areas**

About ICARDA and the CGIAR



Established in 1977, the International Center for Agricultural Research in the Dry Areas (ICARDA) is governed by an independent Board of Trustees. Based at Aleppo, Syria, it is one of 16 centers supported by the Consultative Group on International Agricultural Research (CGIAR).

ICARDA serves the entire developing world for the improvement of lentil, barley, and faba bean; all dry-area developing countries for the improvement of on-farm water-use efficiency, rangeland and small-ruminant production; and the West and Central Asia and North Africa region for the improvement of bread and durum wheats, chickpea, and farming systems. ICARDA's research provides global benefits of poverty alleviation through productivity improvements integrated with sustainable natural-resource management practices. ICARDA meets this challenge through research, training, and dissemination of information in partnership with the national agricultural research and development systems.

The results of research are transferred through ICARDA's cooperation with national and regional research institutions, with universities and ministries of agriculture, and through the technical assistance and training that the Center provides. A range of training programs is offered extending from residential courses for groups to advanced research opportunities for individuals. These efforts are supported by seminars, publications, and specialized information services.



The CGIAR is an international group of representatives of donor agencies, eminent agricultural scientists, and institutional administrators from developed and developing countries who guide and support its work. The CGIAR receives support from a wide variety of country and institutional members worldwide. Since its foundation in 1971, it has brought together many of the world's leading scientists and agricultural researchers in a unique South-North partnership to reduce poverty and hunger.

The mission of the CGIAR is to promote sustainable agriculture to alleviate poverty and hunger and achieve food security in developing countries. The CGIAR conducts strategic and applied research, with its products being international public goods, and focuses its research agenda on problem-solving through interdisciplinary programs implemented by one or more of its international centers, in collaboration with a full range of partners. Such programs concentrate on increasing productivity, protecting the environment, saving biodiversity, improving policies, and contributing to strengthening agricultural research in developing countries.

The World Bank, the Food and Agriculture Organization of the United Nations (FAO), the United Nations Development Programme (UNDP), and the United Nations Environment Programme (UNEP) are cosponsors of the CGIAR. The World Bank provides the CGIAR System with a Secretariat in Washington, DC. A Technical Advisory Committee, with its Secretariat at FAO in Rome, assists the System in the development of its research program.

Plant Nutrient Management under Pressurized Irrigation Systems in the Mediterranean Region

**Proceedings of the IMPHOS International Fertigation Workshop
25 – 27 April, 1999, Amman, Jordan**

Editor

John Ryan

Soil Fertility Specialist

Natural Resource Management Program, ICARDA

Organized by:

World Phosphate Institute (IMPHOS), Casablanca, Morocco

In collaboration with:

**International Center for Agricultural Research in the Dry Areas
(ICARDA), Syria**

**Jordan Phosphate Mines Company
(JPMC), Jordan**

**National Center for Agricultural Research and Technology Transfer
(NCARTT), Jordan**



World Phosphate Institute



International Center for Agricultural Research in the Dry Areas

**Joint Publication of the World Phosphate Institute (IMPHOS) and the
International Center for Agricultural Research in the Dry Areas
(ICARDA)**

© 2000 International Center for Agricultural Research in the Dry Areas

The sponsors encourage the fair use of this material.
Proper citation is requested

Correct citation: Ryan, J. (ed.). 2000. Plant Nutrient Management under Pressurized Irrigation Systems in the Mediterranean Region. Proceedings of the IMPHOS International Fertigation Workshop organized by the World Phosphate Institute (IMPHOS), 25 – 27 April 1999, Amman, Jordan. ICARDA, Aleppo, Syria. 400 pp.

ISBN: 82-9127-101-2

Organizing /Scientific Committee: Dr. I. Papadopoulos, ARI, Cyprus (Chairman); Dr. P. Mountonnet, (IAEA, Austria); Dr. J. Ryan, (ICARDA, Syria); Dr. A. Fardous, (NCARTT, Jordan); Mr. A. Ghosheh, Mr. N.S. Bata, Ms. L. Dabbas, (JPMC, Jordan); and Mr. T. Mrabet, Dr. L. Cisse, Mr. B. Amar, (IMPHOS, Morocco).

Cover Pictures: *The Western Fertilizer Handbook Slide Series Set, Vocational Education Productions, California Polytechnic State University Foundation, San Luis Obispo, California, USA.*

IMPHOS,
3 rue Abdel Kader Al-Mazini,
B.P. 15963, Postal Code 20001
P.O. Box 15963, Postal Code 20001,
Casablanca, Morocco.
Phone: (212-2) 48 41 22 /24 /25
Fax: (212-2) 48 41 21
E-mail: Imphos@casanet.net.ma

ICARDA,
P. O. Box 5466,
Aleppo, Syria
Phone: (963-21) 2213477, 2225 012/112
Fax: (963-21) 213490, 225105, 551860
E-mail: ICARDA@cgiar.org
Web site: <http://www.icarda.cgiar.org>

Table of Contents

	<i>Page</i>
<i>Organizing Institute IMPHOS</i>	vii
<i>Co-Sponsors</i>	ix
<i>Special Collaborators</i>	xii
Foreword	xiii
Preface	xiv
Acknowledgements	xvi

A. FULL PAPERS

Keynote Addresses

Fertigation: Present Situation and Future Prospects Ioannis Papadopoulos	3
Towards Guidelines for Quality Fertilizers under Modern Irrigation Ghassan Hamdallah	56
Irrigation Systems: Potential for Fertigation Musa N. Nimah	72

Session I: Water Management

Role of FAO/IAEA Program in Fertigation Studies in the Mediterranean Region Pierre Moutonnet	97
Water Balance for Optimizing Water Use Efficiency in WANA Region Abed Al-Nabi Fardous and Ali Al-Shrouf	120
Plant Nutrient Management under Pressurized Irrigation Systems in the Mediterranean Region: Crop Water Requirements Pasquale Steduto	138
Approaches for Using Climatic Data to Improve Water-Use Efficiency Ayman F. Abou Hadid	166

Water Quality for Pressurized Irrigation Systems	
Fawzi Karajeh	185

Session II: Nutrient Management Requirements and Interactions

Crop Nutrient Requirements	
Mohammed M. El-Fouly	197
Soil Nutrient Supplying Capacity under Pressurized Irrigation Systems in Morocco	
Mohamad Badraoui	212
Phosphorus Levels in Soils of Different Vegetable Crops in the Jordan Valley	
Sayed Khattari	223
Root Systems and Fertigation	
Munir J. M. Rusan	232

Session III: Fertigation with Phosphorus Fertilizers

Use of Phosphorus Fertilizers in Pressurized Irrigation Systems: Problems and Possible Solutions	
John Ryan and Maher Saleh	249
A Comparison of the Efficiency of Conventional Soil Phosphorus Application and Phosphorus Fertigation	
Leena Ristimaki and Ioannis Papadopoulos	260
Phosphorous Sources for Fertigation	
Bruce A'Bear	269
Management of Phosphorous Fertigation at Farm Level in Tunisia	
Kawther Latiri, Naïma Kolsi, Ali Mhiri, and N. Hamza ..	273
Fertigation under Saline Conditions: Irrigation Management for Minimizing Soil Salinity Risk	
Gevat Kirda and Nafi Baytoru	288

Session IV: Environmental and Economic Issues

Environmental and Health Impacts of Fertigation	
Atef Hamdy	299

B. SHORT COMMUNICATIONS

Management of Fertigation of Protected Cucumber in Coastal Lebanon Using Slightly Saline Water Thérèse Atallah, Talal Darwish, Souhail Awad, and Maroun El-Moujabber	323
Water Balance and Irrigation Scheduling of Cucumber under Protected Cropping Maroun El Moujabber, Rouaida Abi Zeid Daou, Thérèse Attallah, Talal Darwish, and Pierre Metri	326
Irrigation Systems and Plant Nutrient Distribution with Depth in Orchard Soils Bousselham Loudyi	332
Fertigation: Useful Tool in Cyprus Costas Hadjiparaskevas	336
Nitrogen-Water Relations of Tomato by Drip Fertigation Sabri Oruç and Adem L. Bey	339
Adoption of Water-Soluble Fertilizer Technology through Micro- injection Systems under Indian Conditions: Case Study T. T. Fatif	343
Irrigation Water Quality and Nitrogen for Yield and Water-Use Efficiency of Barley (<i>Hordeum Vulgare</i> L. Cv. Ardhaoui) in the Arid Climate of Southern Tunisia Kamel Nagaz, Nétij Ben Mechlia, and Atef Hamdy	344
The Use of Acid Fertilizers for Fertigation Christos Tsiattalos	353
Experiences on Nitrogen and Phosphorus Management under Drip Irrigation System in India G. Dev	357
A Schematic Approach for Fertilization Scheduling Medany, M.A., M.A. Cadel-Rabl, and A.F. Abou-Hadid ..	361
Efficiency of Phosphoric Acid Fertigation in Fine-Textured Calcareous Soils Naïma Kolsi, Ali Mhiri, and Jan Vanderdeelen	363

Efficiency of Phosphate Rock as Fertilizer in Irrigated Saline Conditions of the Algerian Sahara Amor Halitim, N. Abdenbi, and A. Masmoudi	366
Cotton Fertigation Practices in Syria: Nitrogen and Water Effects Moussadak Janat and George Somi	370

C. WORKSHOP FINDINGS

SESSION CHAIRMEN'S REPORTS AND SUMMARY OF DISCUSSION

Keynote Addresses	377
Session I: Water Management	378
Session II: Nutrient Management Requirements and Interactions	379
Session III: Fertigation with Phosphatic Fertilizers	380
Session IV: Environmental and Economic Issues	381
Summary of General Discussion	382
Session V: Conclusions and Recommendations	383
Important Issues Addressed by the Workshop Summary and Recommendations	
List of Workshop Participants	389

Organizing Institute

THE WORLD PHOSPHATE INSTITUTE (IMPHOS)

IMPHOS (Institut Mondial du Phosphate) is non-profit making institute, founded in 1973 by the world's principal producers of phosphate rock. Its primary mandate is to collect and disseminate scientific data to support the rational use of non-renewable, natural phosphate rock, for which the principal use is to both increase and sustain agricultural production to meet the food requirements of humankind worldwide. Recently, the mandate has been broadened to encompass environmental issues arising from the use of phosphates in both agriculture and industry.

IMPHOS has two Divisions at its headquarters in Casablanca, Morocco. The *Agronomy Division* is concerned with the use of phosphorus in agriculture and forestry, and the *Technical Division* is concerned with phosphorus fertilizer production technology. Two committees support the decision-making process: a Scientific Committee, which is chaired by an independent scientist and with members who are specialists in the Committee's fields of interest, and the Agronomy and Technical Committee, whose membership comprises representatives from the IMPHOS member companies.

IMPHOS does not have any in-house research or laboratory facilities. Instead, it achieves its objectives by commissioning, usually with short-term contracts, research with competent organizations worldwide. Among its objectives, it seeks to promote, in both developed and developing countries, the efficient use of phosphorus, both as processed fertilizers and as natural rocks, according to the principles of *integrated plant nutrient management*. It also seeks to improve farming techniques for productive and sustainable crop production, whilst minimizing environmental risks. Technical research includes industrial applications, such as the synthesis of phosphorus compounds of commercial interest, and processing technologies such as the cost-effective elimination of cadmium from processed phosphates.

To optimize the use of published research on phosphorus, IMPHOS makes its expertise available, not only to member companies but also to research organizations, consumers and appropriate agencies at the national, regional and international levels. It organizes international conferences and regional seminars, the publications from which are available from IMPHOS. Jointly with CAB International, IMPHOS has published three volumes of *Phosphorus in Agriculture*, consisting of abstracts derived from the CABI database since 1988. It regularly produces its own *IMPHOS Phosphate Newsletter*.

IMPHOS agricultural projects in the field are often jointly funded. In Africa and Asia, the projects focus on the need to supply phosphorus to phosphorus-deficient soils. On the other hand, projects in Western Europe focus on using

phosphorus efficiently on phosphorus-enriched soils, to both maintain productivity and minimize environmental risk.

*Address: World Phosphate Institute, IMPHOS, 3 rue Abdelkader Al Mazini, BP. 15963, Postal Code 20001, Casablanca, Morocco.
Tel: + 212 2 48 41 22/24. Fax: + 212 2 48 41 21.
E-mail: imphos@casanet.net.ma*

IMPHOS Member Companies

Compagnie des Phosphates de GAFSA

7 - 9 rue du Royaume d'Arabie Saoudite
1002 - Tunis, Tunisia
Tel: 216 1 7 84 488 /799 934 /797 296
Fax: 216 1 793 685

Africa

Tel: 27 15 24 89 20 11

Fax: 27 15 789 20 70

E-mail: msmail@foskor.co.za

Groupe Office Chérifien Phosphates (OCP)

Angle route d'El Jadida et bd. La Grande Ceinture, CASABLANCA, Morocco
Tel: 212 2 23 00 25 /23 10 25 / 23 30 25
Fax: 212 2 23 06 35

Web site: <http://www.ocpgroup.com>

Industries Chimiques du Sénégal (ICS)

Av. A. Sarraut
BP. 3148, DAKAR, Senegal
Tel: 221 8 34 01 22 /34 21 23 /34 08 14
Fax: 221 8 34 07 01

Jordan Phosphate Mines Co. Ltd (JMPC)

P. O. Box 30
AMMAN, Jordan
Tel: 962 6 5 0 70 10 /6 5 0 71 41 /6 5 0 70 19
Fax: 962 6 5 68 22 90 /6 5 69 12 90
Web site: <http://www.ipmc-jordan.com>

EPE FERPHOS

BP. 112, Av. des Jardins
TEBESSA, Algeria
Tel: 213 8 47 31 77 /59 69 71
Fax: 213 8 49 25 50
Tel /Fax: 213 2 21 91 95

FOSKOR LTD

FOSKOR LTD, 27 Selati Road P.O. Box 1
1390 PHALABORWA, Republic of South

Office Togolais des Phosphates (OTP)

BP. 379, LOME, Togo
Tel. 228 22 50 13
Fax: 228 21 71 52 /21 71 05

Co-Sponsors

**The following institutions deserve particular recognition
for their efforts and contribution in organizing the
workshop, and preparing the proceedings**

1. THE INTERNATIONAL CENTER FOR AGRICULTURAL RESEARCH IN THE DRY AREAS (ICARDA)

Established in 1977, the International Center for Agricultural Research in the Dry Areas (ICARDA) is governed by an independent Board of Trustees. Based in Aleppo, Syria, it is one of 16 centers strategically located all over the world and supported by the Consultative Group on International Agricultural Research (CGIAR). ICARDA's research provides global benefits of poverty alleviation through productivity improvements integrated with sustainable natural-resource management practices. ICARDA meets this challenge through research, training, and dissemination of information in partnership with the national agricultural research and development systems.

The results of research are transferred through ICARDA's cooperation with national and regional research institutions, with universities and ministries of agriculture, and through the technical assistance and training that the Center provides. A range of training programs is offered extending from residential courses for groups to advanced research opportunities for individuals. These efforts are supported by seminars, publications, and specialized information services. With its main research station and offices based in Aleppo, Syria, ICARDA works through a network of partnerships with national, regional and international institutions, universities, non-governmental organizations and ministries in the developing world; and with advanced research institutes in industrialized countries.

Mission

ICARDA's mission is to improve the welfare of people through research and training in dry areas of the developing world, by increasing the production, productivity and nutritional quality of food, while preserving and enhancing the natural resource base. The environment in dry areas is harsh, stressful and variable, and agriculture in these areas faces more complex challenges than in areas with adequate rainfall.

ICARDA is committed to the advancement of agricultural research; free exchange of germplasm and information for research; protection of intellectual property rights, including indigenous knowledge of farmers; human resources

development; the sustainable use of natural resources; and poverty alleviation, particularly among women and children.

Who Supports ICARDA?

ICARDA receives its core funding from the CGIAR, which is supported by an international group of donors. Direct donor funding is also received for specific research in a particular country or a group of countries. Donors to ICARDA have included the Arab Fund, Australia, Austria, Canada, China, Denmark, Egypt, the European Commission, FAO, the Ford Foundation, France, Germany, IDRC (International Development Research Center), IFAD (International Fund for Agricultural Development), India, Iran, Italy, Japan, the Netherlands, Norway, OPEC (Organization of Petroleum Exporting Countries), Spain, Sweden, UNDP, UNEP, the United Kingdom, USAID (United States Agency for International Development), and the World Bank.

Address: International Center for Agricultural Research in the Dry Areas (ICARDA), P.O. Box 5466, Aleppo, Syria.

Tel.: (963-21) 2213477, 2225112, 2225012.

Fax: (963-21) 2213490/2225105.

E-mail: ICARDA@CGIAR.ORG

Web site: <http://www.cgiar.org/icarda>

2. THE JORDAN PHOSPHATE MINES CO. (JPMC)

JPMC was established in 1935 as a private company to exploit the phosphate deposit in Jordan and was registered as a public shareholding company in 1953. The Jordanian Government and the Private Sector now jointly own JPMC. The Company's capital has increased several times since its inception.

In addition to Rusaifa mine that has been producing since 1953, JPMC started in 1962 production from El-Hassa mine which is located about 136 km south of Amman and 200 km north of Aqaba port. Production from El-Abiad mine started in 1979 which is located about 20 km north of El-Hassa mine started in 1979. In 1988, production started from Eshidiya mine, which is located about 125 km northeast of Aqaba. In 1982, a fertilizer complex was constructed about 17 km south of Aqaba to produce phosphoric acid, diammonium phosphate acid (DAP) and aluminium fluoride.

JPMC is also involved with foreign partners in a number of joint venture projects in the fertilizer and chemical sectors in order to maximize utilization of Jordan's natural resources by developing new capacities and down-stream products.

JPMC is a commercial enterprise with the status of commercial corporation. A

Board of Directors of eleven members manages it. JPMC has a total of 6000 employees.

Over many years of mining and processing operation, the company has acquired great experience in many fields and has developed a team of qualified and experienced staff who have quickly and effectively adapted to the expanded company schemes and responsibilities.

Address: Jordan Phosphate Mines Company (JPMC)

P.O. Box 30, Amman, JORDAN.

Phone: 962 6 56 071 41

Fax: 962 6 5 68 22 90

Web site: <http://www.jpmmc-jordan.com>

3. NATIONAL CENTER OF AGRICULTURAL RESEARCH FOR TECHNOLOGY TRANSFER (NCARTT), JORDAN.

The National Center for Agricultural Research and Technology Transfer (NCARTT) began operation in July 1985. The center operates now according to a special by law as a semi-autonomous institution with administrative and financial independence. NCARTT consists of a main head office located at 50 km north part of Amman and six regional centers: Deir Alla, Ramtha, Khaldieh, Mushaqar, Rabbah, and Shoubak. The NCARTT operates 12 research stations representing different agroecological conditions in Jordan.

The NCARTT mandate is to conduct and/or coordinate applied agricultural research and transfer of technology activities at the national level in collaboration with public and private agricultural institutions. NCARTT's mandate also provides for the identification, testing, transfer and adoption of improved technologies.

Address: National Center for Agricultural Research and Technology

Transfer (NCARTT), Ministry of Agriculture

P.O. Box 639 – Baqa' 19381 Jordan

Tel.: 4725071, Fax: 4726099

Special Collaborators

The following institutions have joined efforts with the organizers to preparing the workshop and disseminating its outcomes:

- The International Center for Advanced Mediterranean Agronomic Studies (CIHAM/IDM), Bari, Italy, which contributed significantly by presentations and discussions in this workshop, and decided to use the proceedings in training activities in order to further the impact of the Workshop within the Mediterranean region.
- The International Atomic Energy Agency (IAEA), Joint FAO-IAEA Division of Nuclear Techniques in Food and Agriculture, Vienna, Austria, which helped in the preparation of the overview on the theme of fertigation and the identification of speakers and poster presenters.
- The Food and Agriculture Organization of the United Nations (FAO) /Regional Office for the Near East, Cairo, Egypt, which kindly presented a keynote address, and provided sponsorship of a number of participants from the Near East.

FOREWORD

The World Phosphate Institute (IMPHOS) has taken the initiative to organize a workshop on "Plant Nutrient Management under Pressurized Irrigation Systems in the Mediterranean Region". This workshop took place in Amman, Jordan, on 25 – 27 April 1999. IMPHOS is pleased to underline that its initiative attached the interest of many international and national organizations, including the *agricultural research and development sector*, the *fertilizer industry*, *education institutes*, and *private agricultural production cooperatives*.

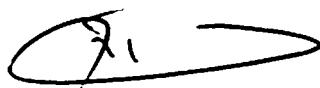
The Workshop provided an exhaustive review of the current knowledge in fertilization systems, addressed water and plant nutrient requirements, and discussed various technical and environmental issues related to fertigation.

Irrigated agriculture can be sustainable provided that the basic principles of good soil, water, and fertilizer management are applied appropriately. With this in view, the Workshop stressed the vital role of plant nutrients, with particular emphasis on phosphorus, as a means of increasing crop yield and improving food quality.

Further, the increasing water scarcity, steadily growing population, and the urgent need to increase food production are forefront issues facing the Mediterranean countries in the Middle East and North Africa. The Workshop provided a platform for information-sharing and discussions on the growing concern for *effective and efficient use of fertilizers, soil, and water*. It helped further the IMPHOS activities in the region, which aim to *promote an intensive and sustained agriculture*.

The World Phosphate Institute is pleased to extend its thanks to all those individuals and organizations that contributed much to the success of this Workshop.

The Secretary General of IMPHOS



Tayeb Mrabet

PREFACE

As we start the new millennium, it is pertinent to reflect upon developments and achievements in the area of agricultural research and its impact on feeding the world's burgeoning populations, and to consider the challenges that lie ahead.

The world is a better place for most people now than a century ago; for the vast majority of the world's population, an adequate and continuous supply of food is taken for granted. But for many millions, especially in the developing areas of the world, hunger is an ever-present reality, together with its disruptive effects on society as a whole.

It is the daunting task of all of us – researchers, educators, commercial sector, administrators – to put our resources and efforts together to banish the specter of hunger and privation from those who are burdened and haunted by it.

In endeavoring to stimulate agricultural output in the national economies of developing countries, we must produce more from existing land resources, since bringing new land into production is not a realistic possibility. That leads to a consideration of the major constraints to increased production. For most of the resource-poor developing countries, mainly located in the low rainfall areas of Africa and large areas of Asia and Latin America, the dominant constraint is shortage of water.

Notwithstanding the benefits of irrigation compared to rainfed farming, sources of surface water and groundwater are invariably limited. Nevertheless, the introduction of pressurized irrigation systems (drip, sprinkler) has been a quantum leap in terms of improving water-use efficiency and producing more from the same amount of water.

Another essential element is crop nutrition. Fertilizers have played an important, if not the major, role in enhancing agricultural productivity in the past century; the role of fertilizers will be no less important in the future for developing-country agriculture. As fertilizers are a costly input, the future focus will be on efficient use of this vital resource. Apart from production, more efficient use of fertilizers has significant environmental implications, especially in developed countries. The concept of fertigation represents significant strides in the efficient use of two major and essential resources in combination.

The World Phosphate Institute (IMPHOS) is to be complemented in convening this workshop on nutrient use in efficient irrigation systems. It coincides with a crucial juncture in the development of the water-starved Middle East and North Africa area, where the current focus is on water and implicitly on the nutrients that sustain growth. The workshop sought to:

- Emphasize the importance of proper plant nutrient management to promote and sustain productive and efficient cropping systems under pressurized irrigation.
- Review the current fertigation systems and the range of phosphorus (P) sources available for fertigation in the Mediterranean region.
- Address various economic and environmental issues related to fertigation.
- Discuss research and development needs in relation to P fertigation in the Mediterranean region.

This significant workshop in Amman, and the resulting proceedings in this volume, is ground-breaking in that it represents an effective collaboration between the fertilizer industry and both national agricultural research systems, and international research centers, in the noble pursuit of improving agriculture and the welfare of mankind. This kind of collaborative response augurs well for the future.



Prof. Dr. Adel El-Beltagy
Director General
ICARDA

ACKNOWLEDGEMENTS

Any successful workshop depends on the efforts of the people who are involved in the organization of the meeting and those who support it financially. The workshop on "Plant Nutrient Management under Pressurized Irrigation Systems in the Mediterranean Region", held in Amman in 25 - 27 April 1999, was eminently successful because of the efforts of those who supported it.

Accordingly, we would like to thank the organizing committee for preparing an excellent program: Dr. I. Papadopoulos, Cyprus (Chairman); Dr. P. Moutonnet, IAEA, Vienna; Dr. John Ryan, ICARDA, Syria; Dr. A. Hamdy, CIHEAM - Bari, Italy; Dr. A. Fardous, NCARRT, Jordan; and Mr. A. Ghosheh, N. S. Batta, and L. Dabbas (Jordan Phosphate Mines Company, Jordan); and Mr. T. Mrabet, Dr. L. Cisse, and Mr. B. Amar from IMPHOS, Casablanca, Morocco.

We thank the Ministry of Agriculture, Jordan, for its patronage of the Workshop. The following institutions that have joined forces with IMPHOS in supporting the workshop deserve our wholehearted appreciation.

- Jordan Phosphate Mines Company (JPMC), Jordan.
- National Center for Agricultural Research and Technology Transfer (NCARTT)
- The Food and Agriculture Organization of the United Nations (FAO), Regional Office for the Near East in Egypt.
- The International Atomic Energy Agency /Joint FAO-IAEA Division of Nuclear Techniques in Food and Agriculture, Vienna, Austria.
- The International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.
- The International Center for Advanced Mediterranean Agronomic Studies (CIHEAM /IAM - Bari), Italy.

As the tangible and lasting output from the meeting is the proceedings volume that contains the papers of presentations and posters, as well as deliberations at that meeting. The technical assistance of Miss Rima El-Khatib, B. Eng., in the mammoth task of completing production of the volume has been invaluable; several iterations were made of the papers, tables were restructured, figures re-drawn, and myriads of detail had to be checked and, finally, the volume had to be prepared electronically for production. The assistance of Communications, Documentation and Information Services (CODIS) staff at ICARDA is appreciated: Miss Joyce Bendki for proof-reading, Mr. Ahmad Shab-Kalyeh for redrawing some of the graphics, and Miss Wafa Meskine for finalizing the typesetting. Similarly, the assistance and support of Dr. S. Varma, Head of CODIS, is acknowledged.

John Ryan,
Editor

A. FULL PAPERS

KEYNOTE ADDRESSES

Fertigation: Present Situation and Future Prospects

Ioannis Papadopoulos

*Agricultural Research Institute, Ministry of Agriculture,
Natural Resources and Environment, Nicosia, Cyprus*

ABSTRACT

A continued improvement in irrigation technology and efficient use of irrigation water and fertilizers are essential to keep food supply in balance with the increasing demand on environmentally sound grounds. However, irrigated agriculture can only be environmentally sustained provided the basic principles of good water and fertilizer management are recognized. *With inappropriate planning, the threat of environmental damage due to irrigation/fertilization is inevitable, whereas intensive irrigated agriculture properly planned, constructed, and managed, can be an environmental and human asset instead of being an environmental problem.* In this paper, fertilization concerns are stressed, with more emphasis given on phosphorus (P) fertigation – the application of fertilizers in irrigation water – as a means to increase yield and improve quality, as well as being the best fertilizer management approach for intensive sustainable agriculture.

Brief evaluation of the various irrigation systems in relation to fertilization-fertigation is made. Particular emphasis is attached to water-use efficiency and to the concept of the "step-by-step fertigation" approach as a means to practice efficient and effective fertilization under improved irrigation systems. In the context of effective, efficient and safe use of fertilizers, irrigation, fertilization, soil fertility, crop nutrient requirement, and fertilizers needed by various crops for yield and quality are integrated and treated as a unique compact system. However, aspects of P fertigation are elaborated more extensively and means and approaches to improve the efficiency and effectiveness of P fertigation at farmer's level are proposed.

The present situation and knowledge, as well as future developments, prospects and priorities in research concerning fertigation, with emphasis on P fertigation, are also discussed. Examples concerning calculations and the methodology of the "step-by-step approach" are attached as Appendices. The review clearly shows that fertilization is *resource – efficient, economically sound, and environmentally friendly.*

INTRODUCTION

It is anticipated that by year 2025 the planet would have double the number of humans it has now. However, in contrast to population growth, water resources are *finite and expansion of cultivated land is limited*. Because of this, we will inevitably move to more intensive agriculture aimed at increasing food production, where chemicals and fertilizers will be extensively used. In this respect, improving agricultural fertilizer management, irrigation methods and water-use efficiency will be of particular importance not only to increase food production but also to protect the environment and public health (Papadopoulos, 1997a).

The recent popular approach of "limiting fertilizer application", leading to decreased yield or practising pure "organic gardening", irrespective of soil fertility, although it might be a solution to control negative environmental impact, cannot be considered a solution for the increased demand for food. For developing countries, sustainable agriculture means providing opportunities to the farmers for a better life. The solution is not to rule out fertilizers, but to provide crops with the required amounts of nutrients in an appropriate and efficient way. We must look at *fertilizers as a valuable economic resource and not as a pollutant source*. Chemical fertilizers are a real and essential asset provided that they are applied whenever needed by the crop (timing of application) in the appropriate form and amount; placement is also of particular importance (Papadopoulos, 1996a; 1996b). It should be stressed that ultimately no irrigation project can be sustainable if it is not profitable at farmers level, and profitability largely depends on fertilizers (Papadopoulos and Chimonidou, 1977)

However, there is an increasing concern about the effective and efficient utilization of water and fertilizers. The promotion of efficient and effective water and fertilizer use, which means best management of water and fertilizers at farmers level, was identified as an important contribution to the strategy needed to address problems of water scarcity and practising intensive agriculture. Improving water-use efficiency, and consequently that of fertilizers at farmers' level, is the major contributor to increasing food production, reversing the degradation of the environment or avoiding irreversible environmental damage, and allowing for *sustainable irrigated agriculture* (Papadopoulos, 1997a). Moreover, given the limitation to further expansion of irrigated land in most countries, a large part of the future food requirements will need to be covered from more efficient and sustainable use of irrigation water and fertilizers, as well as other chemicals (FAO, 1993).

Therefore, full intensification of agriculture in irrigated lands, while taking all possible precautions against the environmental problems that could follow this approach (extensive use of fertilizers), is the challenge of the immediate future. This, of course, affects the needs and modes of future intensive irrigated agriculture. In this respect, *fertigation (application of fertilizers with the irrigation water)* is

proposed and discussed in this paper as a means to increase efficient use of water and fertilizers, increase yield, protect environment, and sustain irrigated agriculture.

As fertigation is directly related to improved irrigation systems and water management, irrigation methods, with emphasis on those which are appropriate for fertigation and which consider crop water requirements and irrigation scheduling, are briefly discussed. It should be stressed that *"no sound fertigation could be practised if not based on good irrigation management"*.

*irrigation methods
fertigation*

IRRIGATION METHODS

Surface Irrigation Methods

Furrows, border strips and level basins are the most commonly used surface irrigation methods. Surface irrigation methods, with particular emphasis placed on furrow, very rarely achieve an efficiency of irrigation water exceeding 50% at farmers' level, due to non-uniform water application and leaching. For these systems, accurate leveling is the most important practice for improving irrigation and fertilization efficiencies. What is required is not to make the land level but to grade the surface to a uniform slope. Precision in land – leveling benefits the crop by permitting uniform application of a smaller irrigation depth at more frequent intervals (Tyagi, 1984). For a constant seasonal irrigation amount, the amount of water per application and the irrigation frequency have an inverse linear relationship.

However, precise land grading techniques are only easily available for large farms, and appropriate solutions have to be found for improvements required by small farmers (Pereira, 1995). Evidently, with surface irrigation methods, due to low irrigation efficiency, it is difficult to practice fertigation and, in reality, it is not recommended; the fertilizer efficiency is low and contamination of drainage water could be a serious problem, which is worsening each year (Spalding et al., 1989). However, some experimental work with furrow fertigation has indicated some positive results (Pereira et al., 1994).

Pressurized Irrigation Systems

With these systems such as center pivot, sprinklers, mini-sprinklers, sprayers, drip and bubblers, potential irrigation efficiency varies from 70–90%, while the distribution uniformity is between 80–90%, (Papadopoulos, 1996b; RNEA/FAO, 1992).

Having compared the effects of three irrigation systems on $\text{NO}_3\text{-N}$ leaching and uptake efficiency, Watts et al. (1993) showed that improved center-pivot sprinkler system used 67% less water and 80% less fertilizer N to obtain 91% of the

grain yield compared to the conventional furrow irrigation (Table 1). They concluded that with better irrigation management and fertigation, the impacts of irrigation on soil and groundwater quality could be minimized; *less fertilizer is even required for increased yield.*

Table 1. Residual soil N and N-uptake efficiency as a function of the irrigation method.

Irrigation		Nitrogen-Use Efficiency				
Irrigation System	Irrigation Water	Fertilizer Soil-Applied	Applied with Irrigation	Residual Soil N	Total N	Yield
	---mm---	-----kg/ha-----				-Mg/ha-
Furrow	940	201	301	106	608	12.53
Surge-Flow	450	123	144	173	440	12.33
Center-Pivot	340	33	109	95	237	12.17

Adapted from Kanwar (1996)

Frequent irrigation, without or with minimal leveling, is one of the main advantages of micro-irrigation systems. With these systems, conveyance losses are limited, wetted soil surface area is restricted, and water and fertilizer efficiencies higher than 80% can be achieved (Papadopoulos, 1993).

Ayars and Phene (1993), comparing the effects of furrow and drip irrigation on groundwater quality, found that the $\text{NO}_3\text{-N}$ concentration was less under the latter drip system. However, this could be the case provided that N is applied in small portions or continuously in low concentrations with the irrigation water (Papadopoulos, 1996b). Irregular N application may induce substantial leaching which, with drip irrigation as a point source for water, might be even more severe (Papadopoulos, 1996a).

With drip-fertigation system, an uptake of N fertilizer exceeding 80% has been obtained with the same amount of water compared to conventional soil N fertilization, where the N efficiency rarely exceeds 50%, even under good irrigation scheduling. Similarly, uptake of P and K are substantially improved. In this respect, per unit of fertilizer and water applied, higher yield and better quality are obtained (Papadopoulos, 1995). With sprinkler fertigation, a portion of the response could be attributed to foliar absorption (Gascho and Hook, 1991).

MICRO-IRRIGATION SYSTEMS

Drippers

Different types of drippers are available; *vortex-type*, *labyrinth-type*, *long path micro-tube drippers*, *self-regulated drippers*, etc. The flow rate of the individual nozzle ranges between 2 and 10 l/h at the recommended operational pressure, i.e., usually 1 bar. Drippers are mainly used to irrigate vegetables grown in rows spaced at a relatively great distance in the row and between rows. One outlet is usually installed to deliver water to each plant. They also find application in permanent tree plantations. One or two lateral lines are usually installed per tree row, or a feeding line with a loop around each tree on which the drippers are installed. The dripper spacing on the irrigation line in the orchards may range between 40 to 150 cm; it is closer in light (sandy) soils and with small dripper discharge rate, while it is wider in heavy (clay) soils and with an increased dripper discharge rate.

Mini-Sprinklers (Spitters)

Different types are available. Their flow rate at 2-bar operational pressure ranges between 30 and 150 l/h and the corresponding wetted area is between 2 and 6 m in diameter. During the first years of tree growth, mini-sprinklers with the least flow and wetting diameter are recommended to avoid water losses and excessive weed growth. With tree growth, the orifice of the nozzle is changed to increase the flow and the wetted area. Recently, nozzles of up to 250 l/h have been manufactured, but their use is not recommended because tree performance is not further improved and the installation cost is higher. Nozzles wetting a full circle, half-circle or a quarter of a circle, are available. The part circle nozzles are used in cases where moistening of the trunk favors disease attack. Various micro-jet systems are also successfully used in orchards.

Low-Capacity Sprinklers

They are plastic rotating sprinklers of low discharge rate, ranging between 120 and 250 l/h at 2-bar operational pressure. They are used to irrigate densely spaced vegetable crops (potatoes, carrots, beans, etc.). They are permanently attached to polyethylene pipes of 25 to 32 mm in diameter, and the recommended spacing in the field is 5 × 5m. The best operational pressure ranges between 2 and 3 bars.

Drip and mini-sprinkler irrigation systems have experienced a major increase in commercial significance and research interest in the past three decades. Both systems, as they are known today, have become practical with the development of plastics that are *inexpensive*, *durable*, and *easily molded into the variety and complexity of shapes required for pipe and emitters* (Shoji, 1977). The earliest

systems were made up of small-bore (1–2 mm ID) plastic micro-tubes (emitters) inserted into a larger-diameter plastic pipe (Kenworthy, 1972). Water emission rate was controlled by friction in the micro-tube, producing irrigation rates of 2 to 6 l/hr per emitter.

Operating pressures were low, often around 103 kPa (Kenworthy, 1972), necessitating careful system design to offset effects of small elevation changes on internal system pressure and emission rate. Emitters have since evolved into a number of forms, from discrete emitter units to various types of porous hose, and more recently to pressure-compensating types that regulate flow over a range of pressures, permitting higher pressures to be utilized in drip irrigation lines.

Recent innovations designed to adapt drip irrigation to different conditions include *moving units*, *simplified bubbler systems*, and the promotion of *spitters* or *micro-sprinklers* rather than *drippers*. Perhaps the most significant trend has been toward greater control and automation of the frequency and amount of water application, using programmable computer-based systems and including such devices as sequential-metering valves and sensors to monitor weather and soil moisture variables. More recently, new drip irrigation systems have been introduced for use with wastewater in both agricultural and garden settings. The rubber tubes of these pipes have a labyrinth “toothed” water passage which facilitates superior filtration. *Chemigation, and particularly fertigation, are yet other developments of major importance.*

Despite being recent, drip irrigation and micro-irrigation, in general, have been the subject of a number of reviews. Early reviews focused on specific developments or practices in different countries (Goldberg, 1972) or discussed the potential for drip irrigation (McNamara, 1970). Phene and Beale (1976) reviewed developments and applications of sub-surface irrigation in humid areas of the U.S.A. The development for sub-surface drip irrigation has been retarded by problems of plugging, which are much more difficult to diagnose, accumulations of salt at the soil surface when saline water is used, and other difficulties that offset the benefits in water savings from reduced evaporation (Rawlins and Raats, 1975). Black (1976) and Mailard (1976) reviewed the history, developments, and applications in drip irrigation through the mid 1970s. More recently, the topics of drip irrigation design, soil-water relations, infiltration phenomena, and salt movement under drip irrigation have been subjected to detailed mathematical analysis (Bresler, 1977).

Advantages of Micro-Irrigation Systems

The advantages of the micro-irrigation systems can be summarized as follows (Papadopoulos, 1996b):

- *Significant water-saving.* Since conveyance losses are eliminated and soil

surface area wetted is restricted, efficiencies higher than 80% can be achieved.

- *Increased yields.* The root zone of crops, with modern irrigation methods, remains continuously moist and the plant, therefore, is not subject to stress cycles.
- In addition, the *required fertilizers can be applied* with the irrigation water (fertigation) whenever and where the plant exactly needs them.
- They may be *used for full chemigation* (fertigation, herbigation, insectigation, fungigation, and nematigation).
- The area between plant rows of trees remains free and dry, thus enabling spraying and harvesting to be done even during water applications.
- *Utilization of steeper slopes and problem soils* otherwise unsuitable for irrigation with conventional irrigation method.
- *Poor quality saline water* can be used with drip and mini-sprinkler irrigation methods because by maintaining high moisture in the soil with frequent irrigations, the salt that is being added with irrigation water is diluted and remains at acceptable levels.
- They can *operate with a limited flow rate* at a relatively low-pressure head, i.e., 1 bar for drippers and 2 bars with mini-sprinklers. This means savings in the cost of the pump, fittings, lines, energy, and labor.
- *They require limited labor.* They can be automated by using automatic metering valves, electronic tensiometers, time switches, etc.

Problems and Drawbacks of Micro-Irrigation Systems

- *Relatively high investment* is required for the installation of the modern irrigation systems, ranging between \$ 2,200 – 7,000/ha. Economic incentives to farmers can help in this respect. Usually the cost of drip irrigation systems is higher than low-capacity sprinklers and mini-sprinklers.
- *Toxicity problems:* They are associated mainly with sprayers and mini-sprinklers due to high bicarbonate, sodium, and chloride concentrations in the water. Wetting of foliage with water high in bicarbonates causes white deposits on leaves, which drastically reduce plant photosynthesis. In addition, high sodium or chloride concentrations of irrigation waters, exceeding 3 meq/L, create problems to sensitive crops if the irrigation water wets their foliage. With such waters, low-angle mini-sprinklers kept close to the ground may reduce wetting of the foliage and, therefore, may help overcome the problem in orchards.

- *Emitter clogging*: The load of suspended matter, chemical precipitates, and biological slimes may cause emitter clogging, particularly in drip irrigation. The plugging potential of irrigation water when emitters with small nozzle openings are used (Bucks et al., 1979) is presented in Table 2.

Table 2. Plugging potential of irrigation water in drip irrigation systems.

Type of Problem	Restriction on Use		
	Little	Slight to Moderate	Severe
<u>Physical</u>	< 50	50 – 100	> 100
Suspended Solids (mg/L)			
<u>Chemical</u>			
PH	< 7.0	7.0 – 8.0	> 8.0
Dissolved solids (mg/L)	< 500	500 – 2,000	> 2,000
Manganese (mg/L)	< 1.0	0.1 – 1.5	> 1.5
Iron (mg/L)	< 0.1	0.1 – 1.5	> 1.5
Hydrogen sulfide (mg/L)	< 0.5	0.5 – 2.0	> 2.0
<u>Biological</u>			
Bacterial populations (maximum number, m/L)	< 10,000	10,000 – 50,000	> 50,000

Components and Design of Micro-Irrigation

Head of the System

The head of the system is similar to all micro-irrigation systems. The following fittings are indispensable: *vacuum valve, check or one-way valve, volumetric water meter, fertilizer injector, pressure-control valve, and filters.*

Main and Sub-Main Supply Lines

Plastic pipes, usually of black polyethylene of high or low density and PVC ranging in diameter from 40 to 90 mm outside diameter (O.D.) are used. They are manufactured to withstand a pressure of 4 to 6 bars.

Irrigation Lines

The diameter of the piping to be installed depends on the length of lateral lines and flow rate. For drip systems, 12 to 25-mm O.D. black polyethylene piping, usually

of low density, is used; for the mini-sprinkler systems, between 20 and 32-mm O.D.; and for low-capacity sprinkler systems, between 25 and 32-mm O.D. The pressure loss in the irrigation lines must not, in general, exceed 20% of the minimum pressure required by the orifice. They are manufactured to withstand a pressure of 4 bars.

SCHEDULING OF IRRIGATION

An irrigation system, which is well designed, operated and maintained, may potentially reach high water uniformity and water-application efficiency. However, in order to achieve high water-use efficiency by the crop, scheduling of irrigation should be based on scientific data and not practised empirically. Two main irrigation parameters are a prerequisite for scientific and sound irrigation /fertigation:

- Crop water requirement, and
- Timing of water application (frequency)

*water requirement
plant water relation*

Crop Water Requirement

The water requirement of crops is a major aspect in irrigated agriculture. It is the basis for the design and operation of irrigation systems, as well as for scheduling irrigation and practising fertigation. *Without efficient irrigation, fertigation would create more problems than being helpful to the farmers.*

In Cyprus, as a simple and practical way for estimating the amount of irrigation water and scheduling irrigation, the fraction of Epan evaporation from the USWB Class A pan is used. This method is tested the last four decades with excellent results. It has been tested in a lot of farms where individual pans have been installed. In Cyprus, the USWB Class A pan has been established as a standard instrument in meteorological stations.

The basic pan evaporation measurements (E_{pan}) are converted to reference evapotranspiration (ET_o) using the equation:

$$ET_o = K_p \cdot E_{pan} \dots\dots\dots (1)$$

Where:

K_p is the pan coefficient, which takes into account the type of the pan, its environment and climate. The evaporative demand of the atmosphere is expressed by ET_o , and is defined as “The rate of evapotranspiration of an extended surface of green grass cover, 8–15 cm tall, actively growing, completely shading the ground and not short of water”.

Potential crop evapotranspiration (ET_{crop}) is calculated from ET_o according to:

$$ET_{crop} = K_c \cdot ET_o \dots\dots\dots(2)$$

Where:

K_c is the crop coefficient, which depends on the kind of crop and its stage of development.

Combining Equations 1 and 2, ET_{crop} can be expressed as function of E_{pan} according to:

$$ET_{crop} = K_c \cdot K_p \cdot E_{pan} \dots\dots\dots(3)$$

The procedure described is the general one suggested by FAO. In Cyprus, the value of K_p coefficient for a specific area is constant over the irrigation season. Therefore, the product $K_c \cdot K_p$ in Equation 3 can be substituted by a coefficient C . The resulting equation is:

$$ET_{crop} = C \dots\dots\dots(4)$$

Crop potential evapotranspiration is, therefore, calculated directly from pan evaporation, using a single coefficient, which expresses the ratio of ET_{crop} to E_{pan} . This ratio depends on the crop under consideration and its stage of development.

Values of the coefficients to be used can be obtained experimentally (Tables 19, 20), or can be derived from the literature (FAO, Irrigation and Drainage Papers 24 and 33). It is always advisable, however, for these coefficients to be checked locally before they are used in irrigation practice. The “C” fraction of the E_{pan} is extensively used in many countries for scheduling irrigation. It is also used in the Fertil-Computerized System Program, which will be presented in following chapter.

Frequency of Irrigation

The amount of water per irrigation and consequently the frequency of irrigation depend on soil hydraulic characteristics, water-holding capacity, the crop, and the irrigation method. The amount of water per irrigation for a crop at full growth, under the prevailing conditions, must be kept constant. The justification is that water should penetrate into the soil always to the same depth where the main rooting system is developed. Therefore, the frequency of irrigation is the flexible parameter for good scheduling of irrigation. Irrigation by time, which is still practised in most counties, is not justified (Papadopoulos, 1997a). *Sound fertigation is based on sound scheduling of irrigation.*

FERTIGATION

The application of chemicals (chemigation) through the irrigation system has become a common practice in modern irrigated agriculture (Bresler, 1977; Elfving, 1982; Hairstone et al., 1981; Phene and Beale, 1976; Phene and Sanders, 1976; Papadopoulos, 1985; 1986a; 1986b; 1987a; 1988). Application of chemicals, especially fertilizers (fertigation), through irrigation systems is a practice of relatively long standing. However, fertigation-chemigation research and practical applications, coupled with advances in irrigation-system design, has recently led to a rapid expansion of both fertigation and chemigation.

Fertilizers were probably the first chemicals injected into modern irrigation systems (Goldberg and Shmueli, 1969; 1970; Stark et al., 1983; Papadopoulos, 1991). Since these initial applications, many types of chemicals have been injected into irrigation systems, including herbicides (Lange et al., 1974; Phene et al., 1979), fungicides and insecticides (Phene et al., 1979; Young, 1980), nematicides (Chesness et al., 1976; Overman, 1975; 1978; Jonson, 1978), growth regulators (Bryan and Duggins, 1978), fumigants (Goldberg and Uzzad, 1976; Overman, 1976), and chlorine, acids and other chemicals to control clogging (Bucks et al., 1979; Ford, 1976; Ford and Tucker, 1975; Nakayama et al., 1977).

Drip and other micro-irrigation systems, which are highly efficient for water application, are also ideally suited for fertigation and are practical for chemigating certain applied chemicals (Goldberg and Uzzad, 1976; Papadopoulos, 1985; 1997b; Bresler, 1987). In this way, water-soluble fertilizers, at concentrations required by crops, are conveyed via the irrigation stream to the wetted volume of soil. Thus, the distribution of chemicals in the irrigation water will likely place these chemicals in the desired location, i.e., the root zone (Bar-Yosef and Sheikholeslami, 1976; Goldberg et al., 1971; Papadopoulos, 1985; 1986a; 1986b; 1997b; Gervin et al., 1979). This reduces water and fertilizer application (Clark et al., 1991). Furthermore, with drip irrigation, the application of herbicides and pesticides for soil-borne diseases and pests, due to the localized application in the wetted area only, results in the chemicals being more effective at lower concentrations (Gerstl et al., 1981). In contrast to drip irrigation systems, sprinkler irrigation systems are exceptionally well suited to spray-chemigation.

Advantages and Disadvantages of Fertigation

Some potential advantages of fertigation are: *higher yield* (Clough et al., 1990) (Table 3), *improved quality of produce* (Table 4), *improved efficiency of fertilizer recovery* (Miller et al., 1981; Phene and Beale, 1976; Nielsen et al., 1990), *minimal fertilizer losses due to leaching* (Bresler, 1977; Klein et al., 1989; Papadopoulos, 1985; 1992a; Stark et al., 1983), *control of nutrient concentration in soil solution* (Bar-Yosef, 1977; Papadopoulos, 1986a; 1986b; 1987b; 1992b), *control of nutrient*

forms and ratio of the various forms particularly for N-fertilizers, and *flexibility in timing* (Hartz and Hochmuth, 1996) of fertilizer application in relation to crop demand based on development and physiological stage of crops (Snyder and Burt 1976; Bresler, 1977; Kovach, 1983).

Table 3. Yields of some crops irrigated with pressurized micro-irrigation systems as influenced by fertigation and traditional fertilization.

Crop	Fertigation	Traditional Fertilization
	-----t/ha-----	
Potatoes	70	37
Carrots	54	42
Tomatoes (greenhouse)	350	150
Tomatoes (open field)	180	55
Cucumber (greenhouse)	300	140
Watermelon (open field)	115	60
Strawberries (low tunnels)	48	20

Source: Papadopoulos (1996b).

Advantages of scheduling fertilizer applications on the basis of needs are potentially reduced nutrient-element losses associated with conventional application methods that depend on the soil as a reservoir for nutrients. In addition, fertigation reduces fluctuations of soil solution salinity due to fertilizers (Papadopoulos, 1985), thereby improving soil solution conditions, particularly for salt-sensitive crops (Papadopoulos, 1986b; 1987c). In general, with fertigation, protection of soil and water from fertilizers on a sustainable basis can be achieved (Papadopoulos, 1997b).

Table 4. Characteristics of potato tubers as influenced by fertigation and traditional fertilization.

Characteristic	Fertigation	Traditional Fertilization
Specific Gravity (%)	1.073	1.064
Dry Matter (%)	19.00	17.06
Starch (%)	13.20	11.38
Nitrate-N (mg/kg DM)	141	290
Yield (t/ha)	70	37

Source: Papadopoulos (1996b).

Eventual disadvantages of fertigation include unequal *chemical distribution when irrigation system design or operation is inadequate*, *over-fertilization* where irrigation is not based on actual water requirements, or *leaching* if rainfall occurs at the time of fertilizer application, and *chemical reactions in the irrigation system* leading to corrosion; *precipitation of chemical materials*; and/or *clogging of outlets*. Most of these problems have been extensively studied, and solutions are available.

Fertigation Systems and Equipment

The fertigation unit is composed of a *fertigator* (fertilizer injector, metering pump), a *fertilizer tank* for the concentrated stock solution, a *non-return valve*, a *main filter*, and *water meter*. Depending on the model of the fertigator, additional equipment (valves, pressure and flow regulators) may be required. The metal tanks may corrode, and therefore plastic containers are preferred. Flushing after fertigation reduces both the corrosion hazard and microbial growth. Chemical injection can be accomplished in four main different ways (Bresler, 1977; Papadopoulos, 1996b).

Venturi Pumps

A constriction in the main water-flow pipe causes a differential pressure ('vacuum') which is sufficient to suck chemical solution from an open reservoir into the water flow. The rate of flow can be regulated by means of valves. This is a simple and inexpensive method of chemical application, but it has some disadvantages; the pressure loss across a Venturi valve is high (about 1/3 of the operating pressure), and precise regulation of flow is difficult because the rate of injection is very sensitive to the pressure and rate of flow in the system.

Recently, it has been suggested to install the Venturi valve on a by-pass of the total irrigation flow. In this way, the head loss decreases considerably, the capacity of the system increases substantially, and the chemigation system can be disconnected and moved easily. The apparatus is quite simple, relatively inexpensive, easy to install, does not have moving parts, and it is particularly convenient for small fertigated areas. The suction is from an open plastic container; the dilution ratio does not fluctuate. Among its limitations are relatively large head loss in the direct connection and sensitivity to changes in pressure and discharge rate. However, installation of a pressure-regulating valve will enable constant injection rate (Eliades and Hadjiloucas, 1985).

By-Pass Flow Tank

This method employs a tank into which the dry or liquid chemical is placed. The tank is connected to the main irrigation line by means of a by-pass so that some of

the irrigation water flows through the tank and dilutes the chemical solution. This by-pass flow is created by a pressure gradient between the entrance and exit of the tank caused by a permanent constriction in the line or by a control valve. The concentration of chemicals in the tank decreases gradually.

Some of the advantages of the system are its simplicity in construction and operation, and its low cost. There is no need for an external power supply, and it is not very sensitive to changes in pressure or flow rate. The disadvantages of the system are: the varying concentration of nutrients causes the bulk of the chemical to be applied at the beginning of the irrigation cycle; and the tank has to be refilled with solution at each irrigation. This system is not suitable for automatic or serial irrigation. This system because of its simplicity and low cost, is the most common fertigation system in use in semi-automatic drip installations.

Pressure-Differential System

This is a variation of the above flow by-pass system. The tank is fitted with a rubber diaphragm to separate the fertilizer solution from the irrigation water. The rate of flow of the solution is determined by the difference in pressure between the inlet and outlet points and is monitored by a flow meter. This technique ensures a relatively constant rate of supply of fertilizer to the irrigation water, provided the flow rate of the chemical solution is adjusted to the flow rate of the irrigation water.

The main advantages of by-pass systems are their simplicity to operate, the absence of moving parts, and the fact that they do not require electric, fuel or water pumps. They can operate wherever water is flowing and pressure drop is present. The primary disadvantage, on the other hand, is that concentration is not uniform, but changes continuously with time.

A modification of the pressure-differential system is a tank that contains a collapsible plastic bag into which the chemical is added. Water is admitted to the area between the tank and the bag, which forces the chemical compound from the bag into the system.

Injection-Pump System

With this method, a pump is used to inject chemical solution from a tank into the irrigation line. The solution is normally pumped from an open un-pressurized tank, and the choice of type of pump used is dependent on the power source. The pump may be driven by water flow, by an internal combustion engine, by an electric motor, or by a tractor power take-off. The electric pump can be automatically controlled and is thus the most convenient to use. However, its use is limited by the availability of electric power, and is therefore, more suited to greenhouse than to field cultivation.

With these injection devices, chemicals may be supplied to the irrigation water at a more or less constant rate. The pumping rate and the concentration of the stock

solution can be adjusted to attain the desired level of chemicals to be applied. However, the water flow and the chemical flow are independently controlled. The dilution factor, therefore, is necessary to be estimated directly in the field and, after being estimated, be checked periodically. Changes in water flow, power failure, or mechanical failure, may cause serious deviation from the planned concentrations. The use of pressure regulators may help overcome the problem.

Another disadvantage of this system is the need for an external power source and the relatively high cost of the system. The use of a hydraulic motor, operated by the line flow, avoids these difficulties. This device requires a minimal pressure (1.5–2.0 bars) to operate. At each stroke of the pump, a certain pre-determined volume of chemical solution is injected into the irrigation system. The number of strokes can be adjusted accordingly. A pulse-generating water-meter may activate the hydraulic motor so that the injected chemical it is proportional to the water flow and a constant concentration is maintained. Automatic computerized control systems are also available to provide proportional injection of chemicals into the water flow.

In general, the volumetric feeding injectors can be used more successfully for fertigation than the Venturi tubes. The chemicals are injected to the irrigation pipes from the pressureless container by a pump operated by the energy of the water, electric energy, or internal combustion engine. They do not cause loss of pressure, and can be regulated accurately. It is possible to use them effectively in mobile operation, and the operation is simple and cheap. The pumps operated by the energy of the water do not need external energy and operate safely at the pressure needed for the irrigation. The operation pressure can regulate the delivery capacity. It is advantageous that the injection of the chemical also stops at the time of stopping the application of irrigation water.

From the piston-type solutions, the $\frac{3}{4}$ " – $1\frac{1}{2}$ " – 2" size versions of the DOSATRON feeders are able for an injection capacity of 0.03 – 400 l/h, and their operation is safe between 0.12 – 10 bar. The disadvantage of the piston-type injectors is that there is a fairly big quantity of the chemical in these injectors, therefore cleaning, emptying, and filling is not so convenient as in the simple injectors. In those types, where the feeding is regulated by the stroke adjustment of the piston, it is necessary to re-start the system after the adjustment.

The injector, AMIAD, eliminates these disadvantages, because it delivers the required amount by a higher-pulse capacity per minute and by a very small size of piston (1 pulse=33 ml). In its operation range, at a pressure of 0.5–8 bar, the injecting capacity is 40–360 l/h, applied by 20–180 pulses /minute. For higher-capacity demands, the Duplex injector unit, and for extremely accurate feeding, the incorporation of a flow meter is suggested. It is possible to transform the pulses electronically, which is the basis of automatization.

The advantage of the diaphragm-type pumps is that they operate with very few moving parts, and only a few of them are exposed to the corrosive effect of

chemicals. Between the instruments operated by the irrigation water and the instruments operated by the oil pressure, the mobility of the earlier ones is better; the T.M.B. fertilizer pump is representative of these types. It is double-membrane equipment (manufactured in size 1/2" – 3/4". Its operational pressure is 0.14–7 bars with an injected amount of 3–1200 l/h, it is regulated by smooth regulation, and the valves needed for its operation also serve as safety valves. It has an electronic impulse marker (one impulse = 250 ml).

The general advantages of the injection pump system are; the high degree of control of the amount and timing of chemical application, centralized and sophisticated control, portability, no serious head loss in the system, labor-saving and relatively cheap in operation. On the other hand, the installation is more complex, costly compared to other applications, and outside power sources may be needed. The equipment for fertigation/chemigation is summarized by Janos (1996).

Back-Flow Devices

Back-flow prevention is critical with a fertigation system. If it is not used, fertilizer that remains in the system when it is shut down will siphon back through the pump into the water source. Contamination of surface water source leads to alga blooms and other environmental consequences. Fertilizer contamination by back-flow into a well source can cause groundwater pollution. In some instances, this results in dangerous nitrate levels in drinking water from groundwater. In USA, there are rigid standards for back-flow prevention (Threadgill, 1985). It is our responsibility to prevent water source contamination. *"The well you save may be your own drinking water"*.

DISTRIBUTION OF FERTILIZERS UNDER DRIP FERTIGATION

The fertilizer application through drip and other micro-irrigation systems is currently the most common application of the chemical injection techniques. Drip fertigation is an attractive concept, as it permits application of nutrients directly at the site of a high concentration of active roots and as needed by the crop. However, following application through drip irrigation, mineral nutrients move into the wetted volume in a manner consistent with the flux of the water in the soil, their solubility and/or reactivity with constituents in the soil solution, and their interaction, if any, with the exchange sites of the soil. Since chemical characteristics of fertilizers differ, mineral nutrients are differently distributed in the soil when applied by drip or other micro-irrigation systems (Bar-Yosef, 1977; Goldberg et al., 1971; Papadopoulos, 1985).

Nitrogen

The nitrate form of N does not react with the soil exchange sites, and is not held in soils. Nitrates move with other soluble salts to the wetted front. This is of particular interest since $\text{NO}_3\text{-N}$ should always be applied with every irrigation and at that concentration needed by the fertigated crop to satisfy its N requirement from one irrigation to the other (Papadopoulos, 1988; Hamdy, 1991). Theoretically, this is in full agreement with experimental results – the distribution of $\text{NO}_3\text{-N}$ and salinity in the soil due to fertilizer, following regular or irregular application is given in Fig.1.

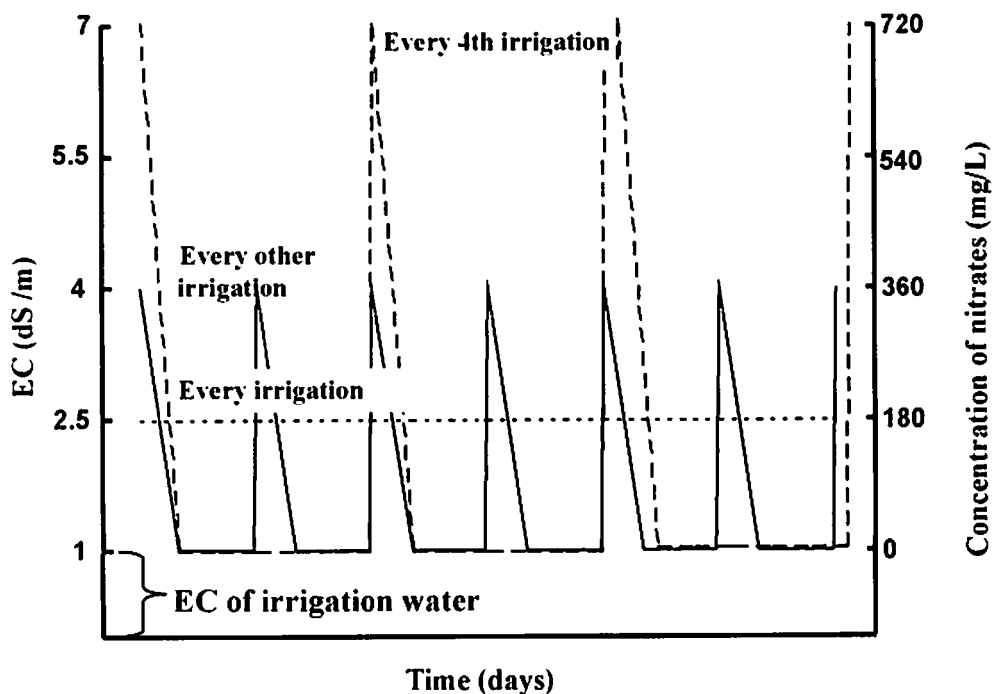


Fig. 1. Schematic distribution of nitrates and salinity in soil below the dripper following fertigation with every irrigation, every fourth or every 7th irrigation, when the irrigation water has EC of 1.0 dS/m and 180 mg $\text{NO}_3\text{-N/L}$ (Papadopoulos, 1996a).

Evidently under irregular $\text{NO}_3\text{-N}$ application, the fertigated crops might be under the over-fertilization stress at the day of fertilizer application and under deficient stress due to leaching following the irrigation without fertilizer. The same applies, although at a lower degree, for other nutrients that are not reacting with

soil, and almost with all nutrients under pure sandy soils (Papadopoulos, 1991). The ammonium form of N derived from ammonium or urea fertilizers is not nearly so subject to immediate leaching losses because it may be temporarily fixed on exchange sites in the soil.

Ammonium and urea, however, may induce acidification, which may create higher solubility of nutrients such as P and Al and their movement in soil (Chung, 1994). Urea is a highly soluble, chargeless molecule which easily moves with the irrigation water and is distributed in the soil similarly to NO_3^- . At 25 °C, it is hydrolyzed by soil microbial enzymes into NH_4^+ within a few days. This hydrolysis results, initially, in an increase in soil pH, which in soils of pH >7.5 may reduce P availability to plants.

Potassium

Potassium is less mobile than nitrate (Goode et al., 1978), and its distribution in the wetted volume may be more uniform due to interaction with soil-binding sites (Kafkafi and Bar-Yosef, 1980; Uriu et al., 1980). Drip-applied K moves both laterally and downward, allowing more uniform spreading of the K in the wetted soil volume. Application of K with the irrigation water is advised since its effectiveness increases substantially and yields obtained are higher (Table 5).

Table 5. Potato tuber yield as influenced by fertigation and traditional fertilization.

Treatment	Yield		
	1991	1992	1993
	-----t/ha-----		
None	31.0 a	47.8 a	31.0 a
Soil K	23.4 b	42.6 b	28.2 b
100 mg K/L	48.5 a	29.3 a	33.7 a
200 mg K/L	30.7 a	49.3 a	30.4 a

¹ 200 mg K/L is equivalent to the amount applied in soil planting.

Phosphorus

Contrary to N and K, P is readily fixed in most soils (Kafkafi and Bar-Yosef, 1980; Lauer, 1988). Movement of applied P differs with the form of fertilizer (Ruiz and Jose, 1992), soil texture (Gustafson, 1974), soil pH (Argo and Biernbaum, 1996) and the pH of the fertilizer (Papadopoulos and Ristimaki, 1998). Under calcareous conditions, P is readily fixed. P fertigation within surface or sub-surface irrigation

is also important (Bar-Yosef et al., 1989). Due to its fixation, P in soil moves very little in depth (Lauer, 1988), but, due to cultivation, P is usually found to the depth of cultivation (20–30 cm). In fertigated orchards, cultivation below the canopy is not advisable. The fine rooting system developed closed to soil surface is the part of the rooting system responsible for absorbing the nutrients such as P with low mobility in the soil.

Phosphorus mobility in soil is very restricted due to its strong retention by soil oxides and clay minerals. The topical or surface soil application of commonly available P fertilizers generally results in poor utilization efficiency, principally because P ions rapidly undergo precipitation and adsorption reactions in the soil, which remove them from the soil solution. Consequently, there is little or no movement of P from point of contact with the soil. This situation is especially serious for irrigated crops under conditions where the surface few cm of soil are subjected to rapid drying and plant roots are unable to grow near the surface and utilize the topically applied P.

Therefore, there is inefficient utilization of surface-applied P fertilizers. Efficiencies on the order of 5–10% are common. Logan and McLean (1973) demonstrated that the reaction capacities of soils differ considerably and that it is possible at high rates of P fertilization to saturate reaction sites and achieve increased movement of P over that normally expected. Continuous application of orthophosphate through the irrigation water was shown to be superior to applying P in adequate quantities as basic fertilization. This stemmed from the fact that both P adsorption and P crystallization, which reduce P concentration in the soil solution and thus decrease P uptake rate by plants, and P migration for any distance in the soil are time-dependent reactions.

The half-life of these reactions is roughly a few hours and several weeks, respectively. Due to the frequent P application via the water, the residence time of P in the soil is reduced appreciably, and P concentration in the soil solution between successive fertigation is considerably higher than expected from adsorption and precipitation equilibrium considerations. On this aspect, Rauschkolb et al., (1976) found that P movement increased five to tenfold when applied through a drip system as compared to the same rates applied in uniform manner; the extent of movement was dependent upon application rate.

Solubility of Fertilizers

The solubility of common fertilizers in water at different temperatures is given in Table 6. Orthophosphate- and sulfate-based fertilizers may form precipitates with Ca and Mg present in the water. Attention should be paid to the fact that solubility considerably decreases with temperature, and it is therefore unwise to leave concentrated fertilizer used in the summer for the winter period, since it may crystallize and block pipes connecting tank and injection part.

Selecting Phosphorus Fertilizers

To be appropriate for fertigation, a fertilizer must be water-soluble. However, most of the common P and K fertilizers are not convenient for fertigation due to their low solubility (Table 6). This is particularly the case with the P fertilizers. In general, conventional P fertilizers have poor good solubility (Nielsson, 1987). Moreover, it has been shown that the traditional application of N, P, K fertilizers in soil before planting are not sufficiently effective and appropriate for modern irrigated agriculture (Papadopoulos, 1992b; Papadopoulos, 1993; Mikkelsen and Jarrel, 1987).

Table 6. Solubility of common fertilizers in water¹.

Fertilizer	Formula	Temperature Range (°C)		
		Cold	Lukewarm	Hot
-----kg fertilizer/m ³ -----				
Ammonium Chloride	NH ₄ Cl	297 (0)	—	758 (100)
Ammonium Nitrate	NH ₄ NO ₃	1183 (0)	1950 (20)	3440 (50)
Monoammonium Phosphate	NH ₄ H ₂ PO ₄	227 (0)	282 (20)	417 (50)
Diammonium Phosphate	(NH ₄) ₂ HPO ₄	429 (0)	575 (10)	1060 (70)
Ammonium Sulfate	(NH ₄) ₂ SO ₄	706 (0)	760 (20)	850 (50)
Potassium Chloride	KCl	280 (0)	347 (20)	430 (50)
Potassium Nitrate	KNO ₃	133 (0)	316 (20)	860 (50)
Potassium Sulfate	K ₂ SO ₄	69 (0)	110 (20)	170 (50)
Monopotassium Phosphate	KH ₂ PO ₄	—	330 (25)	835 (90)
Dipotassium Phosphate	K ₂ HPO ₄	—	1670 (20)	—
Calcium Nitrate	Ca(NO ₃) ₂	1020 (0)	3410 (25)	3760 (100)
Magnesium Nitrate	Mg(NO ₃) ₂	—	423 (18)	578 (90)
Monocalcium Phosphate	Ca(H ₂ PO ₄) ₂	—	18 (30)	—
Phosphoric Acid	H ₃ PO ₄	—	5480 (25)	—
Urea Phosphate	CO (NH ₂) ₂ H ₃ PO ₄	—	—	—
Urea	(NH ₂) ₂ CO	780 (5)	1193 (25)	—

¹Numbers in parentheses are solution temperatures, °C.

Commercial standard P fertilizers may also precipitate in the irrigation lines in reaction with ions in the irrigation water such as Ca or Mg. Therefore, when

choosing the P fertilizer for fertigation, besides solubility, care must be taken to avoid P-Ca and P-Mg precipitation in the tubes and emitters. From this standpoint, acid P fertilizers (e.g., phosphoric acid, urea phosphate, or monoammonium phosphate) are recommended, because the monovalent $(\text{H}_2\text{PO}_4)^-$ Ca and Mg salts are far more soluble than the HPO_4^{2-} Ca and Mg salts. The use of H_2PO_4 and other acid fertilizers in drip and other micro-irrigation systems may be beneficial in many ways other than the direct benefit from the added P.

However, even with phosphoric acid as a fertilizer, particular attention should be attached to its grade and purity. Other favorable effects include; increased P movement from the emitter (O'Neill et al., 1979), increased solubility of soil native P minerals (Ryan and Stroehlein, 1979), and increased availability of micronutrients such as Zn, Fe, and Mn (Ryan et al., 1974), reduced rates of urea hydrolysis and ammonia losses (Bremner and Douglas, 1971; Fenn and Hossner, 1985). Urea phosphate was found to be an excellent source of P and N. As a hypothesis, the "double acidification" effect of UP is presented (Papadopoulos and Ristimäki, 1998).

Due to soil "fixation" of the applied P and the problem of low solubility and precipitation of P in the irrigation system, it has been suggested that under such conditions P should not be applied through irrigation systems. In this respect, the application of P fertilizers through drip irrigation is not recommended by some authors because of the possible precipitation of phosphates in irrigation pipes and emitters (Ibrahim, 1989; 1993); such an approach reduces the availability of P (Tables 7, 8). The solution is to select the appropriate P fertilizers.

Table 7. Relative yield and P uptake of drip-irrigated potatoes in two growing seasons.

Treatment	Yield		Uptake	
	1992	1993	1992	1993
	-----%			
Fertigated P				
50 mg P/L	100	100	100	86
25 mg P/L	93	85	98	100
Soil-applied P	78	82	83	13
None	50	52	—	—

Source: Papadopoulos (1995).

The common granular P fertilizers are not appropriate for fertigation. The most commonly used P fertilizers for fertigation, urea phosphate(UP), monoammonium phosphate(MAP), and phosphoric acid do not create a clogging problem. There is also a variety of soluble NPK's available in the market. These

fertilizers are good, but the price might be the main constraint in certain cases. Phosphoric acid is a useful source of P, and, in recent years, is widely used, particularly in mini-sprinkler and drip fertigation. However, UP and MAP, were found to be more convenient and superior.

During the selection of a combination of fertilizers, the residual salinity of the mixture is an important element to fight salinity due to fertilizers.

Table 8. Phosphorus in French beans derived from fertilizer as affected by soil P application at planting and P application through the irrigation water at various levels and frequencies.

Treatment ¹	% P Derived from Fertilizer
P soil	5.28 a
P ₁ : 15 mg P/L, every irrigation	10.54 b
P ₂ : 45 mg P/L, after the third irrigation	6.74 c
P ₃ : 90 mg P/L, after the sixth irrigation	4.66 d
P ₄ : 45 mg P/L, every third irrigation, starting with first irrigation	10.19 b
P ₅ : 90 mg P/L, every sixth irrigation, starting with first irrigation	13.06 a

¹ all treatments received 180 mg P/pot. Source: Papadopoulos (1995).

Frequency of Phosphorus Application

High-frequency P fertigation may substantially increase the time-averaged P concentration in the soil solution above that expected from P solubility considerations (Bar-Yosef et al., 1989; Rauschkolb et al., 1976; Papadopoulos, 1992). This can be achieved with frequent irrigation and fertilization, thus minimizing the use of the soil as a storage reservoir for water and nutrients (Phene and Beale, 1976; Papadopoulos and Ristimaki, 1998). Combined irrigation and fertilization (fertigation) is ideal for this purpose (Phene et al., 1979), particularly under calcareous conditions (Papadopoulos, 1992). In this way, the fertilizer is placed in the soil volume in which roots are most active (Bar-Yosef and Sheikhsolami, 1976; Phene and Sanders, 1976). It has been shown that frequent P application via the irrigation stream is particularly effective for drip-irrigated crops where local P concentration in the soil solution must exceed the concentration which is needed under other irrigation methods to compensate for the reduced root weight per plant (Bar-Yosef et al., 1989).

Trickle (drip) irrigation, enables flexibility in fertilizer application and is ideally suited for fertigation. It has been reported that N and P fertigation with trickle irrigation is a promising means for high potato yield of good quality. It is possible to maintain N and P concentrations during the growth period at levels

required at critical stages (Tables 4, 9, 10), without excess or undue losses (Papadopoulos, 1988; 1992).

Table 9. Potato yield as influenced by two levels of P applied with the irrigation stream and soil basal P application.

Treatment	Yield	
	1991	1992
	-----t/ha-----	
50 mg P/L	34.4 a	44.3 a
25 mg P/L	31.9 a	41.5 a
Soil P	23.6 b	34.6 b
None	16.7 c	22.2 c

Source: Papadopoulos (1995).

Table 10. Yield and number of tubers of seed potato, var. Spunta as affected by the amount and timing of P application.

Treatment	Number of Tubers	Yield
	-----'000/ha-----	---t/ha---
None	255.2 b	26.7 d
Soil P (15 kg P ₂ O ₅ /1000 m ²)	325.6 a	40.6 c
P-fertigation (whole period)	341.5 a	50.0 b
P-fertigation (until initiation of tuberization)	328.9 a	55.1 a

Source: Papadopoulos (1995).

The concentration of P in the irrigation water to sustain required P concentration in the soil solution under trickle irrigation, particularly at the presence of high CaCO₃, must exceed the concentrations under other irrigation techniques to compensate for the reduced root weight per plant (Bar-Yosef et al., 1989). Such conditions can be achieved by frequent P application via the irrigation stream and, depending on soil, different P concentrations are required (Table 11). Similar results were obtained by acidifying the irrigation water by using P acid or other acid fertilizers (Papadopoulos and Ristimaki, 1998).

Table 11. Phosphorus content in French beans derived from fertilizer as affected in two soils by soil P application at planting and P application at three levels through the irrigation water.

Treatment	% P Derived from Fertilizer	
	Pakhna Soil (65% CaCO ₃)	Zyghi Soil (55% CaCO ₃)
P soil (650 mg P/pot)	4.88 c	8.17 c
P ₁ : 15 mg P/L (217.5 mg P/pot)	12.78 a	13.26 b
P ₂ : 30 mg P/L (435 mg P/pot)	11.85 a	15.54 a
P ₃ : 45 mg P/L (65.5 mg P/pot)	9.43 b	12.73 b

Source: Papadopoulos, (1995).

Fertilizers and pH

Different sources of fertilizers, including P fertilizers, have different effects on irrigation water and soil pH. High pH values (>7.5) in the irrigation water are undesirable. Calcium and Mg carbonates and orthophosphate precipitates may occur in the tubes and the drippers. In addition, high pH may reduce Zn, Fe, and P availability to plants. The desired pH is below 7; the range favored by most cultivated crops is 5.5–6.5. The pH of the irrigation water could be reduced or controlled by using P acid or acid-based fertilizers such as UP and MAP. Diammonium phosphate (DAP), under calcareous and high soil and water pH conditions, is not recommended. Besides being less effective, it may also create a clogging problem to the irrigation system and the fertigator.

The UP and MAP, due to good solubility, are good P sources for fertigated crops; both are acid fertilizers. This characteristic makes these fertilizers particularly attractive for fertigation in areas where water and soils have higher pH (above 7). Acid fertilizers prevent chemical clogging of the micro-irrigation and fertigation systems. Some of the experimental results obtained in Cyprus along this line are given in Tables 12 – 15.

The UP appears superior to MAP, as it affects the pH of the soil in the following two ways: 1) *Direct acidification* of immediate action due to the low pH of UP and; 2) *Indirect acidification* induced by urea hydrolysis. Both reactions have an additive effect on soil pH that consequently affects P activity and uptake. Most probably the availability of other elements (nutrients) is also enhanced.

Urea, under drip irrigation, is rapidly hydrolyzed in the soil to ammonium and then oxidized to nitrate:

Table 12. Number and mean weight of fruits and yield of eggplant as affected by fertilizers applied at two concentrations.

Fertilizer Treatment	Number of Fruits	Fruit Weight	Yield
-----mg/L-----	---'000/ha---	---g/fruit---	---t/ha---
DAP-1, N=120, P=50, K=200	681 d	181.3 ns	123.5 c
DAP-2, N=120, P=35, K=200	666 d	184.4 ns	122.8 c
MAP-1, N=120, P=50, K=200	708 cd	182.7 ns	129.4 cb
MAP-2, N=120, P=35, K=200	723 c	189.4 ns	137.0 b
UP-1, N=120, P=50, K=200	773 b	177.0 ns	136.8 b
UP-2, N=120, P=35, K=200	814 a	182.2 ns	148.4 a

Source: Cyprus (1996).

Table 13. Soil and irrigation water pH as influenced by the fertilizers used for fertigating eggplants (Cyprus, 1996).

Treatment	Stock Solution		Irrigation Water + Stock Solution		Soil pH ¹
	pH	EC (dS/m)	pH	EC (dS/m)	
1	7.05	9.05	7.01	1.60	7.47
2	7.09	9.88	7.07	1.45	7.61
3	5.75	10.78	6.48	1.45	6.80
4	6.04	8.25	6.70	1.31	6.90
5	1.70	11.90	6.06	1.17	6.36
6	2.08	11.15	6.30	1.35	6.40

¹Soil pH taken 10 cm below the dripper during irrigation; pH of the irrigation water was 7.8.

Table 14. Number and yield of sweet pepper as affected by diammonium phosphate (DAP), monoammonium phosphate (MAP) and urea phosphate (UP) applied at two concentrations (Cyprus, 1996).

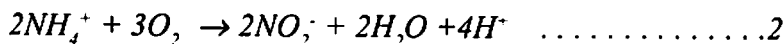
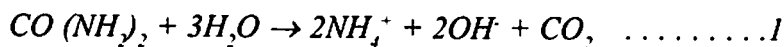
Fertilizer Treatment	Number of Fruits	Fruit Weight	Yield
-----mg/L-----	---'000/ha---	---g/fruit---	---t/ha---
DAP-1, N=120, P=50, K=200	965 a	72.4 c	69.95 c
DAP-2, N=120, P=35, K=200	836 b	72.7 c	60.82 d
MAP-1, N=120, P=50, K=200	922 a	80.1 b	73.86 b
MAP-2, N=120, P=35, K=200	897 a	84.7 ba	75.98 b
UP-1, N=120, P=50, K=200	911 a	81.5 b	74.26 b
UP-2, N=120, P=35, K=200	931 a	88.3 a	82.15 a

Numbers with similar letters are not significantly different ($P \leq 0.05$) according to Duncan's Multiple Range test.

Table 15. Soil and irrigation water pH as influenced by the fertilizers used for fertigating sweet pepper.

Treatment	Stock Solution		Irrigation Water + Stock Solution		Soil pH (10 cm) ¹
	pH	EC (dS/m)	pH	EC (dS/m)	
1	7.37	7.72	7.87	1.74	7.87
2	7.45	8.58	7.97	2.16	7.71
3	6.29	7.48	6.79	1.69	6.80
4	6.25	8.04	7.03	1.71	7.00
5	2.40	6.43	6.32	1.63	6.56
6	2.54	6.57	6.40	1.70	6.75

The treatments are the same as in Table 14. ¹Soil pH taken 10 cm below the dripper during irrigation; /the water pH was about 7.8.



Hydrolysis of urea is an important process influencing the form of N available and availability and mobility of P to plants (Clothier and Sauer, 1988; Eduards et al., 1982). Urea hydrolysis is a rapid process, initially producing ammonium, followed by substantial increase of soil pH (Reaction 1). Thereafter, with nitrification, which is also a rapid process, extensive acidification occurs (Reaction 2). This is particularly the case with drip irrigation due to high application of UP at a relatively small volume of soil below the dripper. Under such conditions, the initial increase in soil solution pH is offset by the acid properties of UP due to P acid component. In this way, one of the main disadvantages of urea, the initial increase in pH, is eliminated.

Soil acidification ultimately results in a substantial increase of P availability, but also the availability of Mg, K, Fe, Zn, and other micronutrients is improved. Increased P uptake has been noted when P is applied with N fertilizers and particularly with urea since the induced low pH near the root increases the concentration of $H_2PO_4^-$ compared with HPO_4^{2-} . Therefore, in soils with high pH, urea from UP might be beneficial for the crops provided that the initial increase in pH due to the first stage of hydrolysis could be controlled. The latter is achieved with UP due to its acid component, the P acid. This is a unique characteristic of the UP fertilizer (Papadopoulos and Ristimaki, 1998).

Yield and quality data of fertigated potato at farmers level using MAP and NPK as sources of P were compared with UP (Table 16). The significantly higher yield obtained might be attributed to the acid characteristics of the UP fertilizer, as such, and to the further decrease of pH following the urea hydrolysis.

Table 16. Yield, specific gravity and dry matter of potato var. “Spunta” as influenced by conventional and UP fertigation (Cyprus, 1996).

Parameters	Urea Phosphate-Fertigation	Farmers' Fertigation
Yield (kg/ha)	81130 a ¹	69160 b
Specific Gravity (g/cm ³)	1.068 a	1.065 b
Dry Matter (%)	17.85 a	17.20 b
Nitrate-N (mg/kg)	68 b	109 a

¹Means in the same row followed by different letters are statistically different at 5% level.

Evidently, the application of N alone with the irrigation water is not as efficient as when all nutrients are applied with the irrigation water. This is particularly important since in practice some farmers apply the P and K in the soil before planting, and only the N with the irrigation water. The main reason for this is the low solubility of some common P and K fertilizers. In this respect, the development of water-soluble P and K fertilizers at a reasonable price in modern intensive irrigated agriculture is highly desirable.

FERTIGATION PRACTICES AND RECOMMENDATIONS

Implementing a Fertigation Program

The principle of fertigation brings much concern to new users and should be handled with care by even the most experienced fertigator. It is not that the basics are all that difficult, only that one must follow a few simple rules – Fertigation just has a few more rules. Here are a few of the principles to remember:

1. The fertilizer type and amount must be soluble so that it can dissolve in nurse tank water (stock solution)
2. The irrigation system should be fully charged (has the farthest point from the pump to full pressure).
3. The time of fertilizer injection should be at least as long as it takes to charge the system.

4. Non-dissolved materials should be filtered or be small enough in size to go through the system.
5. Continuous application of all nutrients is more appropriate.
6. System must be equipped with proper back-flow prevention.

In fertigation, both irrigation and fertilization affect plant behavior, and adjustments in one factor can lead to limits imposed by other. For optimum plant performance under fertigation, all fertilization-irrigation-input factors must be balanced so that none imposes a significant limitation.

The actual water and nutrient requirements of the crops, together with a uniform distribution of both water and nutrients, are important parameters in practising meaningful fertigation. In this respect, extensive research in developing fertigation recipes has been undertaken. The real crop-water requirements, particularly under plastic and greenhouse production, is the most critical link between irrigation and sound fertigation. In this respect, research priority is attached.

Fertigation Recipes

Significant technical skill and management are required to formulate an appropriate fertigation recipe and achieve optimum agronomic, environmental and health results. The main elements for formulating and evaluating fertigation are crop nutrient requirement for a certain yield (Papadopoulos, 1997a), nutrients available from soil (Hartz and Hochmuth, 1996) and eventually from water, the volume of soil occupied by the rooting system and the irrigation method. Fertigation with micro-irrigation, if properly managed, can reduce overall fertilizer and water application rates and minimize adverse environmental impact (Clough et al., 1990; Papadopoulos, 1993).

Step-By-Step Approach

Fertilization and/or fertigation could be practised empirically or on sound scientific way (Papadopoulos, 1997a; Sanders, 1991). The empirical application of fertilizers is associated with severe limitations, which lead to low recovery of fertilizers by the crop. In general, empirical fertilization is based on farmers' experience and on broad recommendations. The scientific approach takes into consideration all main factors influencing crop nutrition and soil fertility and provides the individual grower dependable information regarding the fertilizer needs of his field.

Crop Nutrient and Fertilizer Requirement

The selection of the proper rate of plant nutrients is influenced by a knowledge of the nutrient requirement of the crop, the nutrient supplying power of the soil, the efficiency of nutrient uptake under different irrigation and fertilization methods, and the expected yield. These factors could be taken into consideration, and, for the same crop and for each field, a different fertilization (fertigation) program could be recommended.

When the soil does not furnish adequate quantities of the elements necessary for normal development of plants, it is essential that the required amounts be applied. This necessitates finding a method that will permit the determination of those deficient elements and furthermore help to predict the amount of nutrients needed to supplement the crop requirement.

Removal of Nutrients by Crops from Soil

The quantities of nutrients removed by the crop from soil are useful information which can be used to optimize soil fertility level needed for various crops. Part of the nutrients removed by crop is used for vegetative growth (canopy), and the rest for fruit production. The amount of nutrients removed by crops must be present in the soil, irrespective of the fact that part of them may remain or return to the soil by the end of the growing season as canopy and roots. It is important to have enough nutrients in the right proportions in the soil to supply crop needs during the entire growing season. In crops from which just the fruits are removed, lower quantities of nutrients are lost than if the entire above-ground portion were harvested.

Vegetable crops differ widely in their macro-nutrient requirements and in the pattern of uptake over the growing season. In general, N, P, and K uptake follow the same course as the rate of crop biomass accumulation. Fruiting crops such as tomato, pepper, and melon require relatively little nutrition until flowering, when nutrient uptake accelerates, peaking during fruit set and early fruit-bulking. As fruits mature, macro-nutrient requirement declines. Non-fruited crops such as celery and lettuce have slow nutrient uptake through the first half of the season, but the rate of nutrient acquisition accelerates before harvesting. The approximate amounts of N, P, and K removed from soil by various crops, are given in Table 16, which indicates the comparative uptake among crops. In addition, they are an indication of the rate at which the reserve or "storehouse" of nutrients in the soil are depleted by certain crops.

The amounts of nutrients that indicated in Table 17 are required to be available in soil. However, not all of the nutrients should necessarily come from fertilizer. Part of them could be supplied by the soil. In this respect, estimating the amount of nutrients, which may be available to the crop from soil (nutrient-supplying power of soil), is important. Some soils have sufficient reserves to draw on for an

extended period. This amount is subtracted from the overall amount, which should be supplied by fertilizers.

Nutrients from Soil

Proper fertigation management begins with knowledge of the nutrient status of the soil. Most soils contain substantial quantities of available macronutrients and are frequently sufficiently supplied with micronutrients; using a standard drip fertigation program without soil testing will often lead to *wasteful fertilizer application* and, less frequently, result in a *nutrient deficiency*. Analytical procedures for soil analysis differ widely from location to location; it is important to use a laboratory using test procedures calibrated for the geographic area of interest (Reisenauer, 1983).

Soil Testing

A soil test can help in estimating the nutrient-supplying power of a soil for N, P, K, Ca, Mg, and other nutrients. Soluble N leaches readily during the rainy season or with the irrigation water, so there may be little carry-over. Nevertheless, nitrification may build up the supply of nitrate in soil as the season advances, where organic matter is adequate. Mineral ($\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$) and organic forms of N are present in all soils. Analysis for mineral N is often confined to $\text{NO}_3\text{-N}$, because in most situations $\text{NH}_4\text{-N}$ constitutes < 20% of the mineral N content. Estimating the rate at which soil organic N is mineralized is problematic, but N mineralization potential can be important; net N mineralization rates of 0.5 to 2.0 kg N/ha per day are common (Magdoff, 1991).

A soil test measures a part of the total nutrient present in soil, and is assumed or experimentally found to be well correlated with the available nutrient. However, the values of soil analysis are of little use by themselves. To employ such a measurement in predicting nutrient needs of crops should use those chemical methods, which have been extensively tested and calibrated against nutrient rate experiments. Moreover, no analysis could give good results *if soil samples are not representative*. The results of the soil test could be reliable only if they are based on representative samples.

However, this is becoming particularly difficult with drip irrigation. The place and depth of soil sampling relative to the drippers is a *sensitive issue of particular importance*. Usually it is recommended to get samples beneath the dripper, between the drippers and between the lateral pipes. The problem of representative samples, accurate analyses, correct interpretation particularly with the drip system need careful approach and further research. In this respect, labeled fertilizers may help. The soil test helps reduce guesswork in fertilizer practices.

In order to estimate the nutrient-supplying capacity of a soil, the following parameters are needed: depth of the crop rooting system, proportion of soil % occupied by the root system under different irrigation systems, soil bulk density.

Table 17. Nutrients required by selected crops for canopy formation and fruit production.

Crop		Nitrogen	Phosphorus	Potassium
<u>Potato</u>				
Canopy	(kg/ha)	86	7	120
Tubers	(kg/ton)	3.20	0.54	4.50
<u>Tomato</u>				
Canopy	(kg/ha)	95	12	108
Fruits	(kg/ton)	1.80	0.17	3.13
<u>Eggplant</u>				
Canopy	(kg/ha)	105	13	113
Fruits	(kg/ton)	1.96	0.17	3.2
<u>Pepper</u>				
Canopy	(kg/ha)	90	6	90
Fruits	(kg/ton)	2.0	0.26	1.83
<u>Strawberries</u>				
Canopy	(kg/ha)	85	5	88
Fruits	(kg/ton)	1.17	0.22	1.53
Lettuce	(kg/ha)	115	14	160
<u>Mango</u>				
Canopy	(kg/ha)	70	6	108
Fruits	(kg/ton)	1.35	0.19	1.65
<u>Banana</u>				
Canopy	(kg/ha)	250	26	800
Fruits	(kg/ton)	2.0	0.22	5.0
<u>Citrus</u>				
Canopy	(kg/ha)	85	8	90
Fruits	(kg/ton)	1.44	0.19	1.53

These parameters are needed in order to:

1. Calculate the weight of soil of a certain area to a depth where the active rooting zone of the crop is developed.
2. Estimate the reserves or storehouse available nutrients for the crop.

3. Estimate the volume of soil where water should be applied; this helps in estimating the amount of water per irrigation.

It should be stressed that for a certain crop at full growth the amount of water per irrigation should be constant, if the frequency of irrigation is changed. In most countries, this is one of the most common mistakes at the farmer's level.

Rooting System: The amount of available nutrients in soil is estimated up to that depth of soil where roots are active and, therefore, nutrient uptake occurs. The appearance, growth, and depth to which roots penetrate in soils are in part species properties but prevailing soil conditions usually exert a pronounced influence. If there is a *clay pan, hard pan, compacted layer, or other dense formation, the normal depth of rooting is not possible*. Knowledge of the rooting habits of the crops is helpful in determining in satisfactory way soil exploitation and revealing the depth to which the reserve nutrients in the soil could be available and contribute to the overall nutrition of the crop. In addition the same information helps to give an idea of the most effective placement of fertilizer and irrigation water. The mass of soil occupied by roots is estimated with the following formula:

$$\text{Soil Mass} = \text{Area (m}^2\text{)} \times \text{Root Depth (m)} \times \text{Bulk Density (t/m}^3\text{)}$$

Soil Nutrient-Supplying Capacity: The type and amount of fertilizer to be applied depends on the crop to be grown and the nutrient supplying power of the soils concerned. Determination of the level of nutrients allows deficiencies to be detected and suitable rates of fertilizer to be recommended. The amount of available nutrients per ha is estimated with the following formula:

$$\text{Amount of Nutrient} = \text{Soil Weight (t/ha)} \times \text{Available Nutrients (mg/kg, g/ton or ppm)}$$

Fraction of Soil Occupied by Roots

To avoid calculations, Table 18 could be used to estimate the amount of a nutrient, which could be provided by soil. The two parameters needed are the value of the available nutrient in g/ton (ppm) and the crop rooting depth. The values shown in Table 18 refer to the whole volume of soil up to a certain depth. This is true only when the whole volume of soil up to that depth is exploited by the rooting system. However, this is not the case. Usually, the volume of soil occupied by roots is less and depends on the crop, spacing of planting and irrigation system. For drip irrigated vegetables such as tomato, pepper, eggplant, the wetted soil volume is usually 30–40% of total soil volume. With wider spacing, which is the case for

melon, watermelon, pumpkins, the volume of soil occupied by roots could be even less than 20%. For mini-sprinklers (like mini-sprinkler irrigated potato) the volume of soil occupied up to a certain depth might be 70–80%. The fraction of soil occupied by roots must be taken into account whenever the amount of available nutrients is calculated; otherwise the available amounts could be overestimated.

Soil-Nutrient Safety Margins

In calculating the nutrient-supplying capacity of a soil, the whole amount of the available nutrient to full depletion of soil can be taken into consideration. However, it is preferable that a certain amount of a nutrient be reserved in soil. For intensive irrigated agriculture, safety amounts of P and K in soil could be considered as 30 and 100 ppm, respectively. In other words, farmers in intensive irrigated agriculture are not encouraged to deplete soil below these values. Moreover, in case that a nutrient is below the safety value, the fertilization program may include an amount of nutrient needed to build up soil fertility to the safety margin. These margins are, at the same time, the pool for increased demand in nutrients at eventual crop critical nutrient stages.

Table 18. Available nutrients in soil as determined by chemical analyses at various soils depths, assuming 1.2 soil bulk density.

Soil Depth (cm)	Soil Chemical Analysis										
	10	20	30	40	50	60	70	80	90	100	150
	-----mg/kg-----										
10	12	24	36	48	60	72	84	96	108	120	180
20	24	48	72	96	120	144	168	192	216	240	360
30	36	72	108	144	180	216	252	288	324	360	540
40	48	96	144	192	240	288	336	384	432	480	720
50	60	120	180	240	300	360	420	480	540	600	900
60	72	144	216	288	360	432	504	576	648	720	1080
70	84	168	252	336	420	504	588	672	756	840	1260
80	96	192	288	384	480	576	672	768	864	960	1440
90	108	216	324	432	540	648	756	864	972	1080	1620
100	120	240	360	480	600	720	840	960	1080	1200	1800

It should be emphasized that the amount of nutrients needed by the crop and the amount of nutrients, which should be applied, are not equivalent. The crop does

not use all the nutrients applied by fertilizers. The actual amount applied by fertilizers is higher than the amount required by the crop. Uptake of nutrients depends, among other factors, on the irrigation system.

Table 19. Fertilizer element uptake as influenced by the irrigation system.

Irrigation system ¹	Nitrogen	Phosphorus	Potassium
	-----%		
Furrow	40–60	10–20	60–75
Sprinkler	60–70	15–25	70–80
Micro-irrigation	75–85	25–35	80–90

¹The values refer to well designed and operated irrigation systems.

Irrigation System and Nutrient-Uptake Efficiency

The potential nutrient uptake efficiency by the same crop is different with various irrigation systems. In general, the higher the water-use efficiency of a certain irrigation system, the higher is the nutrient-uptake efficiency. For a well designed irrigation system and with good scheduling of irrigation, the potential N, P and K uptake by the same crop is given in Table 19.

With surface irrigation methods the fertilizer-use efficiency is less. In particular, due to leaching, N use efficiency can be considerably low. Therefore, in order to estimate the overall amount of nutrients, which must be present in soil to meet crop nutrient requirement for certain yield, the efficiency of the fertilizer, nutrient uptake by the crop is needed.

Nitrogen, Phosphorus, and Potassium Requirements of Crops

Taking into account the: a) nutrient requirement for a certain yield (Table 1), b) available nutrient capacity of soil, c) nutrient capacity of wastewater, and d) efficiency of nutrient uptake by crop under different irrigation systems (Table 19), the following formula can be used to estimate the amounts of N, P, and K required being readily available in soil:

$$\text{Nutrient Requirement (kg/ha)} = \frac{NR - (SAN + WN)}{IS} \times 100$$

Where:

NR = Nutrient Requirement for a Specific Yield (kg/ha).

SAN = Soil Available Nutrients (Soil-Supplying Capacity) (kg/ha).

WN = Nutrient Capacity of the Wastewater (kg/ha).

IS = Nutrient Uptake Efficiency of Irrigation System (%).

With the above formula, a good estimate of the nutrients required could be obtained. In case that the nutrient supply capacity of a soil is below the safety margin, corrections could be made by gradually increasing the annual amount of fertilizer until it reaches the safety margin.

Irrigation

With fertigation, all fertilizers are applied with the irrigation water. In this respect, the amount of irrigation water needed must be calculated. Using any known formula, estimating evapotranspiration or E_{pan} evaporation of the plantation area is could do this. In cases where meteorological data are available, any of the following known methods could be used for estimating water requirement: *Blaney-Criddle, Radiation, and Penman*.

Table 20. Crop water requirements of selected vegetables expressed as a fraction of E_{pan} evaporation.

Crop ¹	Days after Planting					
	0-15	15-30	30-45	45-60	Thereafter	Last month
Potato	0.4	0.7	0.9	0.8	0.7	
Carrots	0.3	0.5	0.9	0.9	0.8	0.8
Tomato	0.3	0.5	0.8	0.9	1.0	0.8
Cucumber	0.3	0.5	0.7	1.0	1.0	0.8
Lettuce	0.3	0.8	0.9	0.9		
Cabbage	0.3	0.5	0.8	0.9	0.9	
French Beans	0.3	0.4	0.5	0.7	0.8	
Onion	0.3	0.5	0.9	0.9		
Celery	0.3	0.6	0.9	0.9		
Eggplant	0.3	0.5	0.8	0.9	1.0	0.8
Bell Pepper	0.3	0.5	0.7	0.8	0.8	0.7
Watermelon	0.3	0.5	0.9	0.9	0.8	
Melon	0.3	0.5	0.9	0.9	0.8	

¹ Under less convenient conditions for growth, the changes in the amount of water may go every 3-weeks' interval.

Table 21. Crop water requirements of selected fruit trees expressed as a fraction of E_{pan} evaporation.

Citrus	: Fully developed trees	0.55
Avocado	: --/--	0.55
Olives	: Full development	0.33
Durian	: Fully developed trees	0.75 – 0.85
Rambutan	: --/--	--/--
Mango	: --/--	--/--
Table grapes	: Value increases gradually from	0.2 to 0.5 – 0.6
Banana	: Increases gradually from	0.6 to 1.0

The E_{pan} method is recommended for its simplicity for the farmers. Fractions of E_{pan} recommended for selected vegetables and fruit trees are given in Tables 20 and 21.

Nutrient Sources (Fertilizers)

A variety of fertilizers can be injected into drip irrigation systems. Common N sources include ammonium sulfate, urea, ammonium nitrate, urea-ammonium nitrate, calcium nitrate, magnesium nitrate, and potassium nitrate. Potassium can be supplied from potassium chloride, potassium sulfate, potassium thiosulfate, or potassium nitrate. In case that salinity is a problem, potassium chloride and potassium sulfate should be avoided. Any fertilizer should be avoided if it is not clean and has extensive impurities. The choice of P products is more limited; phosphoric acid, urea phosphate or ammonium phosphate solutions are used most commonly. Monoammonium- or mono-potassium phosphate are available, but are infrequently used.

The choice of fertilizer suitable for a specific application should be based on several factors: *nutrient form, purity, solubility, and cost*. The appropriate balance of NO_3 -N to NH_4 -N (or urea) depends on environmental conditions. In cool weather, 25% to 50% of applied N should be in the NO_3 -N form (Hochmuth and Hanlon, 1995). In warm weather, nitrification occurs rapidly, allowing greater use of ammoniacal-N or urea fertilizers, which are significantly less expensive than nitrate fertilizers. *All common N sources are available in clean, high-analysis, liquid solutions.*

Solubility is not an issue with potassium products. Potassium chloride is inexpensive and reasonably good if salinity is not a problem. Potassium nitrate is

the preferable form. Liquid P fertilizers, except for food-grade phosphoric acid, may have impurities that complicate the already difficult task of eliminating chemical precipitation in the drip lines. However, with sufficient knowledge and attention to detail, fertilizer-grade phosphoric acid and ammonium phosphate solutions can be delivered successfully.

Fertigation under Saline Conditions

According to Bar-Yosef (1991), a 10-meq/L solution has an electrical conductivity (EC) of about 1 dS/m and an osmotic pressure of approximately 0.30 bar (25°C). According to the U.S. Salinity Laboratory, irrigation water with an EC exceeding 1.44 and 2.88 dS/m constitutes a moderate and a high salinization hazard, respectively. Assuming a daily irrigation of 5 mm (50 m³/ha), N and K concentrations in the irrigation water at the time of maximum consumption rate may reach values of 15 to 20 meq/L, which correspond to an EC of 1.5 to 2.0 dS/m. Under such conditions, especially where the water EC > 1, which is common in arid zones, care should be taken to minimize the amount of accompanying ions added with the N or K.

For example, KCl, which is a cheap source of K, should be replaced by KNO₃ and K₂HPO₄, while NH₄NO₃ and urea should be preferred over (NH₄)₂SO₄. Sodium-based fertilizers (e.g., NaNO₃ or NaH₂PO₄) are unlikely sources due to the adverse effect of Na on soil hydraulic conductivity (Bresler et al., 1992) and on plant functioning (Mengel and Kirkby, 1987). With balanced fertigation, good results can be obtained under saline conditions (Papadopoulos, 1987c).

Fertil-Computer Program for Fertigation.

Based on E_{pan} evaporation, crop nutrient requirements, soil fertility and uptake efficiency of the various nutrients under different irrigation systems, a software program has been developed which is capable of predicting and recommending irrigation/fertigation scheduling to farmers (Papadopoulos, 1997a). The program is based on the principle that the ET_{crop} depends on the climatic conditions, and therefore, the absolute amount of water needed by the crop is different in different places and countries. However, the fraction of E_{pan} "C" is relatively constant. This fact is used in the FERTIL program in order to estimate the crop water requirement.

Therefore, for running the program, the parameter needed is the evaporation of an area since the fractions of E_{pan} for the crops are known. For most fruit trees at full growth, the fraction of E_{pan} is constant throughout the year, i.e., for citrus it is 55% and for olives 35%. In the program, the water requirements of the fruit trees until their full growth increase gradually from year to year. Under good

management we consider that full growth could be achieved in the sixth year. However, this could be corrected for each fruit tree.

For vegetables, the "C" gradually increases from the time of planting until full growth of the plants. This is taken into consideration in the program for each vegetable crop separately. It is therefore necessary to specify the date of planting.

Contrary to the crop-water requirement, the crop-nutrient requirement is not dependent on climatic conditions and, therefore, for a crop with a certain target yield, the nutrient requirement is relatively constant everywhere. However, how many nutrients should be applied to meet this requirement depends on the uptake efficiency of each particular nutrient with a certain irrigation system and the supplying capacity (fertility of the soil). Both parameters are taken into consideration in the FERTIL program.

This FERTIL program provides the opportunity to select the fertilizer from those available in the market which best fit to those required by the crop. Moreover, the program may provide for a crop the required form and amount of fertilizer for different yields. After loading, the program, the title, and information page appear on the screen. These are followed by the *Main Menu*, presenting the different program fertilization application options of FERTIL:

- A. Calculation of water and fertilizer requirements (Table 22,23).
- B. Addition of the fertilizer requirement of the produce.
- C. Updating fertilization requirements of the produce.
- D. Addition of Epan fraction values of new produce.
- E. Updating Epan fraction values of produce.
- F. Addition of evaporation-effective rainfall at a new location.
- G. Updating evaporation-effective rainfall at a location.
- H. Addition of fertilizers and their N, P and K values.
- I. Updating with new fertilizers.
- J. Printing records from a database.
- K. Quit application and return to system's menu.

Example of the recommendation given by the FERTIL program for mature citrus, on a sandy soil without P and K input from the soil. Water requirement and

fertilization of: CITRUS, GROWN at:(Zyghi), BY: ×
 PLANTED (years): Mature

Table 22. Water requirement, m³ /ha /month.

Jan.	0	May	979	Sep.	957
Feb.	0	June	1106	Oct.	737
Mar.	0	July	1232	Nov.	198
Apr.	781	August	1155	Dec.	0
				Total	7145

Table 23. Water requirement and fertilizers.

Fertilizers (g/m ³ of irrigation water)		Ratio	"Best-Fit" Fertilizer
N	62	1.00	30
P ₂ O ₅	22	0.35	10
K ₂ O	22	0.35	10

Economic Benefits of Micro-Irrigation and Fertigation Systems

Modern irrigation systems, including a fertigation unit, represent a substantial investment for the farmer. Therefore, the potential use of the fertigation technology is directly related to the extent to which the farmers are financially rewarded by using this technology. The level of increase in production, improvement of quality of produce, efficient use of inputs and saving in energy and labor are the main factors which are directly related to the acceptance of the fertigation approach by the farmers.

In this respect, Table 3 indicates the striking increase in yield obtained in open field and greenhouses with modern irrigation systems by the same farmers before and after introducing fertigation in Cyprus. The results obtained under experimental conditions are even more striking, and it is expected that the progressive farmers will achieve comparable yields in the near future.

Beside the increase in yield with fertigation, by providing carefully balanced nutrient solutions to suit particular growth stages of the crop, fertigation has also been established as an effective means which potentially may improve the quality of yield. It has been experimentally found that fertigation is an effective way for increasing yield of vegetables and to maintain the nitrate-N level in produce at low and acceptable levels for even the most demanding consumers in Europe.

In Cyprus, the area covered by modern irrigation systems accounts more than 98% of the total irrigated area. In this way, the water application efficiencies achieved at the farmers level is 75–80, 80–90%, and 85–95% by conventional sprinkler, mini-sprinkler and drip irrigation systems, respectively, assuming that the farmers follow the recommendations and irrigate according to the crop-water requirements. This application efficiency, as compared to the traditional surface irrigation that has been practised some years ago with water application efficiency ranged from 40–50%, is really substantial.

The saving of water enabled further expansion of irrigated agriculture in Cyprus. With such high levels of water efficiency achieved, no further significant improvement of water application efficiency due to the irrigation system is expected. However, improving other limiting factors may further increase the yield per unit of water applied. In this respect fertigation has been found to be one and probably the most important single factor for such further improvement.

CONCLUSIONS AND RECOMMENDATIONS

Modern irrigation technology has moved very rapidly from an experimental technique to a commercially significant method of irrigation. The ability to carefully control water application not only offers improved efficiency in the use of an increasingly scarce natural resources for agriculture, but opens the door to new and more efficient ways to manage fertilizers and other agricultural chemicals. However, future potential of modern irrigation/fertigation as means for sustainable agriculture on an environmentally sound basis depends on a number of factors to which particular attention should be placed.

1. Availability and cost of micro-irrigation/fertigation systems. This should not be considered any more as a real constraint since in most countries *reliable and relatively cheap equipment is available*.
2. The micro-irrigation systems must *operate properly*, since any failure and/or losses of water also cause losses of fertilizers and of other chemicals applied with the irrigation water. In this respect, design and operation of the micro-irrigation systems must be proper to ensure *uniform water distribution* without losses.
3. Sound irrigation based on modern irrigation technology requires *sufficient background on crop water requirements*. Under micro-irrigation systems, however, there are indications that the crop water requirements are changing. Therefore, research on this aspect could be of particular help to further improve water-application efficiency.

4. In order to expect the highest possible benefits out of the use of modern micro-irrigation technology, fertigation should be considered as an *indispensable component* of the system.
5. Research on fertigation should be intensified since the application of nutrients through the irrigation water, which is not based on nutrients crop requirement, might create serious environmental problems.
6. Fertilizers should be considered as *economic resource* and not as *environmental pollutant*.
7. Intensification of irrigated agriculture and therefore increased fertilizer application should be considered as the main way to increase yield meet the pressing demand for more food production.
8. Phosphate-fertilizers are *not a problem for fertigation*. *There are good and convenient fertilizers*.

REFERENCES

- Argo, W.R., and J.A. Biernbaum. 1996. The effect of lime, irrigation-water source, and water-soluble fertilizer on root zone, pH, electrical conductivity, macronutrient management of container-root media with *impatiens*. *J. Am. Soc. Hort. Sci.* 121:442–452.
- Ayars, J.E., and C.J. Phene. 1993. Impact of improved irrigation on groundwater quality. p. 475–477. *In* Proc. Nat. Conf. "Agricultural Research to Protect Water Quality". Soil Cons. Soc., Ankeny, Iowa, USA.
- Bar-Yosef, B. 1977. Trickle irrigation and fertilization of tomatoes in sand dunes; water, N and P distribution in soil and uptake by plants. *Agron. J.* 69: 486–491.
- Bar-Yosef, B. 1991. Fertilization under drip irrigation. p. 285–329. *In* D. A. Palgrave (ed.), *Fluid Fertilizer Science and Technology*. Marcel Decker.
- Bar-Yosef, B., and M.R. Sheikholeslami. 1976. Distribution of water and ions in soils irrigated and fertilized from trickle source. *Soil Sc. Soc. Am. J.* 40:575–582.
- Bar-Yosef, B., B. Sagiv, and T. Markovitch. 1989. Sweet corn response to surface and sub-surface trickle phosphorus fertigation. *Agric. Res. Org.*, Bet Dagan, Israel.
- Black, J.D.F. 1976. Trickle irrigation – a review, *Hort. Abstr.* 46: 69–74.
- Bremner, J.M., and L.A. Douglas. 1971. Decomposition of urea phosphate in soils. *Soil Sci. Soc. Am. Proc.* 35:575–578.
- Bresler, E. 1977. Trickle-drip irrigation: Principles and application to soil-water

- management. *Adv. Agron.*, 29: 343–393.
- Bresler, E., B.L. McNeal, and D.L. Carter. 1982. Saline and sodic soils. Springer-Verlag, N.Y., USA.
- Bryan, H.H., and R.B. Duggins. 1978. Chemical injection through drip irrigation on row crops: Compatibility, crop response and effect of flow, p. 166–171, *Intern. Agr. Plastics Congr.*, San Diego, Ca., U.S.A.
- Bucks, D.A., F.S. Nakayama, and R.G. Gilbert. 1979. Trickle irrigation, water quality and preventive maintenance. *Agric. Water Manage.*, 2: 149–162.
- Chesness, J.S., J.R. Dryden, and U.R. Brady. 1976. Nematicide application through porous subsurface irrigation tubing. *Trans. Am. Soc. Agr. Eng.* 19: 105–107.
- Chung, JB, R.J. Zasoski, and R.G. Burau. 1994. Aluminum-potassium and aluminum-calcium exchange equilibria in bulk and rhizosphere soil. *Soil Sc. Soc. Am. J.* 58:1376–1382.
- Clark, G.A., C.D. Stanley, D.N. Maynard, G. J. Hochmuth, E.A. Hanlon, and D.Z. Haman. 1991. Water and fertilizer management of micro-irrigated fresh market tomatoes. *Am. Soc. Agric. Engin.*, 34: 429–435.
- Clough, G.H., D.S.J. Locascio, and S.M. Olson. 1990. Yield of successively cropped polyethylene-mulched vegetables as affected by irrigation method and fertilization management. *Am. Soc. Agric. Engin.* 115: 884–887.
- Clothier, B.E., and T.J. Sauer. 1988. Nitrogen transport during drip fertigation with urea. *Soil Sci. Soc. Am. J.* 52: 345–349.
- Edwards, J.H., R.R. Bruce, B.D. Horton, J.L. Chesness, and E.J. Wehunt. 1982. Soil cation and water distribution as affected by ammonium nitrate applied through drip irrigation system. *J. Am. Soc. Hort. Sc.* 107: 1142–1148.
- Eliades, G., and C. Hadjiloucas. 1985. A simple fertilizer injection pump, *Misc. Reports, 19. Agric. Res. Inst.*, Nicosia, Cyprus.
- Elfving, D.C. 1982. Crop response to trickle irrigation. *Hort. Reviews* 4: 1–48.
- FAO. 1977. Crop water requirements. *Irrig. Drain. Paper N° 24*, Rome, Italy.
- FAO. 1979. Yield response to water. *Irrig. Drain. Paper N° 33*, Rome, Italy.
- FAO. 1993. The state of food and agriculture. *FAO Agric. Series N° 26*, Rome, Italy.
- Fenn, L.B., and L.R. Hossner. 1985. Ammonia volatilization from ammonium or ammonium-forming nitrogen fertilizers. *Adv. Soil Sci.* 1: 123–169.
- Ford, H.W. 1976. Controlling slimes of sulfur bacteria in drip irrigation systems. *Hort Sci.* 11: 133–135.
- Ford, H.W., and D.P.H. Tucker. 1975. Blockage of drip irrigation filters and emitters by iron-sulfur-bacterial products. *Hort Sci.* 10: 62–64.
- Gascho, G.J., and J.E. Hook. 1991. Development of a fertigation program for sprinkler-irrigated corn. *Agron.J.*, 4: 306–312.
- Gerstl, S., S. Saltzman, L. Klinger, and B. Yaron. 1981. Distribution of herbicides in soil in a simulated drip irrigation system. *Irrig. Sci.* 155–166.

- Gerwing, J.R., A.C. Caldwell, and L.L. Goodrad. 1979. Fertilizer nitrogen distribution under irrigation. *J. Environ. Qual.*, 8: 281–284.
- Goldberg, D., B. Cornat, and B. Bar-Yosef. 1971. Distribution of roots, water and minerals as a result of trickle irrigation. *J. Am. Soc. Hort. Sci.*, 96: 645–648.
- Goldberg, S.D. 1972. Irrigation methods and techniques in Israel: A review of modern practices. *Citrus Sub-Tropical Fruit J.* 1: 9–12.
- Goldberg, D., B. Gornat, and D. Rimon. 1976. Drip irrigation: principles, design, and agricultural practices. *Drip Irrigation Sci. Publ.*, Israel.
- Goldberg, D., and M. Shmueli. 1969. Trickle irrigation-method of increased agricultural production under conditions of saline water and adverse soils. *In Proc. Conf. Arid Lands in a Changing World*, Tucson, Arizona.
- Goldberg, D., and M. Shmueli. 1970. Drip irrigation – a method used under arid and desert conditions of high water and soil salinity. *Trans. Amer. Soc. Agr. Eng.*, 13:38–41.
- Goldberg, D., and M. Uzzad. 1976. Fumigation of soil strips through a drip irrigation system. *Hort Sci.* 11: 138–140.
- Gustafson, C.D. 1974. Drip irrigation in USA. p. 111–115, *In Proc. Tech. Conf. Sprinkler Irrigation Assoc.*, Denver, Co., USA.
- Goode, J.E., K.H. Higgs, and K.J. Hyrycz. 1978. Trickle irrigation of apple trees and the effects of liquid feeding with NO_3^- and K^+ compared with normal manuring. *J. Hort. Sci.* 53: 307–316.
- Hamdy, A. 1991. Fertigation prospects and problems in Italy. p. 207–214. *In* *FAO Proc. "Fertigation/Chemigation"*, FAO, Rome, Italy.
- Hairston, J.E., J.S. Schepers, and W.L. Convil. 1981. A trickle irrigation system for frequent application of nitrogen to experimental plots. *Soil Sc. Soc. Am. J.* 45:880–882.
- Hartz T.K., and G.J. Hochmuth. 1996. Fertility management of drip-irrigated vegetables. *Hort Technol.*, 168172.
- Hochmuth, G.J., and E.A. Hanlon. 1995. Commercial vegetable and nutrient requirements. *Fla. Coop. Ser. Circ.* SP-170.
- Ibrahim, A. 1989. Fertilization and irrigation management of tomato production under arid conditions. *Egypt J. Soil Sci.* 32:81–96.
- Ibrahim, A. 1993. Non-classic fertilizer sources for fertigated crops. p. 13.1–13.6. *In Proc. "Environmentally Sound Water Management of Protected Agriculture under Mediterranean and Arid Climates"*. Bari, Italy.
- Janos L. 1995. Application of chemicals through irrigation systems. *ICID J.* 45 N^o. 2., 125–146.
- Johnson, A.W. 1978. Effects of nematicides applied through overhead irrigation on control of root-knot nematodes on tomato transplants. *Plant Dis. Rep.* 62: 48–51.
- Kafkafi, U., and B. Bar-Yosef. 1980. Trickle irrigation and fertigation of tomatoes

- in high calcareous soils. *Agron. J.* 72: 893–897.
- Kanwar, R.S. 1996. Agrochemicals and water management. p. 373–393. In L.S. Pereira et al., (eds.), NATO ARW on “Sustainability of Irrigated Agriculture”, *Kluwer Academic Publ.*
- Kenworthy, A.L. 1972. Trickle irrigation – the concept and guidelines for use. *Mich. State Univ. Agr. Expt. Sta. Res. Rpt.* N°165, East Lansing, Michigan, U.S.A.
- Klein, I., I. Levin, B. Bar-Yosef, R. Assaf, and A. Berkovitz. 1989. Drip nitrogen fertigation of “Starking Delicious” apple trees. *Plant Soil*, 119: 305–314.
- Kovach, S.P. 1983. Injection of fertilizers into drip irrigation systems for vegetables. *Citrus and Vegetables Magazine*. 14: 40–47.
- Lange, A., F. Aljiburig, B. Fischer, W. Humphrey, and H. Otto. 1974. Weed control under drip irrigation in orchard and vineyard crops. p. 422–424. In *Proc. second Intern. Drip Irrig. Congr.*, San Diego, Ca., U.S.A.
- Lauer, D.A. 1988. Vertical distribution in soil of sprinkler-applied phosphorus. *Soil Sci. Soc. Am. J.* 52:862–868.
- Logan, T.J., and E.O. McLean. 1973. Effects of phosphorus application rate, soil properties, and leaching mode on P movement in soil columns. *Soil Sci. Soc. Am. Proc.* 37:371–374.
- Magdoff, F. 1991. Understanding the Magdoff pre-sidedressing nitrate test for corn. *J. Proc. Agric.* 4: 297–305.
- Mailard, R. 1976. Irrigazione a goccia in impianti arborei israeliani (Drip irrigation in orchards in Israel). *Fruitcoltura* 38, 33–43.
- McNamara, J.B. 1970. Subirrigation: the basis of tomorrow’s agriculture. *Proc. Nat. Irrig. Symp.* Univ. Nebraska, Lincoln, Nebraska, USA.
- Mengel, K., and E.A. Kirkby. (1987). Principles of plant nutrition, 4th ed., *Intern. Potash Inst.*, Basel, Switzerland.
- Mikkelsen, R.L., and W.M. Jarrel. 1987. Application of urea phosphate and urea sulfate to drip irrigated tomatoes grown in calcareous soil. *Soil Sci. Soc. Am. J.* 51:464–468.
- Miller, R.J., D.E. Rolston, R.S. Rauschkolb, and D.W. Wolfe. 1981. Labeled nitrogen uptake by drip-irrigated tomatoes. *Agron. J.* 73: 265–270.
- Nakayama, F.S., D.A. Bucks, and O.F. Fench. 1977. Reclaiming partially clogged trickle emitters. *Trans. Amer. Soc. Agric. Eng.* 20: 278–280.
- Nielsen, G.H., E. J. Hogue, and J. Summerland. 1990. Response of fruit trees to phosphorus fertilization. *Acta. Hort.* 347–359.
- Nielsson, F.T. 1987. Manual of fertilizer processing. Marcel Dekker Publ.
- O’Neill, M.K., B.R. Gardner, and R.L. Roth. 1979. Orthophosphoric acid as a phosphorous fertilizer in trickle irrigation. *Soil Sci. Soc. Am. J.* 43:283–286.
- Overman, A.J. 1975. Nematicides in linear drip irrigation for full-bed mulch of tomato. *Proc. Soil Crop Soc. Fla.* 34: 197–200.

- Overman, A.J. 1976. Efficacy of soil fumigants applied via a drip irrigation system. *Fla. State Hort. Soc.* 89, 143–145.
- Overman, A.J. 1978. Crop response to nematicides and drip irrigation on sandy soil. p. 172–179. *Proc. 7th Intern. Agric. Plastics Congr.*, San Diego, Ca., U.S.A.
- Papadopoulos, I. 1985. Constant feeding of field-grown tomatoes irrigated with sulfate water. *Plant Soil* 88, 231–236.
- Papadopoulos, I. 1986a. Nitrogen fertigation of greenhouse-grown cucumber. *Plant Soil*, 93: 87–93.
- Papadopoulos, I. 1986b. Nitrogen fertigation of greenhouse-grown French beans. *Commun. Soil Sci. Plant Anal.* 17: 893–903.
- Papadopoulos, I. 1987a. Nitrogen fertigation of greenhouse-grown tomato. *Commun. Soil Sci. Plant Anal.* 18: 897–907.
- Papadopoulos, I. 1987b. Nitrogen fertigation of greenhouse-grown strawberries. *Fert. Res.* 13: 269–276.
- Papadopoulos, I. 1987c. Effects of residual soil salinity resulting from sulfate waters on lettuce. *Plant Soil* 97:171–177.
- Papadopoulos, I. 1988. Nitrogen fertigation of trickle irrigated potato. *Fert. Res.* 16: 157–167.
- Papadopoulos, I. 1991. Fertigation in Cyprus and some other countries of the Near East region. p. 67–82. *FAO Proc. "Fertigation/Chemigation"*. FAO, Rome, Italy.
- Papadopoulos, I. 1992a. Fertigation of vegetables in plastic-houses: Present situation and future prospects. *Acta Horticulturae* 323, *Soil and Soilless Media under Protected Cultivation*; 151–174.
- Papadopoulos, I. 1992b. Phosphorus fertigation of trickle-irrigated potato. *Fert. Res.* 31:9–13
- Papadopoulos, I. 1993. Agricultural and environmental aspects of fertigation-chemigation in protected agriculture under Mediterranean and arid climates. p. 103–1033. *In Proc. "Environmentally Sound Water Management of Protected Agriculture under Mediterranean and Arid Climates"*, Bari, Italy.
- Papadopoulos, I. 1995. Use of labeled fertilizers in fertigation research. p. 399–410. *In Proc. "International symposium on nuclear and related techniques in soil/plant studies on sustainable agriculture and environmental preservation"*, Vienna, 1994.
- Papadopoulos, I. 1996a. Irrigation systems, water-use efficiency and environmental impacts. p. 113–123. *In* M.G. Bos (ed) *The inter-relationship between irrigation, drainage and environment in the Aral Sea Basin*.
- Papadopoulos, I. 1996b. Micro-irrigation systems and fertigation. p. 309–322. *In* L.S. Pereira et al. (Ed.), *NATO ARW on "Sustainability of Irrigated Agriculture"*, Kluwer Academic Publ.
- Papadopoulos, I. 1997a. Irrigation/fertigation modeling. p. 79–90. *In Proc. of the*

- Intern. Conf. "Water Management, Salinity and Pollution Control towards Sustainable Irrigation in the Mediterranean Region", CIHEAM, Bari, Italy, 22–26 Sept., 1997.
- Papadopoulos, I. 1997b. Fertilizers in irrigated agriculture and potential pollution impact. p. 193–215. *In* Proc. Intern. Conf. "Water Management, Salinity and Pollution Control towards Sustainable Irrigation in the Mediterranean Region". Advanced Short Course, CIHEAM, Bari, Italy, 27 Sept. – 4 Oct. 1997.
- Papadopoulos, I., and D. Chimonidou-Pavlidou. 1997. Nutrient and agro-chemical management for pollution control under intensive irrigated agriculture. p. 45–65. *In* Proc. Intern. Conf. "Water Management, Salinity and Pollution Control towards Sustainable Irrigation in the Mediterranean Region", CIHEAM, Bari, Italy, 22–26 Sept., 1997.
- Papadopoulos, I., and L. Ristimaki. 1998. Nitrogen and phosphorus fertigation of tomato and eggplant. *In* Proc. of the HIS. Belgium, 2–9 Aug., 1998.
- Pereira, L.S. 1996. Surface irrigation systems. p. 269–289. *In* L.S. Pereira et al. (Ed.), NATO ARW on "Sustainability of Irrigated Agriculture", Kluwer Academic Publ.,
- Pereira, L.S., A. Hamdy, N. Lamaddalena, and M. Abdelmalek. 1994. Fertigation with surface irrigation. p. 309–325. *In* Proc. Conf. "Land and Water Management in the Mediterranean Region" Bari, Italy.
- Phene, C.J., and D.W. Beale. 1976. High-frequency irrigation for water nutrient management in humid regions. *Soil Sci. Soc. Am. J.* 40: 430–436.
- Phene, C.J., and D.C. Sanders. 1976. Influence of combine row spacing and high frequency trickle irrigation on production and quality of potatoes. *Agron. J.* 68: 602–607.
- Phene, C.J., J.L. Fouss, and D.C. Sanders. 1979. Water-nutrient-herbicide management of potatoes with trickle irrigation. *Amer. Pot. J.* :56–59.
- Rawlins, S.L., and P.A.C. Raats. 1975. Prospects for high-frequency irrigation. *Science* 188: 604–610.
- RNEA/FAO. 1992. Irrigation methods, crops, and practices using wastewater. FAO, Rome, Italy.
- Rauschkolb, R.S., D.E. Rolston, R.J. Miller, A.B. Carlton, and R.G. Bureau. 1976. Phosphorus fertilization with drip irrigation. *Soil Sci. Soc. Am. J.* 40:72.
- Rolston, DE., R.S. Rauschkolb, and D.L. Hoffman. 1975. Infiltration of organic phosphate compounds in soil. *Soil Sci. Soc. Am. Proc.* 39:1089–1094.
- Reisenauer, H.M., (ed.) 1983. Soil and plant tissue testing in California. Univ. Calif. Bull. N°1879, Davis, Ca.
- Ruiz, S., and G. Jose. 1992. Effect of acid and ferric drip irrigation on alkaline soil and on *Prunus salicina* L. cv. Methley under mulching. Montecillo, Mexico.
- Ryan, J., S. Miyamoto, and J.L. Stroehlein. 1974. Solubility of Mn, Fe, and Zn as affected by application of sulfuric acid to calcareous soil. *Plant Soil*

40:421–427.

- Ryan, J., and J.L. Stroehlein. 1979. Sulfuric acid treatment of calcareous soils: Effects on phosphorus solubility, inorganic phosphorus forms, and plant growth. *Soil Sc. Soc. Am. J.* 43:731–735.
- Sanders, D.C. 1997. Drip fertigation systems. North Carolina A & T State University, U.S. Leaflet No. : 33–D. p. 7.
- Shoji, K. 1977. Drip irrigation. *Sci. Amer.* 237: 62–68.
- Snyder, G.H., and E.O. Burt. 1976. Nitrogen fertilization of Bermudagrass turf through an irrigation system. *J. Amer. Soc. Hort. Sci.* 101: 145–148.
- Spalding, R.F., M.E. Burbach, and M.E. Exner. 1989. Pesticides in Nebraska's groundwater. *Groundwater Monit. Rev.* 9(4):126–133
- Stark, J.C., W.M. Jarrell, J. Letey, and N. Valoras. 1983. Nitrogen-use efficiency of trickle-irrigated tomatoes receiving continuous injection of nitrogen. *Agron. J.* 75: 672–676.
- Threadgill, E.D. 1985. Fertigation via sprinkler irrigation: Current status and future development. Applied Engineering in Agriculture 1:16–23. In Hoffman et al., (ed.) Management of Farm Irrigation Systems.
- Tyagi, N.K. 1984. Effect of land surface uniformity on some economic parameters of irrigation in sodic soil under reclamation. *Irrig. Sci.* 5(3):151–160
- Uriu, K., R.M. Carlson, D.W. Henderson, H. Schulbach, and T. M. Aldrich. 1980. Potassium fertilization of prune trees under drip irrigation. *J. Am. Soc. Hort.* 105: 508–510.
- Watts D.G., J.S. Schepers, R.F. Spalding, and T.A. Peterson. 1993. The Nebraska MSEA: Management of irrigated corn and soybeans to minimize groundwater contamination. p. 60–68. In Proc. Nat. Conf. Agric. Res. to Protect Water Quality. Soil Cons. Soc., Ankeny, Iowa, U.S.A.
- Young, J.R. 1980. Suppression of fall army-worm populations by incorporation of insecticides into irrigation water. *Fla. Entomol.* 63: 447–450.

APPENDIX I

Fertigation Step-by-Step Approach

Example:

Crop, is drip-irrigated tomato with rooting depth of 40 cm. Drippers are wetting 35% of the soil. Soil analyses indicated no N, 40 ppm P, and 150 ppm K. Safety margin values are 30 and 100 ppm for P and K, respectively. Find the N, P, K required for yield of 80 and 125 t/ha. Nutrient uptake efficiency of the irrigation system is 80, 30, 85, for N, P, K, respectively. The nutrient requirements of tomato are:

Yield	Irrigation Method	Nitrogen	Phosphorus	Potassium
-----t/ha-----		-----kg/ha-----		
50	Drip	227	67	184
	Furrow	333	133	208
75	Drip	283	80	275
	Furrow	415	161	312
100	Drip	340	94	367
	Furrow	497	189	416
125	Drip	396	108	459
	Furrow	579	216	520
Each additional 10 tons	Drip	23	5.5	37
	Furrow	33	11	42

For conversion to P_2O_5 , multiply P values by 2.29; from K to K_2O , multiply by 1.20.

1. Calculate the weight of soil of one hectare to a depth of 40 cm

$$\begin{aligned}
 \text{Wt of soil (t/ha/0.4 m depth)} &= 10000 \text{ (m}^2\text{)} \times 0.4 \text{ (m)} \times \text{Bulk density (t/m}^3\text{)} \\
 &= 4000 \text{ m}^3 \times 1.20 \text{ t/m}^3 \\
 &= 4800 \text{ t}
 \end{aligned}$$

2. Calculate available P and K above safety margins

$$\begin{aligned}
 P \text{ (kg/ha)} &= (40-30 \text{ g/t}) \times 4800 \text{ t/ha} = 48000 \text{ g/ha} = 48 \\
 K \text{ (kg/ha)} &= (150-100 \text{ g/t}) \times 4800 \text{ t/ha} = 240000 \text{ g/ha} = 240
 \end{aligned}$$

3. Actual P and K available above safety level in the 35% soil occupied by roots

$$P = 48 \times 35/100 = 16.8 \text{ kg P/ha}$$

$$K = 240 \times 35/100 = 84 \text{ kg K/ha}$$

Case 1. (For 80 t/ha):

$$N = 239 \text{ kg/ha}$$

$$P = 25.6 - 16.8 = 8.8 \text{ (20 } P_2O_5)$$

$$K = 358 - 84 = 274 \text{ (329 } K_2O)$$

Case 2. (For 125 t/ha):

$$N = 320 \text{ kg/ha}$$

$$P = 33.3 - 16.8 = 16.5 \text{ (38 } P_2O_5)$$

$$K = 499 - 84 = 415 \text{ (498 } K_2O)$$

4. Amount of N, P, K needed to be applied as fertilizer

Case 3. (For 80 t/ha):

$$N = 239 \times 100/80 = 299 \text{ kg/ha}$$

$$P = 8.8 \times 100/30 = 29 \text{ (67 } P_2O_5)$$

$$K = 274 \times 100/85 = 322 \text{ (386 } K_2O)$$

Case 4. (For 125 t/ha):

$$N = 320 \times 100/80 = 400 \text{ kg/ha}$$

$$P = 16.5 \times 100/30 = 55 \text{ (128 } P_2O_5)$$

$$K = 415 \times 100/85 = 488 \text{ (303 } K_2O)$$

5. Uptake efficiency of N, P, and K by drip-irrigation (80, 30, 85%, respectively)

6. Select the most appropriate fertilizer

The most appropriate fertilizers under these conditions are:

For 80 t/ha with N: P_2O_5 ; K_2O of 4.5: 1: 4.8 (e.g., fertilizer 27-6-29)

For 125 t/ha with N: P_2O_5 ; K_2O of 3.1: 1: 3.8 (e.g., fertilizer 30-8-30)

7. Calculate the amount of fertilizers

So if the fertilizers 27-6-29 or 30-8-30 are available, they may be applied in the following amounts:

$$27-6-29 = 299 \times 100/27 = 1107 \text{ kg/ha}$$

$$30-8-30 = 400 \times 100/30 = 1333 \text{ kg/ha}$$

Fertigation

With fertigation, all fertilizers are applied with the irrigation water. In this respect, the amount of irrigation water needed must be calculated. This could be done by using E_{pan} evaporation of the area where the plantation is. Fractions of E_{pan} recommended for selected vegetables are given in Table 20.

Example:

Calculate the amount of irrigation water for tomato in Bank Khen in Thailand

Month	Jan		Feb		March		April		May	
	1-15	15-31	1-15	15-28	1-15	15-31	1-15	15-30	1-15	15-30
Rain (mm)	6	6	6	5	11	12	37	38	73	73
E_{pan} (mm)	63	64	69	68	90	90	93	94	78	78
$E_{pan} - \text{Rain}$ (mm)	57	58	63	63	79	78	56	56	5	3
Fraction of E_{pan}	0.3	0.5	0.8	0.9	1.0	1.0	1.0	1.0	0.8	0.8
Irrig. water (mm)	17	29	50	57	79	78	56	56	4	4
m ³ /ha	170	290	500	570	790	780	560	560	40	40

Total amount of water is 4300 m³/ha.

The above calculations indicate that the calculated amount of fertilizer will be applied with 4300 m³/ha of irrigation water.

1. Calculate the concentration of N, P, and K in the irrigation water

Case 1. For 80 t/ha

$$N \text{ (g/m}^3\text{)} = 299000 \text{ g/ha} : 4300 \text{ m}^3/\text{ha} = 70 \text{ g/m}^3 \text{ of irrigation water}$$

$$P \text{ (g/m}^3\text{)} = 29000 \text{ g/ha} : 4300 \text{ m}^3/\text{ha} = 7 \text{ g/m}^3 \text{ of irrigation water}$$

$$K \text{ (g/m}^3\text{)} = 322000 \text{ g/ha} : 4300 \text{ m}^3/\text{ha} = 75 \text{ g/m}^3 \text{ of irrigation water}$$

Case 2. For 125 t/ha

$$N \text{ (g/m}^3\text{)} = 400000 \text{ g/ha} : 4300 \text{ m}^3/\text{ha} = 93 \text{ g/m}^3 \text{ of irrigation water}$$

$$P \text{ (g/m}^3\text{)} = 55000 \text{ g/ha} : 4300 \text{ m}^3/\text{ha} = 13 \text{ g/m}^3 \text{ of irrigation water}$$

$$K \text{ (g/m}^3\text{)} = 488000 \text{ g/ha} : 4300 \text{ m}^3/\text{ha} = 114 \text{ g/m}^3 \text{ of irrigation water}$$

2. Calculations for fertigation

Calculate the amount of fertilizer required to prepare the concentrated stock solution. The concentrated stock solution can be calculated with the following equation:

$$C = \frac{F \cdot DF \cdot n \cdot 100}{a}$$

Where:

C = Weight of the fertilizer in the stock solution (g)

- F = Desired concentration of a nutrient in the irrigation water (g/m³)
 n = Volume of the reservoir for the stock solution (m³)
 a = Amount of a pure nutrient in the fertilizer (%)
 DF= Dilution factor

$$\text{Dilution Factor} = \frac{\text{Flow rate of the irrigation system}}{\text{Flow rate of the fertigator}}$$

Example for Calculations:

The fertigated crop is tomato with the following requirement: N = 70 (g/m³), P = 7 (g/m³), K = 75 (g/m³). The available fertilizer is 27–6–29.

1. Characteristics of the irrigation/fertigation system

With direct measurements in the field it has been found that the

- Flow rate of the irrigation system is 10000 L/h.
- Flow rate of the fertigator is 100 L/h.
- The capacity of the reservoir for the stock solution is 1 m³.

$$\text{Dilution Factor} = \frac{\text{Flow rate of the irrigation system}}{\text{Flow rate of the fertigator}} = \frac{10000}{100} = 100$$

Calculations for the Fertilizers

$$27-7-29 = \frac{70 \times 100 \times 1 \times 100}{27} = 25926 \text{ g/m}^3 \text{ stock solution}$$

APPENDIX II

Example how to mix different fertilizers

The concentrated stock solution can be calculated with the equation:

$$C = \frac{F \cdot DF \cdot n \cdot 100}{a}$$

Where:

C = Weight of the fertilizer in the stock solution (g)

F = Desired concentration of a nutrient in the irrigation water (g/m³)

n = Volume of the reservoir for the stock solution (m³)

a = Amount of a pure nutrient in the fertilizer (%)

DF= Dilution factor

$$\text{Dilution Factor} = \frac{\text{Flow rate of the irrigation system}}{\text{Flow rate of the fertigator}}$$

Example for Calculations

The fertigated crop is tomato and we want to apply the following: N = 170, P = 40, K = 250. The available fertilizers are:

Urea	(46-0-0)	
KNO ₃	(13-0-46)	[46% K ₂ O]
Urea Phosphate (UP)	(18-44-0)	[44% P ₂ O ₅]

1. Characteristics of the irrigation/fertigation system:

With direct measurements in the field it has been found that the

- Flow rate of the irrigation system is 10000 L/h.
- Flow rate of the fertigator is 100 L/h.
- The capacity of the reservoir for the stock solution is 1 m³.

$$\text{Dilution Factor} = \frac{\text{Flow rate of the irrigation system}}{\text{Flow rate of the fertigator}} = \frac{10000}{100} = 100$$

2. Calculations for the Fertilizers:

a) Calculations for potassium

$$\text{Potassium nitrate} = \frac{250 \times 100 \times 1 \times 100}{46/1.2^1} = 65217 \text{ g/l}^3 \text{ stock solution}$$

$$\text{N from potassium nitrate} = \frac{65217 \times 13}{100 \times 1 \times 100} = 85 \text{ g/m}^3 \text{ of irrigation water}$$

b) Calculations for phosphorus

$$\text{Urea phosphate} = \frac{40 \times 100 \times 1 \times 100}{44/2.29} = 20818 \text{ g/m}^3 \text{ stock solution}$$

$$\text{N from urea phosphate} = \frac{20818 \times 18}{100 \times 1 \times 100} = 37 \text{ g/m}^3 \text{ of irrigation water}$$

c) Calculations for nitrogen

$$\text{N from KNO}_3 = 85 \text{ g/m}^3$$

$$\text{N from UP} = 37 \text{ --/--}$$

$$\text{Total} = 122 \text{ --/--}$$

$$\text{Additional N} = 170 - 122 = 48 \text{ g N/m}^3$$

$$\text{Urea} = \frac{48 \times 100 \times 1 \times 100}{46} = 10435 \text{ g/m}^3 \text{ stock solution}$$

Summary of the Fertilizers Needed:

In a reservoir of one m³, the following amounts of fertilizers are needed to provide 170, 40, or 250 g/m³ of N, P, K, respectively:

$$\text{Potassium nitrate} = 65217 \text{ g/m}^3$$

$$\text{Urea phosphate} = 20818 \text{ --/--}$$

$$\text{Urea} = 10435 \text{ --/--}$$

¹Note: K₂O/1.2 = K; P₂O₅/2.29 = P

Towards Guidelines for Quality Fertilizers under Modern Irrigation

Ghassan Hamdallah

The FAO Regional Office, Cairo, Egypt

ABSTRACT

Increased levels of agricultural output have become the target of almost all nations for satisfying the accelerated demand for food. In irrigated agriculture, fertilizer /water management surmounts any other single factor in its impact on crop production. The widespread of modern irrigation systems has made fertilizer application simple, easily manageable, and possible to more precisely match the crop requirements. For traditional and obvious reasons, nitrogen is the most commonly used fertilizer, followed by phosphorus and the least used is potash. Near East countries are constrained by limited water and soil resources, superimposed with arid and semi-arid ecological zone for the major part. FAO maintained its role in promoting the role of mineral fertilizers, within the appropriate management concept of "Integrated Plant Nutrition System, IPNS".

Fertilizers, being chemical compounds, evidently would have their *positive* and *negative environmental impacts*, particularly if misused or overused. In developing countries, the rate of fertilizer use is far lower than in other developed countries, and therefore the fertilizer-borne hazards to the environment might be exaggerated. Fertilizer-producing sector is urged to respond to the new demand for fertilizer types and formulations that would be commensurate with the modern irrigation system.

Soluble powders, slow release, suspensions and liquid formulations and minor elements carriers are all to be given due consideration. Some adequate standards and technical specifications for the fertilizer manufacturing, trade and usage ought to be harmonized, monitored and implemented. Both fertilizer users (farmers) and producers (factories) should work jointly to apply the integrated management practices of plant nutrients soil /water systems. This is to be coupled with the "Best Available Technology" (BAT) by the procedures to reach the objective of *efficient* and *environmentally-sound fertilizer use*.

INTRODUCTION

The fertilizer role for sustainable agriculture cannot be over-emphasized. In 1960, farmers harvested about 1.4 billion hectares. By the 1990s, this area was still less than 1.5 billion, yet food and feed supplies had been doubled in the interim (IFA, 1998a). If this had not happened, the world would have lost more than 2.6 billion hectares of natural habitat, in addition to incalculable food shortage consequences.

In irrigated farming, fertilizer-water management has a greater impact on crop production than any other single factor. Population growth rates and shrinking arable land share per capita, in most developing countries, render intensive farming patterns as inevitable for meeting the increased demand for agricultural outputs. With the spread of 'modern' or pressurized irrigation systems, the application of fertilizers through the water applied to plants (i.e., fertigation) has become common. At present, fertigation is widely used and has a longer history of use than the other chemigation practices (Threadgill, 1991). Fertigation represents a feasible and sound method due to its higher use efficiency and safer effect on the environment.

The agronomic advantages of fertigation are achieved through the delivery of plant nutrients at times conforming with the crop physiological needs. On the environmental side, it is also possible to minimize the potential hazard of excess nutrients from being leached or lost from the soil-water-plant system. Since nitrogen (N) is the most nutrient used by plants, its application is dominant through fertigation, and, to lesser extent phosphorus (P) and potassium (K). Minor elements can be injected with irrigation water or added as foliar sprays, mainly to correct deficiency symptoms on crops.

With the merits cited above for fertigation methods, it becomes essential to ensure using the right type and formulation of fertilizers that fit such systems. For any fertilizer to be injected in the irrigation pipe or to be safely sprayed on plants, adequate standards and precautions are needed, including the fertilizer's raw material properties such as being non-corrosive to pipes and equipment, having low salt index, being highly soluble and of high purity, and of a favourable pH effect.

LAND AND WATER CONSTRAINTS IN THE REGION

Arable lands available in the Near East Region (29 countries) amount to 125 million ha, out of which some 48 million ha are under irrigation. This allows only 0.22 ha of arable land per capita. Such regional average is misleading, as the arable land share per inhabitant ranges from 0.002 ha (Kuwait, Qatar) to 0.45 ha (Sudan, Turkey). Some countries with extensive arable areas, such as Sudan, lack the capital and adequate infrastructure, which adds to the complexity of shrinking share of arable lands. The new move in Egypt to expand their agriculture beyond the narrow strip along the Nile is a courageous long-term step, and therefore the initial

investment costs and the overall feasibility need to be assessed on this basis. Protected farming offers an alternative for intensive production of some horticultural crops. Plastic tunnels and fibreglass houses have spread in 1970s in the Jordan Valley, Lebanon, Syria, Gulf States, and in the Morocco. These greenhouses brought along with them new modes of agricultural practices, more efficient irrigation techniques (*drip, mist, and micro-jet*). High-yielding hybrid seeds of vegetables, new fertilizer forms (crystallized, liquid, suspensions, chelated minor elements), as well as cooling and heating systems for environmental control of these houses.

Water resources in the Near East Region are characterized by two main constraints: the *scarcity* and *disparity among various countries*. Some 16 countries in the region are below the 500 m³ per capita per annum of renewable water, which is the recognized water deficiency level (FAO, 1997). Water table draw-down is occurring in many countries, leading to water quality deterioration and higher costs paid for pumping. Non-conventional water resources are still of low magnitude, either due to their high capital costs, as in the desalination projects, or due to their limited supply and use, such as treated sewage effluent, covering less than 1% of water used in agriculture.

The other challenge facing water use in agriculture (about 91% of total consumption) comes from the other competing economic sectors which can claim much higher efficiency of water, use such as the urban, tourism and industry sectors. This poses a real challenge that agriculturists have to face at present, and one that requires "more efficient" systems for land and water resources utilization. Fertigation represents one of the most adequate delivery systems to this effect.

FAO WORK TO PROMOTE FERTIGATION

Since its first use in modern pressurized irrigation, fertigation received a good deal of attention from FAO. In September 1991, an Expert Consultation convened in Cairo on Fertigation/Chemigation, and the panel of experts endorsed the adoption of these new practices and recommended their inclusion in college curricula, which were introduced in some countries of the Region. In 1995, another training course on fertigation was convened in Beirut, jointly with IAM, Bari Institute.

The Regional Office issued several volumes of proceedings and bulletins covering various aspects of fertigation. In December 1996, the FAO/RNE held a Regional Workshop on Fertilizer Use for Sustainable Agriculture in Amman, jointly with the Arab Fertilizer Association (AFA). It emphasized the need to promote environmental impact assessment (EIA), the Integrated Plant Nutrition Approach (IPNS) and the adoption by manufacturers of the Best Available Technology (BAT).

In December 1998, a Regional Workshop was held in Cairo, in collaboration with the Arab Fertilizer Association on Quality Fertilizers for Modern Irrigation.

The Workshop further called for promoting the use of quality fertilizers in fertigation systems, recognized as efficient water and fertilizer-saving techniques.

FAO stresses the role of fertilizer as been responsible for about 55% of the growth achieved in yield increases in developing countries during the past three decades. After the conclusion of the FAO Fertilizer Program that lasted over 30 years, the Soil Fertility Initiative (SFI) was launched during the World Food Summit, held in Rome in November 1996. This summit brought the food problem in front of the highest level of political forum in order to ensure political commitments to implementing of its Plan-of-Action, and through the diligent campaign that FAO is leading calling for "Food for All".

The pivotal role of fertilizes in addressing the global food issue can be visualized from the estimate given in the FAO Study on "World Agriculture Towards 2000", stating "that about two-thirds of the needed increase in crop production, in developing countries, will have to come from yield increases on land already under cultivation" (FAO, 1981). This qualifies the role of plant nutrients as the most important input to reckon with for vertical expansion. A typical response ratio to fertilizers, documented by various researchers, was around 10 kg cereals per each kg fertilizer applied (IFA, 1998b).

FERTILIZER USE AND THE ENVIRONMENT

The long-term sustainability of any system basically requires trade-offs between benefits and losses, and the use of fertilizes is no exception. The critical opinion of environmentalists criticizing mineral fertilizer use, mainly in developed countries, is a luxury that developing nations cannot afford, since many of them are facing food insecurity, and their fertilizer use is far below the recommended levels. Evidently, there are several environmental impacts that stem from the manufacturing side, as well as from the users of fertilizers; hence, their potential hazard ought to be elucidated in the course of search for quality fertilizers.

At Fertilizer-Factory Level

There are a number of issues and environmental concerns that should be dealt with at the source, i.e., the fertilizer plant level. Addressing this is very often a costly and complicated process. Fertilizer industry is a major one in many producing nations, due to its significant investments to produce this commodity (fertilizers) whose global sales value hit the level of 50 billion US dollars in 1996 (IFA, 1998b).

The environmental impact of a fertilizer plant depends on a wide variety of circumstances, including:

- Nature of the plant,
- Processes and raw materials used in production,

- Location of the site,
- Type and nature of the surroundings,
- Regulations and norms to which the industry should conform to, and
- The expertise of the plant staff and management.

For various reasons, many fertilizer plants do not yet practice the best available technologies. It is therefore difficult to assess the general impact of fertilizer complexes on the environment; however, these are the main problems encountered:

Ammonia and Nitrogen Fertilizer Production

The production of ammonia and other N fertilizers results in the emissions of gases, including carbon dioxide (2-7 tons of CO_2 per ton of N produced). However, the addition of CO_2 from fertilizer industry to the atmosphere amounts only to 0.1 – 0.2 % of the total amount of CO_2 released annually by biological processes. The other main N gas produced is nitrous oxide (N_2O), which like CO_2 is considered a global warming agent. Although the N_2O produced is estimated at 1 – 10 kg per ton of nitric acid produced, the portion produced from the fertilizer industry accounts for only 6% of man-made N_2O emissions. This is to be compared with about 50% that are coming from motor vehicles.

Phosphate Fertilizer Production

Sulphur compounds are emitted, resulting mainly from the production of sulphuric acid and phosphate fertilizers. Most of the gaseous sulphur compounds emitted can be recovered by scrubbing and filtration, but much depends on the age and efficiency of the fertilizer plant. The other major environmental concern is the waste phosphogypsum resulting from the fertilizer reaction process, at a rate of 4 – 5 tons of this waste per each ton of P_2O_5 converted into phosphoric acid. The phosphogypsum produced contains other trace elements, some of which constitute an environmental concern, particularly cadmium (Cd). Depending on the origin of the rock phosphate used, the Cd content ranges from 0 to 300 mp/kg P_2O_5 . Cadmium can be absorbed by crops at varying levels and can be toxic at certain limits. Other sources of this Cd environmental problem come from sewage sludge and animal manure when added to the soil. Technologies for separating Cd from the rock phosphate are expensive in fertilizer production, and are presently confined to phosphates for human and animal consumption.

Waste Disposal

In addition to the problem of phosphogypsum waste, the disposal of other solid and liquid wastes are also a main environmental concern. The spent chemical catalysts, which are usually replaced every few years, have to be disposed of properly as they contain some oxides of metals and several chemicals. Other sulphur compounds such as sulphuric acid are also produced and need to be treated or used as soil amendment. Wastes requiring special treatment include wastewater, sludge, scrubber and filter dust, filter bags and empty containers. When an ageing factory is shut down, for economic or environmental reasons, the problems of site rehabilitation and clean-up are major and costly processes.

Fertilizer Use Preceptions

Most of the adverse impact of fertilizers stems from their improper use, due to lack of knowledge among farmers on the proper agricultural practices for applying fertilizers. However, enabling the farming community to acquire adequate information or have access to agricultural extension and training is a complex and costly process. There is about 2 billion farmers world-wide, and spreading the word to such a huge population is beyond reach of many nations. The FAO Fertilizer Program, which lasted over 30 years, made some significant achievements in this regard.

Some of the commonly stated negative impacts of fertilizer use are listed below, along with the parallel arguments (IFA, 1998a):

- 1. They destroy the soil fertility – you need more fertilizer doses to achieve the same crop yields.***

The long-term experiments at Rothamsted, UK, with continuous use of mineral fertilizers for more than 150 years have proved that the soil was more productive than before. Fertilizer application is actually looked upon as a safeguard against soil depletion of its nutrients (mining) through the crop removal, especially in intensive farming.

- 2. They diminish food quality, presenting organic farming as healthier and of better quality product.***

If this argument can be accepted at the micro (garden) level, its application globally can be detrimental to soil productivity, food security and to soil management. As reported by IFPPI, “*Past and current failures to replenish soil nutrients in many counties must be rectified through the balanced and efficient use of organic and inorganic plant nutrients and through improved soil management practices. It is critical that fertilizers use be expanded in*

developing countries; where a large share of the population is food-insecure", (IFPRI, 1997).

3. They pollute the soil with toxic heavy metals such as cadmium.

The soil naturally contains some heavy metals, whose high levels could be toxic to plants or animals. Mineral and organic fertilizers do have some of these metals, and they should be applied at recommended rates that are within the allowable limits. For animal organic manure, human waste (sludge) and industrial wastes, countries have sets of guidelines for the maximum allowable limits that match the loading capacity of the soil.

4. They pollute groundwater.

Nutrients added to the soil through fertilizers are removed by crops and the excess are either leached down to the drainage system, volatilized as gases, or join the shallow groundwater table. Phosphorus goes through rapid conversion of its soluble forms to other less soluble ones in the soil, while potassium ions can be fixed in the soil clay, or converted to other exchangeable forms.

Nitrogen, therefore, stands as the main fertilizer element also most commonly used by crops - that can undergo *leaching* or loss to the atmosphere through *denitrification* or *gaseous volatilization*. The fate of added N, whether from mineral or organic fertilizer, is the nitrate (NO₃) ion, which is already soluble. The leached nitrate can reach the shallow groundwater directly or through the drainage system. Therefore, nitrate levels in drinking water have become an issue in recent years.

The health concern came from the fact that the nitrate entering the body is reduced to nitrite (NO₂). which can reduce the oxygen-carrying capacity of the blood. Due to that, the World Health Organization in mid 1980's recommended a limit of 50 mg of NO₃ per litre of drinking water. The US and other countries adopted a more strict limit of NO₃ concentration at 10 mg/litre in drinking water. In addition, concentrations of N and P, if discharged to surface inland water, lead to eutrophication.

However, in order that these undesirable impacts are minimized, and to enhance the efficiency of applied N-fertilizers, the following basic approaches ought to be sought:

- Proper fertilizers recommendation rates based on validated crop requirements.
- Improving soil and crop management practices, including split application, timing, and fertilization methods.

- Use of coated, controlled and slow – release N fertilizers in order to reduce gaseous losses and leaching.
- Use of biofertilizers and microbial inoculants, such as biological N fixation in combination, or to partly replace mineral fertilizers.

THE NEED FOR AN INTEGRATED APPROACH

The Integrated Plant Nutrition System

Since the mid 1980s, FAO has been promoting the concept of Integrated Plant Nutrition System (IPNS) which aims to maintain and enhance the soil productivity through a balanced use of mineral fertilizers combined with organic plant nutrient sources, including biological N fixation. The viability of this approach stems from its ecological, social and economic basis, leading to sustaining the soil productivity and ensuring optimum crop production levels. *Soil fertilization rather than crop fertilization ought to be the guiding principle.* It follows that these elements constitute the basis for IPNS: 1) cropping system and not individual crop, 2) management of plant nutrients in the whole-farming system; and 3) the concept of village or community areas to be considered rather than the individual fields.

In 1998, FAO produced a “Guide to Efficient Plant Nutrition Management” (FAO, 1998) to promote this approach and introduce it as a safeguard to sustainability of soil productivity under intensification of agriculture. Intensive farming, requiring more mineral fertilizer use, poses a matter of a somehow contrasting situation. In industrialized countries, environmental issues and international trade agreements restricting surplus food production are bound to further limit intensification. On the other hand, developing countries, who pay high prices for imports of food as well as for external fertilizer sources, would have probably no choice but to have farming intensification.

Due to the importance of fertilizer use, it is necessary to develop a balanced relationship between crop yield, plant nutrients added, economic feasibility, and the environmental quality. The IPNS approach, if well applied, offers an attractive and sustainable solution from the user side. FAO, realizing the mounting concern, particularly in developed countries, over the environmental impact of mineral fertilizers use, calling for organic farming, and also knowing the pivotal role of fertilizers in today’s agriculture have summarized those *four* issues as guiding principles:

- Fertilizers are often referred to as agro-chemicals, a term which groups plant nutrients with *insecticides, herbicides and fungicides*. A clear distinction must be made between fertilizers, which provide nutrients that are essential for plant

growth, and biocides, which are compounds that *kill* and are used for *plant protection*.

- The environmental effects of applying plant nutrients can be *positive* or *negative*, and statements on the issue should be objectively balanced.
- The amounts of plant nutrients, both mineral and organic, that are applied in developing countries are relatively low. Local excesses in some industrial countries should not prejudice increased agricultural production in the developing world.
- Environmental problems related to application of plant nutrients depend less on the nature of the nutrients than on the amounts and the way they are applied. Detrimental effects are mostly due to overdoses or to improper or unbalanced use that can be corrected by improved management practices.

Best Agricultural Practices

For the successful application of the IPNS approach, other integrated systems ought to be also utilized to achieve the best agricultural practices by the farmers. Integrated crop management addresses the basic farming issues such as crop rotation, crop variety selection, cultural practices, precise use of fertilizers, as well as crop protection measures and products that also protect the environment. The utilization of automated land evaluation systems and agro-ecological zoning also contributes to the better mastering of the *fertilization process* from all its dimensions. These various integrated systems should be looked upon to have a synergetic effect in relation to the IPNS concept and ensures its fruitful implementation. When best agricultural practices are followed by farmers and best available technology is adopted by manufacturers, then the optimum *agronomic, economic, and environmental conditions* can be expected from the use of quality fertilizers.

QUALITY FERTILIZERS AND THE USER NEEDS

Producing quality fertilizers is an essential and pressing demand on both economic and environmental grounds. From the economic angle, the loss due to fertilizer-use inefficiency could cost the world economy about 10.6 billion US dollars for N alone, assuming only 20% loss of N out of the global total use of 80 million tons in 1996 (IFA, 1998a). On the environmental side, cleaning of inland and coastal waters costs significant budget allocations, and the environmental protection issues are on the top of communities' agenda in the USA and in many parts of the world as well. In 1996, the Agri-environmental "Accompanying Measures" of the European Union accounted for about 1.8 billion US dollars (IFA, 1998b).

In effect, fertilizer could be described as the one that satisfies the *timely agronomic needs of plants*, be *technically and economically feasible*, and be *friendly to the environment*. Evidently all these qualities are equally important; below is a brief account on the main considerations in this regard.

Fertilizer Elemental Analysis and Formulations

This refers to the content of the soluble forms of the three basic elements of N, P, and K expressed as elements or in their oxide forms. The higher this analysis, the higher value of the fertilizer. Some countries put a condition that in order to import a fertilizer material it should have at least 50% of one or a combination of the three elements. Of course, there is a wide variety of chemical forms that differ in their solubility and availability to plants for each fertilizer, such as NO_3 , NH_3 , HNO_3 , NH_2 , ... for N, and H_2PO_2 , HPO_4 , and PO_4 for P, and so on. The fertilizer formulations are also difficult to survey and include soluble powders, granulated, coated, pellets, brackets, sticks/poles, liquid, suspension, ... etc. *Each formulation has its properties, merits and usage for certain crops and special user needs.*

Raw Materials

Mineral fertilizers are generally produced from a small number of different raw, naturally existing materials, and other intermediate products. Natural gas, other hydrocarbons, rock phosphate and potassium salts are the main sources for raw materials. The discussion below will focus on describing some guidelines for selecting an appropriate raw material, at the factory level, for producing the finished product of fertilizer that fits foliar sprays or used for fertigation.

Soluble Powder Fertilizers

Good quality soluble powder fertilizers are produced from completely soluble crystalline raw materials that are crystal clear and 100% soluble in water, with no dissolved particles to clog irrigation lines or equipment. Once a fertilizer is dissolved in water, it should stay in solution and not precipitate out at the same temperature. Soluble powder fertilizers should be formulated from blending a uniform mixture of soluble salts that are not corrosive to irrigation lines or equipment, has low salt index, highly soluble and highly pure. Soluble powder fertilizers may be used for fertigation or foliar fertilization.

Nitrogen Fertilizers

Urea is one of the most suitable N sources for soluble powder fertilizer, as well as

foliar liquid fertilizers. It has low salt index and high solubility in comparison to other N sources. Urea should be low in biuret content (less than 0.2%). Urea produced in the Middle East is low enough in biuret (for example, less than 1% in Saudi Arabia) and will not result in biuret hazard to plants, even if applied as a foliar fertilizer. Other sources of N can be obtained from ammonium nitrate, ammonium sulfate, ammonium phosphate, and urea phosphate. These sources are excellent supplemental N carriers with minimal side effects.

Phosphorus Fertilizers

Most dry P fertilizers produced for general farm applications cannot be used for the production of soluble powder fertilizers because they contain a high percentage of insoluble material. Monoammonium phosphate (MAP, 12-61-0), diammonium phosphate (DAP, 21-53-0), monobasic potassium phosphate (MKP, 0-52-34), and urea phosphate (17-44-0) are common P sources for the production of soluble fertilizers.

Farmers using hard water may experience some precipitation problems with neutral fertilizers. Farmers who inject P through drip and micro-irrigation systems should use acidic forms of P fertilizers rather than neutral forms. Caution should be exercised because low pH values (below 5.) may cause corrosion of metal hardware and increase toxicity of certain micronutrients.

Urea phosphate materials are quite excellent fertilizers. They have a low enough pH to prevent Ca and Mg precipitation. In addition, they are an excellent source of N. They can also retard P precipitation in highly calcareous soils and improve P availability in the soil (Bashour and Nimah, 1998).

Potassium Fertilizers

All potassium fertilizers are water-soluble. Potassium sulfate, potassium nitrate and monobasic potassium phosphate are used as raw materials for potassium in powder soluble fertilizers. Although potassium chloride has high solubility, it is not a desirable source of K in soluble powder fertilizers used for the vegetables and crops that are sensitive to high levels of chloride.

Calcium Carriers

Calcium nitrate is the most suitable source for Ca in soluble powder fertilizers. Calcium carriers should not contain any P or sulfate because Ca combines with P and/or S and form insoluble salts. Fertilizers, which contain Ca, should be flushed from tanks, pumps, filters and tubing prior to injecting P - or S - carrying fertilizers.

Micronutrient Carriers

Several metal micronutrient forms are relatively insoluble, and therefore should not be used in fertilizers for fertigation or foliar application. These include the carbonates, oxides or hydroxide forms of Zn, Mn, Cu and Fe. *The sulfate form of copper, manganese, iron, and zinc is the most common and usually the least expensive source of micronutrients.* These metal sulfates are water-soluble and easily injected into irrigation water.

However, using these materials for fertigation is not very successful in alleviating a micronutrient deficiency when applied through sprinkler, furrows and border strips. This is because these metals are positively charged and become attracted to the exchange sites of clay and organic matter, and therefore, they tend to stay near the soil surface. Consequently, the micronutrients don't reach the major portion of the plant root zone. With buried drip and foliar fertigation, sulfates can be effective. The soil pH controls the availability of sulfate forms of Mn, Fe, Cu and Zn. If the metal sulfate solutions are acidified, the availability of the micronutrients can be prolonged in the soil. The nitrate and chloride forms of micronutrients are very soluble and can be used for fertigation, but like the sulfate forms, the metal ions will accumulate at the soil surface rather than moving down in the soil.

Micronutrients chelates are used as good sources of soluble fertilizers. The sources most commonly used are EDTA, DTPA (Fe, Zn, Cu, Mn), EDDHA-Fe and lignosulfonates. Before deciding on the source of micronutrients, a mix test should be made to ascertain its compatibility. The following table shows solubility of various fertilizer raw materials used in formulation of soluble powder fertilizers and liquid fertilizers.

Fertilizer Compatibility

Compatibility problems may occur when liquid or soluble powder fertilizers are combined. When preparing fertilizer solutions from various materials, the following should be considered: *the safety involved in making the solution, effect of solutions on each other, type of irrigation system and its susceptibility to plugging or other problems.*

It is always advisable to run a "jar test" to check fertilizer compatibility before preparing a large batch of liquid fertilizer before injecting the fertilizer solution in the irrigation system. This test involves dissolving some of the fertilizers into a jar of irrigation water, and watching for any precipitation or milkiness which may occur within one hour. If cloudiness does occur, there is a chance that injection of the fertilizer/chemical will cause emitter plugging. If more than one fertilizer are to be injected simultaneously into the irrigation system, then the two are to be mixed in

a jar and used at the approximate dilution rate that would be expected when the products are injected into the irrigation system.

Some Precautionary Measures for Mixing

The basic mixing rules are summarized by Burt et al. (1995) as follows:

- Always fill the mixing container with 50-75% of the required water to be used in the mix.
- Always add liquid fertilizer materials to the water in the mixing container before adding dry soluble fertilizers. The additional fluid will provide some heat in case the dry fertilizers have the characteristic of making solutions cold.
- Always add dry ingredients slowly with circulation agitation to prevent the formation of large, insoluble or slowly soluble lumps.
- Always add acid to water, not water to acid.
- When chlorinating water with chlorine gas, always add chlorine to water, and not *vice versa*.
- Never mix an acid or acidified fertilizer with chlorine, neither in its gas form or liquid form. Never store acids and chlorine together in the same room.
- Do not attempt to mix either anhydrous ammonia or aqua ammonia directly with any kind of acid. *The reaction is violent and immediate.*
- Do not mix concentrated fertilizer solutions directly with other concentrated fertilizer solutions.
- Do not mix a compound containing sulfate with another compound containing calcium. *The result will be a mixture of insoluble gypsum.* For example, injecting both calcium nitrate and ammonium sulfate fertilizers into the same irrigation water will cause the formation of calcium sulfate (gypsum), which has a very low solubility. Although the calcium nitrate is very soluble and the ammonium sulfate has good solubility, they create problems when mixed together in the same container or when poured together from separate mixing tanks. Gypsum crystals will form and can clog drip emitters or filters.
- Always check with the chemical supplier for information about insolubility and incompatibility.
- Be extremely cautious about mixing urea – sulfuric fertilizers with most other compounds. Urea-sulfuric acid is incompatible with many compounds.
- Since fertilizer solutions are applied in very small amount and, if injected at separated locations in the irrigation line, many incompatibility problems tend to

disappear. The jar test is essential when it comes to deciding if solutions can be simultaneously injected into the irrigation system.

- Do not mix P-containing fertilizer with another fertilizer containing calcium without first performing the jar test.
- Extremely hard water (containing relatively large amounts of calcium and magnesium) will combine with phosphate, neutral polyphosphate or sulfate compounds to form insoluble substances.
- A good rule of thumb: "when in doubt leave it out".

Label Information

The following information is recommended to be included in the label:

Total N	Urea %	NH ₄ %	NO ₃ %	
Available P ₂ O ₅	_____	Sources	_____	
Available K ₂ O	_____	Sources	_____	
Available Ca,	Mg,	S,	Cl,	(Sources & Concentration)
Available Fe,	Zn,	Cu,	Mn,	(Sources & Concentration)
pH, 1: 100	(Fertilizer:Water)			
EC, 1:1000	(Fertilizer:Water)			
Compatibility with agrochemicals	_____	_____	_____	
Recommendation to users	_____	_____	_____	
Precautions	_____	_____	_____	

CONCLUDING REMARKS

1. Pressurized irrigation – usually equipped with fertigation systems – are gaining more acceptance, and this should be promoted as an efficient system for water-fertilizer use.
2. Fertilizers of special properties, types, formulations and grades are required for meeting the changing demand for various crops and users needs.
3. For achieving the main goal of using fertilizer in sustainable agriculture, the best available technology is required by the fertilizer producers as well as the adoption by farmers of best agricultural practices.

4. A set of guidelines is called for to ensure the proper formulation and usage of quality fertilizers in order to grasp the technical, environmental, agronomic and economic benefits of fertilizers for sustaining soil productivity.
5. Cooperation and effective linkages are needed to be established between all stakeholders, including farming community, research institutions, agricultural extension and training, international / regional institutes and organizations, as well as the producing sector for furthering the goals of efficient and environmentally-friendly use of mineral fertilizers.
6. International organizations/centers and the fertilizer-producing sector are urged to assume an effective role in providing material support to governmental research/extension systems in order to enable them to reach farmers to deliver adequate knowledge on fertilizer use for the benefit of all parties.

REFERENCES

- Bashour, I., and M. Nimah. 1998. User's needs for quality fertilizer: types and formulations. FAO/AFA Regional Workshop on "Guidelines for Efficient Fertilizer Use through Modern Irrigation". Cairo, Egypt, 14-16 Dec.
- Burt, C., K. O'Connor, and T. Ruehr. 1995. Fertilization. Irrigation Training and Research Center, California Polytechnic State Univ., San Luis Obispo, Ca., USA.
- FAO. 1981. "Agriculture: Towards 2000", FAO, Rome, Italy.
- FAO. 1997. Irrigation in the Near East in Figures. Water Reports No. 9. FAO, Rome, Italy.
- FAO. 1998. Guide to efficient plant nutrition management. AFO/AGL Publ., Rome, Italy.
- International Fertilizer Industry Association (IFA). 1998a. Mineral fertilizer use and the environment. IFA/LINEP Publ., IFA, Paris, France.
- International Fertilizer Industry Association (IFA). 1998b. The fertilizer industry, world food supplies and the environment. IFA/LNEP Publ. IFA, Paris, France.
- International Food Policy Research Institute (IFPRI). 1997. Report on the world food situation, IFPRI, Washington, DC, USA.

Table 1. Solubility information of fertilizers used to prepare soluble powder fertilizers.

Fertilizer	Grade / %	Form	Temperature ---°F---	Solubility gm/100 ml
Nitrogen Fertilizers				
Ammonium Nitrate	34-0-0	NH ₄ NO ₃	32	18.3
Ammonium Sulfate	21-0-0	(NH ₄) ₂ SO ₄	32	70.6
Calcium Nitrate	15.5-0-0	Ca(NO ₃) ₂	62	121.2
Urea	46-0-0	CO(NH ₂) ₂		100.0
Urea Ammonium Nitrate	32-0-0	CO(NH ₂) ₂ ·NH ₄ NO ₃		High
Phosphate Fertilizers				
Monoammonium Phosphate	12-61-0	NH ₄ H ₂ PO ₄	50	30
Dimmonium Diphosphate	21-53-0	(NH ₄) ₂ HPO ₄	50	63
Potash Fertilizer				
Potassium Chloride	0-0-60	KCl	68	34.7
Potassium Nitrate	13-0-45	KNO ₃	50	20.9
Potassium Sulfate	0-0-50	K ₂ SO ₄	77	12
Monobasic Potassium Phosphate	0-52-34	KH ₂ PO ₄		33
Micronutrients				
Borax (B)	11	Na ₂ B ₄ O ₇ ·10H ₂ O	32	2.10
Boric Acid (B)	17.5	H ₃ BO ₃	86	6.35
Solubor (B)	20	Na ₂ B ₈ O ₁₃ ·4H ₂ O	86	22
Cooper Sulfate ¹ (Cu)	25	CuSO ₄ ·5H ₂ O	32	31.6
Cupric Chloride ¹		CuCl ₂	32	71
Iron Sulfate ¹ (Fe)	20	FeSO ₄ ·7H ₂ O		15.65
Magnesium Sulfate (Mg)	9.6	MgSO ₄ ·7H ₂ O	68	71
Manganese Sulfate ¹ (Mn)	27%	MnSO ₄ ·4H ₂ O	32	105.3
Ammonium Molybdate (Mo)	54	(NH ₄) ₆ Mo ₇ O ₂₄ ·4H ₂ O		43
Sodium Molybdate (Mo)	39	Na ₂ MoO ₄	44.3	
Zinc Sulfate (Zn)	36	ZnSO ₄ ·7H ₂ O	68	96.5
Zinc Chelate (Zn)	5 - 14	DTPA & EDTA		v. sol.
Manganese Chelate (Mn)	5 - 12	DTPA & EDTA		v.sol.
Iron Chelate (Fe)	6 - 14	DTPA, & EDDHA		v. sol.
Copper Chelate (Cu)	5 - 14	DTPA & EDTA		v. sol.
Zinc Lignosulfonate (Zn)	6	Lignosulfonate		v. sol.
Manganese Lignosulfonate (Mn)	5 - 14	Lignosulfonate		v. sol.
Iron Lignosulfonate (Fe)	6	Lignosulfonate		v. sol.
Copper Lignosulfonate (Cu)	6	Lignosulfonate		v. sol.

Source: California Fertilizer Association (1980). ¹ (Acidified)

Irrigation Systems: Potential for Fertigation

Musa N. Nimah

*Faculty of Agricultural and Food Sciences, American
University of Beirut, Lebanon*

ABSTRACT

The application of plant nutrients, in the form of animal manure, through the irrigation water may have been practiced shortly after the commencement of irrigation, i.e., a few thousand years ago. Fertigation or applying fertilizers through irrigation systems is becoming popular and wide spread in many countries. It is a convenient and efficient method for applying fertilizers to irrigated crops. It has also spread because of the greater profits farmers obtain from increased production, especially if several fertilizer applications are required during the growing season.

Chemigation/fertigation is closely associated with the particular irrigation system. *Its uniformity of application is a function of the uniformity of the irrigation system* and is also affected by the chemical being used and the velocity of flow in the irrigation conduits. Hence, any advancement in the irrigation system design and management are directly reflected in the improvement and efficiency of the chemigation process and water-use. Advances in irrigation system design in the 1960s (center pivot) and in the 1970s (micro or trickle irrigation) facilitated the use and the expansion of chemigation. Recently, chemigation is incorporating a wide variety of chemicals. New terminology has appeared in the literature such as: *fertigation, herbigation, fungigation, nemagation, bacterigation, and isectigation*. Researchers are working to further develop the chemigation technology in order to optimize crop production and sustain the soil and water resources. Chemigation nowadays is utilizing a variety of chemicals in several irrigation systems for a wide range of crops grown both in protected environments and open fields.

Growers clearly market water through their crops. Any means of improving water-use efficiencies improves the return of investment and increases profit. Proper fertilization practices have been shown to directly increase water-use efficiency. Fertigation is widely used nowadays, and has been practiced a longer period of time than other chemigation practices. To reduce potential of environmental risks and improve fertilization efficiency, application of fertilizers through irrigation systems makes good sense because nutrients can be delivered at the proper time and in suitable quantities so that the amounts applied meet the needs of the crop.

Nitrogen is the principal element applied by fertigation because of the large quantities usually applied to crops, as well as high water solubility and the possibility of being leached with drainage water. Phosphorus and potassium may be applied by fertigation, but since both elements do not usually move readily, except in sandy soils, most of P and K usually are applied at or before planting. The application of sulfur (S) and boron (B) with irrigation water is usually done to correct deficiencies during the growing season. Micronutrients such as iron, zinc, copper and manganese are applied via irrigation systems or sprayed on to the foliage feeding to correct deficiencies. Successful fertigation action involves detailed consideration of all aspects of the system, from design and management to water quality.

INTRODUCTION

Fertigation or applying fertilizers through irrigation systems or "spoon-feeding" is becoming popular and widespread in many countries. It is a convenient and efficient method for applying fertilizers to irrigated crops. It generates greater profits for farmers from increased production, especially if several fertilizer applications are required during the growing season. In irrigated farming, fertilizer-water management has a greater influence on crop productivity than any other single factor. The grower's ability to deal with factors such as available nutrients, controlling weed populations, and insect pests determines how close actual yield comes to the maximum potential yield. Growers clearly market water through their crops. Any means of improving water-use efficiencies will help in the return of investment and increase profit. Proper fertilization programs have been shown to directly increase water-use efficiency (Nimah, 1998). Fertigation is widely used nowadays and has been going for a longer period of time than other chemigation practices. To reduce the potential of environmental risks and improve fertilization efficiency, application of fertilizers through irrigation systems makes good sense because *nutrients can be delivered at a proper time and in suitable quantities* so the amounts applied meets the needs of the crop.

IRRIGATION SYSTEMS AS A MEANS OF FERTIGATION

Water is applied to the soil in one of three ways: 1) above the soil surface, as with sprinkler and some of the micro-irrigation systems; 2) on the surface, as in furrow, flood, and drip irrigation systems, and 3) under the surface, as in sub-irrigation (water table control) and drip irrigation systems. Also, irrigation methods can be classified as *pressurized* and *non-pressurized* systems; they can also be classified as *continually moving*, and *stationary* systems. The irrigation method influences (i) whether or not chemicals must be injected at a constant rate, (ii) the optimum

duration of chemical injection, (iii) if the chemical injection rates vary during irrigation set.

Continuous-Moving Irrigation Systems

These include *center-pivot* sprinklers, *linear-move* sprinklers, *big sprinklers* (travelers), *furrow*, and *border-strip* surface irrigation systems. These irrigation methods have special fertigation/chemigation requirements. The rate of injection must be calibrated so that injection continues for exactly the duration of the injection. *Fertilizer injection must be done at a constant rate to ensure uniform chemical distribution.* If the farm management does not observe these two conditions, the distribution uniformity of the fertilizer will be low and varies across the irrigated field. As an example, chemical injection rate may vary due to improper mixing of fertilizers, system flow rate fluctuations, and system pressure fluctuations. In addition, if the fertilizer injection does not continue all through out the duration of the irrigation event in continuously moving irrigation system, that part of the field (when there is no injection) does not receive any fertilizer.

On the other hand, the following rules should be observed, with furrow and border strip irrigation systems, in order to have effective fertigation. These considerations are summarized below:

- Tailwater is to be collected and re-used. The tailwater will have the same fertilizer concentration (ppm) as the irrigation water at the head of the field. Therefore, re-mixing it with source water will not cause problems.
- The advance time of water should be between one quarter and one half of the total irrigation time in order to have good irrigation distribution uniformity.
- Different irrigation sets, on the same field, should be operated for the same duration having the same flow rates.
- Inject fertilizer continuously and at the incoming irrigation water at a constant rate.

Burts *et al.* (1995) summarized the dynamics of surface irrigation, and how those dynamics influence the above points, especially the recommendations of injecting fertilizers and/or chemicals at constant rates and throughout the irrigation set:

- Time is necessary for water to advance down the furrow or border strip. This is analogous to a moving center pivot or linear move or traveler.
- The rate of water infiltration into the soil at a point varies with time. The infiltration rate decreases with time.

The above two concepts of *unsteady advance* and *unsteady infiltration* result in greater depth of infiltration at the inlet of water to the border strip and furrow than at the end. It is possible to reduce the deep percolation of fertilizers at the head of the furrow or border strip, if fertilizers are injected between one third and one half the furrow or the strip length, or by collecting the tailwater runoff and recycling it. If tailwater runoff is recycled, the distribution uniformity will improve, and the system initial cost will increase. Thus, it is an *economical/management decision*.

Stationary Irrigation Systems

The stationary irrigation systems are *hand-move sprinklers, permanent and solid-set sprinkler systems, and micro-irrigation systems*. Fertigation with stationary irrigation methods is simple if fertigation begins and ends with a single set, because a specific quantity of fertilizers will be applied per area (irrigation set). The following guidelines should be considered, when injecting fertilizers through a stationary irrigation system. These are:

1. Fertilizers should be well mixed with the irrigation water. Otherwise, variability and poor distribution might occur from one point to another across the field. Therefore, the proper fertilizer should be selected. Outlines to select and mix fertilizers are outlined in Bashour and Nimah (1998).
2. The fertilizer application rate within a set should be constant in order to obtain high uniformity. Therefore, selection of the right fertilizer injector will help getting a high uniformity. Types and characteristics of fertilizer injectors is described below.

Fertigation can be continuous with stationary irrigation systems having multiple sets, if the fertilizer injection rate is constant, all sets have the same duration, each set has the same total flow rate, and covers the same area. Otherwise, the fertigation program should be adjusted for each set. There are two types of injection practices regarding when to start and stop injecting fertilizers set in stationary irrigation systems. These are:

1. *Continuous fertigation at a constant rate*. In this case, farmers "spoon feed" their crops by injecting small dosage of fertilizers on continuous basis during the growing season. Generally, in this practice, flushing of the irrigation system is not implemented. This fertigation practice will not damage the fittings and emitters because the concentration of chemicals in the irrigation water is low.
2. *Quarter-half-quarter rule*. In this practice, fertigation takes place during the

middle half of the irrigation duration. This method of fertigation takes place when large dosages of fertilizer or chemicals or corrosive materials are applied. Such practice might cause damage to the system hardware from the prolonged contact with the chemical. In this case, farmers should make sure: 1) that the last quarter of irrigation is long enough to flush all the chemicals from the whole system, especially from the distal ends of the irrigation system; 2) to use a mobile fertilizer injector to calculate the chemical travel time in the system; and 3) adjust the place of the mobile fertilizer injector or the time of fertigation and flushing accordingly. The chemical travel time can be calculated as follows:

$$Time = \frac{Distance}{Velocity} = Distance \times \frac{A}{10 Q} \dots\dots\dots (1)$$

Where:

Time: time of chemical to travel a certain distance, seconds.

Distance: the distance from the injector to the point in question, meters.

Velocity: the velocity of flow in the conduit, meters per second.

A: Inside area of the pipe segment, cm²

Q: the flow rate in the pipe segment, l/sec.

Although fertigation can be applied in all irrigation systems, it is easy and simple to implement, *but proper management is necessary*. Fertigation uniformity might vary due to the irrigation system, as discussed before. Variations in the chemical injection concentrations might occur, and users should pay attention to this variation that will significantly affect the uniformity. This variation in chemical concentrations might result for the following reasons:

1. Poor mixing/agitation of the chemical in the holding tank. Proper selection of the fertilizer and agitator can overcome this problem.
2. The injection hardware changes the injection rate with time. This may be due to the type of injector. Types of injectors are discussed below. The techniques used to measure the distribution uniformity for each irrigation system differ from one irrigation system to another. For example, in sprinkler irrigation we measure the distribution uniformity using "catch cans" placed on grid lines. While in surface irrigation, we measure the water content of the soil profile along the furrow at equi-distant stations along the furrow. In micro-irrigation, we can use both methods depending on the micro-irrigation system under consideration. *Example*: Venturi-type injectors will have a change in suction pressure if the flow rate through them does change; suction screens on the injection device might be partially clogged.

3. The irrigation flow rate changes with time. This may be due to the topography of the area under irrigation of moving irrigation systems, or to the different area sizes under different irrigation sets.

IRRIGATION MANAGEMENT: SCHEDULING FOR UNIFORM FERTIGATION

There are many ways to inject fertilizers into irrigation systems. The choice of method and equipment will depend on the following:

1. *Injecting liquid versus solid material.* Liquid fertilizers may not need agitation or mixing in the field, whereas it is necessary for solid chemicals.
2. *Potential hazard of the chemical.* Injection of most fertilizers can be done without serious concern to worker safety, whereas injection of herbicides or pesticides with the fertilizer require special precautions
3. *Portability versus permanent installation.*
4. *Availability of power.*

As a “rule of thumb”, fertilizer injection should be possible at a rate of 0.1% of the irrigation flow rate; for example: if the irrigation pump delivers 100 m³/hour, a fertilizer injector should be capable of delivering at least 0.1 m³ per hour.

Irrigation Scheduling, Leaching and Fertilizer Uniformity

All irrigation systems apply water with different degrees of non-uniformity. Many users of irrigation systems assume that all areas in the field are identical and that water is distributed uniformly across the field, leading to uniform deep percolation losses. *This fundamental flaw in understanding of fertigation management must be corrected.* To manage irrigation water properly, especially as it relates to fertigation efficiency, one must understand the difference between *non-uniformity* and *irrigation scheduling*.

Uniformity can be evaluated by many methods. The newly preferred method of uniformity is called “ Low Quarter Distribution Uniformity (DULQ)” and is defined as:

$$DU_{LQ} = \frac{\text{Min } X}{X} \dots\dots\dots (2)$$

Where:

Min X $\cong$ Minimum depth infiltrated = average depth infiltrated in the field receiving the lowest 25% of the water.

X $\cong$ Average depth of water infiltrated in the field.

The causes of non-uniformity vary depending on the irrigation-system type, design, and management. For example, sprinklers and emitters might have pressure differences along the laterals; thus, they have different application rates on different parts of the field, but proper design and selection of the hardware can correct this. Also, sprinkler heads and emitters might be partially clogged due to dirt, insects, lime, and algae that will lead to different application depths across the field; proper management can fix this. For surface irrigation methods, non-uniformity is caused by factors such as infiltration rate uniformity along the furrow, flow rate per furrow, advance time; this can be corrected by proper design and management.

The non-uniformity in all irrigation methods will lead either to under-fertigation, where the plant will suffer from lack of adequate water and nutrients, or over-fertigation and deep percolation of water and fertilizer that might cause underground water pollution and increase in production cost.

Very good *distribution uniformity* ranges between 85 – 95% depending on the irrigation method, soil topography and uniformity, and timing and duration of irrigation. A more typical *field distribution* uniformity for a well managed field ranges between 75 – 80%, resulting in 20 – 25% deep percolation if the irrigation duration is managed perfectly so that there are neither dry areas nor over-irrigated areas at some spot in the field which receives the least amount of water.

In poor irrigation scheduling (irrigation not at the proper time), water might infiltrate uniformly, but a large amount of water deep-percolates, leading to fertilizer leaching. *In fertigation, the distribution uniformity of fertilizers cannot be better than the distribution of water*; thus, a major aspect of controlling leaching is to decrease deep percolation by improving the system distribution uniformity and irrigation scheduling, hence improving the system irrigation efficiency.

Irrigation scheduling is the technique by which we determine the time to irrigate and the depth of water to apply in order to keep the plant environment favorable and not under stress. It can be defined as the ratio of depth of water held in the root zone at the allowable soil moisture depletion over the crop water evapotranspiration. Mathematically, it is equal to:

$$II = \frac{WHC}{ET_c} \dots\dots\dots (3)$$

Where:

$\Delta \cong$ Irrigation interval in days.

WHC $\cong$ Water-holding capacity in the root zone at the allowable soil moisture depletion.

ETc $\cong$ Actual plant evapotranspiration.

Applying irrigation scheduling helps in controlling deep percolation losses and, thus, improving the irrigation efficiency of the system and decreasing fertilizer leaching due to water percolation. Nitrogen in the nitrate (NO_3^-) form is the nutrient most noted for leaching. Since nitrate is an anion (i.e., having a negative charge), it is not held on the negatively charged cation exchange sites which exist on clay and organic matter particles. Consequently, nitrate will flow through the soil with irrigation water. If one fertigrates continuously with nitrate and 20 % of the water deep-percolates, approximately 20 % of the applied nitrate will also deep-percolate.

On the other hand, ammonium (NH_4^+) cation is adsorbed onto the soil cation exchange sites within a few centimeters of the soil surface. Therefore, there is relatively little leaching of ammonium ions compared to nitrate ions. After ammonium is converted to nitrate through nitrification, the nitrate will be re-distributed through the root zone during subsequent irrigation. If during subsequent irrigation deep percolation occurs, a portion of the nitrate will deep percolate with the water.

Urea ($\text{CO}(\text{NH}_2)_2$) has no electrical charge, and therefore penetrates into the soil until it is transformed by the urea enzyme. This process can occur within a few centimeters of the soil surface, and there is rarely deep percolation of urea on most soils. The urea is transformed first to ammonium and later to nitrate. Once it has converted to nitrate, the N may move freely by the irrigation water. For sprinkler and surface (flood irrigation methods) the best form of fertilizers maybe a combination of nitrate and urea in medium and heavy-textured soils. The nitrate will be immediately available to the plants and will penetrate with the water, while urea will be eventually be converted to ammonium and nitrate.

The previous discussion of fertilizer leaching assumed that water moves through a matrix of soil particles and small pores. This type of water movement is referred to as *laminar flow*. The flow through this soil matrix allows ample time for adsorption of fertilizer ions onto the cation exchange site. However, recent studies have focused on the concept of *preferential flow*, in which water and solutes flow through cracks and old roots paths.

Preferential flow is very significant in areas with cracking-clay soils. In these soils, perhaps 5 – 10 % of the surface irrigation volume may flow vertically directly past the root zone via the cracks, with little or no soil particle contact. This 5 – 10 % of the irrigation volume may represent more than 50 % of the leached water on a heavy cracking clay soil.

Decreasing the leaching caused by preferential flow must focus on minimizing the amount of cracks which reach the soil surface, closing the cracks with minimum of water application, and minimizing the concentration of fertilizer application at the beginning of the irrigation, thus decreasing the total chemical amount which will be leached. With fertigation, areas receiving more water (thus having excess leaching) will also receive more fertilizer. Therefore, the soil fertility level across the field remains fairly uniform over time if the fertilizer is “spoon-fed” (continuous fertigation).

Hardware Needed for a Successful Fertigation

There are many types of injector systems available in the market. This paper will cover some of the most commonly used in fertigation.

Venturi Type Injectors

The Venturi injectors are commonly used for fertigation because of their simplicity. They are typically made from materials, which are inert and have no moving parts. Because they inject chemicals at a constant rate, as opposed to the piston and diaphragm pumps, they can be easily calibrated with in-line flow meters. They are composed of an *injector*, a *check valve*, and a *metering valve* that is connected to the chemical solution tank. They are easy to install and to operate with low cost of maintenance.

Float-Valve Injectors

Float valves have been used for many years to inject chemicals into canals and open water sources, and low-pressure pipeline stands without the need of an injector pumps. They can also be used to inject chemicals into pressurized irrigation systems by locating the assemblies over the water supply upstream of the main irrigation booster pump.

Differential-Pressure Tank

These tanks are a modification of the Venturi-type injectors. The water flows from the main irrigation pipeline into a pressurized tank, the water flow is controlled by a flow control valve, then the chemical solution flows out from the pressurized tank back into the mainline pipe. The inlet and the outlet of water from the mainline are separated by a constant-pressure drop device. These types of injectors are expensive and their accuracy is almost the same as the above-described injectors.

Chicken-Feeders Injector Systems

Chicken feeders are used to drip low to medium flow rates of chemical solutions into open water supplies or canals. They provide a constant discharge rates regardless of the height of the chemical solution in the main closed chemical tank. They can be used in pressurized irrigation system like the float-valve injectors systems. They are easily operated and maintained.

Diaphragm Pumps

Diaphragm pumps are very popular and extensively used in center pivot irrigation systems specially where the water source is a deep well and there are no booster pumps. They are very popular in the Gulf region, where a source of electricity is available. They are used for pesticide and other chemical injection, as well as for fertigation. Diaphragm pumps cannot maintain a constant discharge flow rate if the discharge pressure varies significantly. They have a distinct advantage over piston pumps in that they are easy to adjust while the pump is operating.

Piston Pumps

They have the same characteristics as the diaphragm pumps in terms of power supply and maintenance. The main advantage of this kind of pumps is that they have a positive displacement action; the discharge flow rate will not change as the irrigation pipeline pressure varies. Their major disadvantage is that flow rates cannot be adjusted while the pump is operating.

When selecting an injector device for a certain fertilizer, the following points should be considered:

- Injection rate and capacity.
- Ease of loading.
- Ability to maintain consistent injection rate of the chemical.
- Availability of spare parts and service.

Irrigation Methods as Means of Chemical Application

Surface irrigation systems and micro-irrigation systems are suitable for fertilizers and chemicals that are applied to the soil surface. *Besides macro-nutrient fertilizers, these chemicals include some herbicides, nematicides, fungicides and insecticides.* On the other hand, sprinklers and overhead irrigation systems can apply chemicals to the crop foliage and soil surfaces, like micro- and macro-nutrients, most insecticides, and fungicides. Thus, the type of irrigation system available at the farm might limit the type of fertilizer or chemical to be used.

Beside the limited capability of the use of surface irrigation methods in fertigation, the following drawbacks are important (Nimah, 1995). First, we need to consider the impact on the contamination of surface water supplies if the tailwater runoff is not collected and recycled; also, if surface irrigation systems are not designed and managed properly, they might cause sub-surface water contamination due to deep percolation. Second, surface irrigation methods are characterized by non-uniform distribution, which might render them uneconomical for fertigation. However, the introduction of laser-leveling (Dedrick, 1979) and automated surface irrigation system (Thomas and Kincaid, 1989) improved the distribution uniformity of irrigation under these systems, thus the distribution uniformity of fertigation.

Like surface irrigation methods, trickle/micro-irrigation is suitable for soil-applied fertilizers and chemicals. An additional problem of using the chemicals in the system is the clogging of the emission outlets. Therefore, good filtration is necessary, and assurance that the fertilizer injected will not form precipitates when mixed with water will minimize this problem. Moreover, fertilizer with high adsorptivity may be deposited in higher concentration near the emission point and with decreasing concentration further from the emitter, resulting in a spatial non-uniformity within the wetting root zone (Nimah, 1995). Also, the flow rate of solution in the pipes with multiple outlets decrease with distance from the inlet and the flow characteristic changes from turbulent flow to laminar flow, causing uneven uniformity along the lateral line. Therefore, proper management practices are essential to minimize the variation in uniformity under these systems.

Almost all soluble fertilizers and chemicals can be used with sprinkler irrigation systems. Also, sprinkler irrigation systems have their own drawbacks if not properly operated and managed. Wind drift is a major problem in fertilizer uniformity distribution, also pressure variation along the lateral and mainline leads to uneven flow among sprinklers that will affect the sprinkler distribution uniformity.

All irrigation systems, sprinklers, micro-irrigation, and surface irrigation systems can be used to apply fertilizer efficiently and uniformly, if they are properly designed and operated. Their uniformity of application might be as high as 90%, which exceeds the uniformity distribution of the conventional methods (Nimah, 1995). The cost of applying fertilizers through the irrigation system is less than the conventional methods of application. Fertigation saves both fertilizer and labor when appropriately implemented.

Fertilizer Injection Rates into the Irrigation System

The rate at which any chemical is to be injected into the irrigation water should be calculated carefully. It depends on the concentration of the liquid fertilizer solution and the desired quantity of nutrients to be applied during the irrigation. It can be calculated as follows:

$$Q_c = \frac{F_r A}{C R_t T_a} \dots\dots\dots (4)$$

Where:

$Q_c \cong$ Rate of injection of liquid fertilizer solution into the system, l/hr.

$F_r \cong$ Fertilizer application rate (quantity of nutrients to be applied) per irrigation cycle, kg/ha.

$A \cong$ Area irrigated per set, ha.

$C \cong$ Concentration of actual nutrients in the liquid fertilizer, kg/l.

$R_t \cong$ Ratio between fertilizing time and irrigation application time.

$T_a \cong$ Irrigation application time or set time, hr.

Example

For a hand-move system (stationary system) with four laterals, that are 400-m long and are moved every 18.0 m each set; and a center-pivot sprinkler system that is 520-m long. Urea ammonium nitrate, a liquid fertilizer with 32% N and weighing 1.32 kg/l is to be used in the fertigation process. Find the injection rates to apply 50 kg/ha of elemental N, in the liquid fertilizer.

Calculations

The concentration of elemental N in the liquid fertilizers:

$$C = 1.32 \times 32/100 = 0.42 \text{ kg/L}$$

For *hand-move system*: The irrigated area by the four laterals during each set is equal to:

$$A = (4 \times 400 \times 18)/10,000 = 2.88 \text{ ha.}$$

Assume that the irrigation time is 11 hours, and the time ratio of fertilizer application to total application time is 0.5. So the injection rate will be:

$$Q_c = (50 \times 2.88)/(0.42 \times 0.5 \times 11) = 62 \text{ l/hr.}$$

For the center-pivot system, the irrigated area, $A = 85$ ha; the ratio of fertigation time over irrigation time is $= 1$; continuous-move irrigation system, and the time of irrigation is 24 hr; one circle per day. Then the rate of injection should be:

$$Q_c = (50 \times 85) / (0.42 \times 1 \times 24) = 421.6 \text{ l/hr.}$$

For solid fertilizers, the calculation is as follows:

$$\text{Fertilizer, kg/ha} = FN / \%E$$

Where:

$FN \cong$ kilogram of elemental nutrient per hectare to be applied.

$\%E \cong$ % nutrient in the solid fertilizer.

Using the above example to apply 50 kg/ha of N per hectare, the source is urea (46-0-0)

$$\text{Urea per hectare (kg)} = 50 \text{ kg/ha} / 46\% = 108 \text{ kg/ha of urea}$$

When dissolving the urea in water, it is important to know its solubility in order to know how many liters of water are needed to dissolve the fertilizers. Different solid fertilizers have different solubility in water. Bashour and Nimah (1998) presented tables of solubility of different fertilizers. For urea, the solubility is 1 kg/l; therefore, the needed volume of water per hectare to dissolve the urea can be computed as follows:

$$\text{Water volume/ha} = (\text{kg fertilizer/ha}) / \text{solubility} = 108 / 1 = 108 \text{ liters water.}$$

To get the total volume of fertilizer solution for the whole area, multiply the volume of fertilizer solution (in this example, 108 liters) by the area irrigated by the set in one irrigation interval. Then the flow rate of injection can be calculated as outlined above or dividing the total volume of water solution needed by the time of fertigation.

Fertilizer Solubility and Suitability for Fertigation

Fertilizer solubility and purity, and their compatibility with other chemicals should be considered when using fertigation. Some fertilizers might have cooling effect when mixed with water, other might lower the acidity ($\text{pH} < 7.0$) of the irrigation water which might lead to adverse effect on the system hardware and on the plants. Most liquid or water-soluble fertilizer grades are soluble and can be injected directly into irrigation system. Farmers should insure that uniform mixing of fertilizers with irrigation water takes place prior to applying the fertilizer/water mixture to plants (Fischbach, 1971).

Hard Water

Hard-water sources used for irrigation are desirable for crop production. Hard-water usually has good balance between concentrations of calcium, magnesium and sodium ions (Burt et al., 1995). Various forms of N fertilizers such as urea, ammonium nitrate, and ammonium sulphate have been injected into irrigation systems without difficulty.

However, when ammonium phosphate was added to irrigation systems with hard water, deposits of calcium/magnesium phosphates were observed in the irrigation piping. Tests have shown that the precipitate that forms depends on the composition of the fertilizer. When the polyphosphate level of a base solution is increased and its pH is decreased, the amount of dilution and water hardness that can be tolerated will also increase. The problem with using hard water is that the higher the dilution rate the more Ca and Mg ions are available to react with the fertilizer.

When 10-34-0 liquid fertilizer is used with hard water, precipitation is expected to take place; however, these precipitates will not form or be minimal if the 10-34-0 liquid has a high polyphosphate content (more than 70%). Polyphosphate will sequester large quantities of Ca and Mg from the water. If the irrigation water contains high concentrations of Ca and Mg, "hard water", a precipitate will form which deposits on pipe walls and plugs orifices of the drip irrigation tube. Therefore, it is recommended to run a small-scale test to determine how much precipitate will be formed before using 10-34-0 liquid fertilizer in a sprinkler or drip system.

Acid Fertilizers: Field Data

When liquid or soluble powder fertilizers are applied to irrigation water in such a ratio that an acidic condition exists, less soluble precipitates are formed than when the solution is neutral or alkaline. Exploratory studies of TVA many years ago on using ammonium polyphosphate in "hard" irrigation water showed that the formation of insoluble Ca and Mg phosphates could be avoided by lowering the pH of the mixture to 4 or lower. Injecting liquid acid-based NP, NPK or NPK+TE liquid fertilizers into irrigation water at a rate which results in a water-acid solution having a $\text{pH} \leq 4$ prevented the formation of precipitates into sprinkler and drip irrigation systems. It was also noticed that this practice dissolved some of the precipitates that existed in the irrigation pipes. Presently, many farmers use liquid acidic fertilizers, urea phosphate (8/48/0, 2/52/8+TE), or liquid phosphoric acid (0-52-0) to fertigate and at the same time clean out old precipitates from the irrigation pipes.

Farmers and researchers directly felt the following advantages to fertigation:

1. Good fertigation practices can reduce fertilizer usage by 25–35% and simultaneously increase yield by up to 20%.
2. Dissolving an adequate amount of acidic fertilizer into a slightly alkaline water (pH, 7.2 – 7.5), as is the case in most the well water in the Middle East, the pH value of the irrigation water can be changed to slightly acidic (pH, 6 – 6.5) level. This improves water quality, reduces bicarbonate concentration in water, improves leaching of salts in soil profile, decreases soil salinity level in root zone, and leads to the liberation of many nutrients tied up with soil particles in unavailable form to become available for absorption by plant roots, such as Ca, Mg, P, Fe, Zn, Cu, Mn, and B.
3. Upon fertigation through sprinkler irrigation systems, wetting of crop foliage occurs during each irrigation and a portion of the nutrients absorbed by the leaves (foliar fertilization). This method of fertilization usually gives a fast response, especially if the crop is nutrient-deficient.

Del Amor et al., (1989) recommended the use of phosphoric acid both as a fertilizer and for lowering the pH. He stressed the point that a continuous supply of nutrients through the irrigation water during the season improves availability of nutrients and increases production. Another advantage to fertigation is the possible correction of nutrient deficiencies in mid season due to the immediate availability of nutrients applied with irrigation water. Moreover, the orthophosphoric acid base of liquid acidic fertilizers is an excellent source of P for plants; it lowers the pH of the irrigation water and prevents the precipitation of salts in irrigation lines and simultaneously liberates fixed nutrients in the soil.

Fluid Fertilizers

Fluid fertilizers usually are produced in two forms: liquids and suspensions:

Liquids: Cold-mixing or hot-mixing usually occurs in the production of liquid fertilizers. Cold-mixing is simple and no heat is released during mixing. Hot-mixing involves processes in which heat is released. The materials that usually are used in the production of NPK liquid fertilizers are: ammonia, urea-ammonium-nitrate solution (UAN) ammonium polyphosphate solution (10-34-0), potassium chloride, potassium nitrate, potassium sulfate and potassium hydroxide, phosphoric acid, mono-potassium phosphate, micronutrients (sulfate or chelates) and water.

When these materials mixed in the right proportions, the resulting mixture is a clear solution. The major difference between a liquid hot-mixing operation and

cold-mixing operation is that phosphoric acid and either anhydrous or aqua ammonia are used. In hot-mixing, no external heat source is required because heat is generated from mixing acid and ammonia.

Solubility is the quantity of salts present in a given amount of saturated solution at certain temperature. In fluid fertilizers, it is usually expressed as grams of salt per 100 grams of water. The composition of saturated solution is important in fluid fertilizers because the temperature of the saturated solution and “salt-out” temperatures are directly related.

The temperature at which a liquid becomes saturated in the presence of materials being dissolved is the “salt-out” temperature. “Salt-out” temperatures are important to be recognized by producers of liquid fertilizers because it is the safe temperature below which unwanted crystals form. In suspension fertilizers, “salt-out” is not considered to be a problem because the mixture contains crystals from the beginning.

Suspensions: Such fertilizer is defined as a fluid fertilizer that contain solid nutrients dispersed throughout the fluid. Suspensions are saturated solutions that have solid nutrients held in suspension by a suspending agent, needle-type clays. These clays cause a fluid gel to form, helping suspend the solids in a saturated solution. Suspension fertilizers usually have from 10 – 40 % of their total weight as suspended solids. Suspension fertilizers offers similar advantages of liquid fertilizers and at the same time permit the utilization of less expensive ingredients and allow formulators to produce products with analyses comparable to dry compound fertilizers. Many different types of raw materials have been used to produce suspensions; however, the materials that have been used and given best results are:

- Nitrogen sources: urea, ammonium nitrate, ammonium sulphate, and ammonia.
- Phosphate sources: monoammonium-phosphate, diammonium-phosphate, ammonium -polyphosphate and phosphoric acid.
- Potassium sources: potassium chloride, potassium sulphate, and potassium nitrate.

Almost any soluble solid or liquid material can be used in suspensions. Solid particles should not be coarser than 1 mm, and viscosity should not be more than 500 centipoise. The main impurities that cause quality problems are F, Ca, Al, Fe, MgO, SiO₂ and SO₄. The impurities are often combined with phosphate and with each other to form complex compounds, *creating problems for the producer of suspensions.*

Phosphoric acid is the primary acid used by the acid-based fluid fertilizer industry. It has the advantages of supplying P and it is capable of neutralizing

alkaline materials. It is used by the industry as ortho-phosphoric acid or super-phosphoric acid. Sulfuric acid can be used in several strengths for reduction of pH. Also, nitric acid may be used for lowering pH as well as supplying nitrate-N for liquid fertilizers. All acids are corrosive and can cause injury to personnel if improperly handled. The potential hazards of the three acids are as follows:

Personnel handling acids should be familiar with first aid procedures. Flushing contact areas with sufficient quantity of water, as quickly as possible, is the best way to reduce injuries. The safe preparation, storage, transport and application of fluid fertilizers require close adherence to safety procedures and precautions. Posting safety orders, educating personnel and making periodic checks can help reduce or prevent accidents.

Acid	Reaction with Water	Toxic Fumes	Contact Hazard	
			Concentrate	Dilute
Phosphoric	None	No	Stings	Negligible
Nitric	Moderate	Yes	Dissolves flesh	Stains skin
Sulfuric	Violent	No	Chars flesh	Dissolve clothes

Soluble Powder Fertilizers: Raw Materials

Good quality soluble powder fertilizers are produced from completely soluble crystalline raw materials that are crystal-clear and 100% soluble in water, with no dissolved particles to clog irrigation lines or equipment. Once a fertilizer is dissolved in water, it should stay in solution and not precipitate out at the same temperature. Soluble powder fertilizers should be formulated from blending a uniform mixture of soluble salts that are not corrosive to irrigation lines or equipment, have low "salt index", and be highly soluble and a high degree of purity. Soluble powder fertilizers may be used for fertigation or foliar fertilization.

Nitrogen: Urea is one of the most suitable N sources for soluble powder fertilizer as well as foliar liquid fertilizers. It has low "salt index" and high solubility in comparison to other N sources. Urea should be low in biuret content (less than 0.2%). Urea produced in the Middle East is low enough in biuret and will not provide any biuret hazard to plants, even if applied as a foliar fertilizer. Other sources of N can be obtained from ammonium nitrate, ammonium sulfate, ammonium phosphate, and urea phosphate. These sources are excellent supplemental N carriers with minimal side-effects.

Phosphorus: Most dry P fertilizers produced for general farm applications *cannot* be used for the production of soluble powder fertilizers because they contain high

percentage of insoluble material. Monoammonium phosphate (MAP, 12-61-0), diammonium phosphate (DAP, 21-53-0), monobasic potassium phosphate (MKP, 0-52-34), urea phosphate (17-44-0) are very common sources for P in the production of soluble fertilizers.

Farmers using “hard” water may experience some precipitation problems with neutral fertilizers. Farmers who inject P through drip and micro-irrigation systems should use acidic forms of P fertilizers rather than neutral forms. Caution should be exercised because low pH values (below 5.5) may increase corrosion of metal hardware and increase toxicity of certain micronutrients. *Urea phosphate materials are excellent fertilizers.* They have a low enough pH to prevent Ca and Mg precipitation; in addition, they are an excellent N source. They can also retard P precipitation in highly calcareous soils and improve P availability in the soil (Purdy, 1994).

Potassium: All potassium fertilizers are water soluble. Potassium sulfate, potassium nitrate and monobasic potassium phosphate are used as raw materials for potassium in soluble powder fertilizers. Although potassium chloride has high solubility, it is not a desirable source of K in soluble powder fertilizers because it is not a good source of potassium for the vegetables and crops that are sensitive to high levels of chloride.

Calcium: Calcium nitrate is the most suitable source for Ca in soluble powder fertilizers. Calcium-containing fertilizers should not contain any phosphorus or sulfate because Ca will combine with P and/or S and form insoluble salts. Fertilizers containing Ca should be flushed from tanks, pumps, filters and tubing prior to injecting P or S carrying fertilizers.

Micronutrients: Several metal micronutrient forms are relative insoluble, and therefore should not be used in fertilizers for fertigation or foliar application. These include the carbonates, oxides or hydroxide forms of Zn, Mn, Cu and Fe. The sulfate form of copper, manganese, iron and zinc is the most common and usually the least expensive source of micronutrients. These metal sulfates are water soluble and easily injected into irrigation water.

However, using these materials for fertigation is not very successful in alleviating a micronutrient deficiency when applied through sprinkler, furrows, or border strips. This is because these metals are positively charged and become attracted to the exchange sites of clay and organic matter. Therefore, they tend to stay near soil surface, and consequently, do not reach the major plant root zone. With buried drip and foliar fertigation, sulfates can be effective. The soil pH controls the availability of sulfate forms of Mn, Fe, Cu and Zn. If the metal sulfate solutions are acidified, the availability of the micronutrients in the soil can be prolonged.

The nitrate and chloride forms of micronutrients are very soluble and can be used for fertigation, but like the sulfate forms, the metal ions will accumulate at the soil surface rather than moving in the soil.

Micronutrient chelates are used as good source of micronutrients in soluble fertilizers. The sources most commonly used are EDTA, DTPA (Fe, Zn, Cu, Mn), EDDHA-Fe and lignosulfonates. Before deciding on the source of micronutrients, a mix should be made to ascertain compatibility. The solubility of various fertilizer raw material used in formulations of soluble powder fertilizers and liquid fertilizers are shown by Hamdallah (this volume).

Compatibility problems may occur when liquid or soluble powder fertilizers are combined. When preparing fertilizer solutions from various materials, the following should be considered; safety involved in making the solution, effect of solutions on each other, and type of irrigation system and its susceptibility to plugging.

Guidelines for Handling Fertigation for Safety Measures

Bashour and Nimah (1998) summarized the safety rules and precautions in mixing fertilizers and other chemicals for fertigation purposes. This section will focus on the hardware selection of the irrigation system in order to achieve a successful fertigation/chemigation system. The United States Environmental Protection Agency (USEPA) has created certain laws and regulations to protect the environment, including surface and groundwater, and for worker safety. The USEPA laws describe the devices that are required in the design of the fertigation unit.

The fertigation unit should be constructed from polyethylene (PE) and or ethyl vinyl acetate (EVA) hoses. These hoses have the following characteristics: flexible at a wide range of temperature, capable of working under high pressures (up to 14 bars), do not deteriorate in sunlight, are chemically compatible with fertilizers and other agricultural chemicals, and do not collapse under suction if they are thick. The fittings should be made of plastic and/or polyethylene or stainless steel. The manufacturers of the chemicals to be injected and the injection equipment should be consulted regarding the *compatibility and corrosivity of materials*.

The mixing tanks and the solution supply tanks could be constructed of fiberglass; mild steel tanks should be avoided because of their potential for corrosion. There should always be an on-off valve attached to the tank so that the injection mechanism can be removed. A filter 40 – 80 mesh should be attached downstream from the on-off valve. The injection system should be *isolated from other chemical storage areas and kept neat and clean*.

It is also important to follow directions regarding the order of mixing. Adding chemicals in the wrong order can be extremely dangerous, For example, *always add*

acid to water rather than water to acid. Always follow label instructions and USEPA rules of safety. Some basic mixing rules that should be followed (Burt et al., 1995) are presented by Hamdallah (this volume). In addition to the well known guidelines of Burt et al. (1995), A & L Agricultural Laboratories summarized the do's and don'ts of foliar application as follows:

1. **Do** obtain an accurate plant tissue analysis before foliar spraying.
2. **Don't** foliar spray plants under drought conditions, or when plants are under other forms of stress, such as disease or insect damage.
3. **Don't** foliar spray during hot, dry, mid-day temperatures. The best time is late evening; however, early morning or overcast days are acceptable.
4. **Don't** foliar spray under windy conditions if drift into adjacent fields is a factor.
5. **Do** use narrow tires and foliage deflectors on ground applicators, and adjust wheels to accommodate row widths to avoid damage to plant foliage.
6. **Do** clean application equipment thoroughly before spraying.
7. **Do** use wide angle hollow cone spray nozzle in ground applicators.
8. **Do** select the proper nozzle spray tip that will operate within the desired pressure range of your pump capacity.
9. **Do** calibrate each spray nozzle for proper volume using pressure-setting and ground speed desired.
10. **Do** adjust nozzles on boom to spray at a 90° angle straight down from spray boom.
11. **Do** adjust boom height above plant canopy for uniform spray pattern.
12. **Do** make sure all hoses, pumps or pipelines are thoroughly drained of any other plant food products and flushed with water before use.
13. **Do** flush residual amounts of fertilizer solution from aluminum equipment with water after use to avoid possible pitting of equipment from prolonged exposure.

ADDITIONAL LITERATURE

- Achorn, F.P., 1994. Fluid fertilizers. Vol. 1&2. *ARA Professional Dealers Manual*. Agric. Retailers Assoc., St. Louis, Miss., USA.
- Bashour, I. I., and M. N. Nimah, 1998. User's needs for quality fertilizer: types and formulations. Regional Workshop on "Guidelines for Efficient Fertilizer Use Through Modern Irrigation", 14 – 16 Dec., Cairo, Egypt.
- Bruns, V. F., J. M. Hodgson, H. F. Arle, and F. L. Timmons. 1955. The use of aromatic solvents for control of submersed aquatic weeds in irrigated channels. *USDA Circ.* No.971. USDA, Washington, DC.
- Bryan, B. B., and E. L. Thomas, Jr. 1958. Distribution of fertilizer material applied through sprinkler irrigation system. *Bull.* 598. *Univ. Arkansas Agric. Exp. Stat.*, Fayetteville, AR, USA.
- Burt, C., K. O'Connor, and T. Ruchr. 1995. Fertigation. Irrigation Training and Research Center, Calif. Polytechnic State Univ., Ca., USA.
- Chandler, L. D., and H. R. Summer. 1991. Effect of various chemigation methodologies on the suppression of the fall armyworm (*Leidoptera: noctuidae*) in corn. *Florida Entom.* 74.
- Dedrick, A. R. 1979. Land leveling- precision with laser controlled drag scrapppers. Paper No. 79-2565, ASAE, St. Joseph, MI., USA.
- Del Armor, F., P. Summers, and A. Dominguez 1989. Seminar on "The role of phosphates in balanced fertilization". 24–27 Oct., Marrakesh, Morocco, 1989.
- Evert, D. R., P. Bertand, K. Harrison, and J. Young. 1988. Chemigation of peach trees with a center pivot. *Hort Sci.* 23(5):862–863.
- Fischbach, P.E. 1971. Applying chemicals through irrigation Parts I, II and III. *Fert. Solutions Magazine*, Jan/Feb.
- Hamdy, A. 1995. Fertilizers and their efficient use. p 111-166. *In* Advanced short course on "Fertigation". FAO/RNE, CIHEAM/IAM-B and Université Libanaise, Faculté d' Agric. Nov. 26 – Dec. 3, 1995. Beirut, Lebanon.
- Hickey, M., and R.M. Seymour 1996. Application of fertilizers through center pivot sprinkler systems. *Arab World Agribusiness.* Vol. 14, No. 1.
- Hoffman, G. I., T.H. Howell, and K.H. Solomon. 1990. Management of farm irrigation systems, Amer Assoc. Agric. Engin., St. Joseph, MI, USA.
- Johnson, A. W. 1978. Effects of nematicides applied through overhead irrigation on control of root-knot nematodes on tomato transplant. *Plant Dis. Rep.* 62:48 – 51.
- Larhrafti, M., and S. Nishiyama, 1995. Hydraulic characteristics of an economical by-pass injector for micro-irrigation. *Proc. Fifth Intern. Micro-irrigation Congr.* April 2 – 6, Orlando, FL., USA.
- Musick, J. T., F. B. Pringle, and J. D. Walker. 1988. Sprinkler and furrow irrigation trends in the Texas high plains. *Appl. Eng. Agric.* 1:46-52.
- Nimah, M. N. 1995. Technological development and new concepts for efficient

- distribution and use of irrigation water and fertilizer. *In*: A. Hamdy (ed): *Advanced short course on "Fertigation"*. CIHEAM/FAO.
- Nimah, M. N. 1998. Crop water-use and irrigation scheduling. Regional training course on "Use of Nuclear Techniques in Water and Nutrient Management Practices". May 3 – 28, [A.E.C.S], Damascus, Syria.
- Nimah, M.N. 1996. Fertigation / chemigation methods as a tool for controlling adverse environmental effects. FAO regional workshop on "Fertilizer Use for Sustainable Agriculture", 4 – 6 Nov., Amman, Jordan.
- Nimah, M. N., and I. I. Bashour, 1998. Fertilization as an efficient and safe tool for water and fertilizer applications. Regional Workshop on Guidelines for Efficient Fertilizer Use Through Modern Irrigation. 14 – 16 Dec., Cairo, Egypt.
- Papadopoulos, I. 1991. Fertigation in Cyprus and some other countries of the Near East region *In*: Fertigation/Chemigation. Proc. "Expert Consultation on Fertigation / Chemigation". 8–11 Sept. 1991, Cairo, Egypt. FAO Publ. AGL/MISC/19/91. Rome, Italy.
- Peers T. 1996. Foliar feeding: fact vs fiction. *Arab World Agribusiness*. 14(1).
- Potter, H. S. 1981. Fungidation on vegetables. p. 74–81. *In*: J. R. Young (ed). Proc. National Symposium on Chemigation. Univ. Georgia, Tifton, GA, USA.
- Thomas, J. T., and D. L. Kincaid. 1989. Border cablegation system design. *Trans. ASAE* 32(4):1184–1192.
- Threadgill, E. D. 1981. Why chemigation? p. 1–6. *In*: J. R. Young (ed). Proc. "National Symposium on Chemigation". Univ. of Georgia, Tifton, GA. USA.
- Threadgill, E. D. 1991 Advances in irrigation, fertigation, and chemigation. p. 30–44. Proc. "Expert Consultation on Fertigation/Chemigation". FAO, Rome, Italy.
- Threadgill, E.D., D. E. Eisenhauer, J. R. Young, and B. Bar-Yosef. 1990. Chemigation, p. 749–780. *In*: Hoffman et al. (ed) Management of farm irrigation system. ASAE, St. Joseph, MI, USA.

SECTION I:

WATER MANAGEMENT

Role of FAO/IAEA Program in Fertigation Studies in the Mediterranean Region

Pierre Moutonnet

Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, Vienna, Austria.

ABSTRACT

Recognising the potential use of nuclear techniques in fertigation studies, the FAO/IAEA Program implemented a "Regional Technical Co-operation Project" during the period 1995-1998 with eight participating countries from Europe and the Middle East: Turkey, Cyprus, Syria, Jordan, Lebanon, Iran, Saudi Arabia, and United Arab Emirates. The main objective was to establish water-balance and fertigation practices using nuclear techniques, which included soil moisture neutron probe and ^{15}N -labelled fertilizers, with a view to improving crop production in arid and semi-arid zones. In particular, this project aimed to: 1) compare the conventional fertilization method with fertigation, 2) evaluate the recovery of N fertilizer applied with either the conventional method or fertigation, 3) evaluate water-use efficiency and estimate crop water requirements under conventional fertilization and N-fertigation, and 4) evaluate potential nitrate pollution with the conventional method and fertigation.

To achieve the above objectives, field experiments which included the following treatments were carried out: 1) N_s = soil N application at recommended rate and surface irrigation, 2) N_0 = control, no N application and drip irrigation, 3) N_1 = N applied by means of fertigation at 50% N_s rate, 4) N_2 = N applied by means of fertigation at 100% N_s rate, and 5) N_3 = N applied by means of fertigation at 150% N_s rate.

At least four sets of experimental data have been collected for each of the countries involved; crops included tomatoes, pepper, potatoes, cotton, lettuce, garlic and cucumber. *Results clearly showed the efficiency of fertigation in terms of water use, N fertilizer recovery, and crop yields.* Data from the Atomic Energy Commission of Syria show that fertigation of cotton is a very efficient technique for conserving both water and N fertilizer: 1) 36% of irrigation water was saved under drip irrigation, 2) 22 % increase in seed-cotton yield for fertigation compared with traditional fertilizer and water management practices, 3) 93 % increase for irrigation water-use efficiency based on dry matter yield. Further studies are envisaged under

a new Regional Project for Middle Eastern Countries on "Fertigation for improved water-use efficiency and crop yields".

INTRODUCTION

It is well known that Mediterranean countries have a severe shortage of water resources for agricultural, municipal and industrial purposes. This situation is aggravated every day due to the rapidly increasing population in the area. It is agreed that the optimal water requirement per capita is around 1,700 m³/year; in West Asia, 8 out of 18 states have less than 500 m³/capita/year (Table 1). The situation will deteriorate further through the next two decades. It should be noticed that agriculture is the biggest user of this scarce resource; about 80% of the renewable resources are used for irrigation. Usually, traditional irrigation methods are highly inefficient; it is admitted that only about one-third of the water used in irrigation is actually transpired by the crops (Moore, 1988). Clearly, there is great scope for improved irrigation management.

Table 1. Water availability and withdrawal in some countries of the West Asia-North Africa region.

Country	Renewable Resources per Capita		Share of Withdrawals	
	1990	2025	Domestic	Agriculture
	-----m ³ /year-----		-----%-----	
Algeria	737	354	22	74
Egypt	1.112	645	7	88
Israel	467	311	16	79
Jordan	224	91	29	65
Lebanon	1.407	809	11	85
Libya	154	55	15	75
Morocco	1.185	651	6	91
Saudi Arabia	156	49	6	91
Syria	439	161	7	83
Tunisia	532	319	13	80
U.A.E.	189	113	11	80

Source: Kemp (1996).

Furthermore, the lack of water hinders economic growth. According to Kemp (1996), "the World Bank argues that the allocation of water to agriculture, which accounts for about 90% of regional water use, no longer makes economic sense. In Morocco, for example, it is estimated that the value added by a cubic meter of water in irrigated agriculture is a mere 15 cents; used in industry, it is a striking \$25. In Jordan, which uses highly efficient drip irrigation for over half of its irrigated agriculture, the equivalent figures are 30 cents for agriculture and \$15 for industry.

Therefore, there is a growing concern for improving irrigation water efficiency, inasmuch as high-input agriculture associated with the mismanagement of irrigation poses a threat to groundwater quality.

There are several ways of reaching this objective: *conservation, re-cycling, re-use and improved water-use efficiency* are some of the techniques developed (Pimentel et al., 1997). The drip or micro-irrigation technique developed in the 1960s has spread rapidly worldwide, especially to the Mediterranean countries. This method uses 30 – 50% less water than surface irrigation (Tuilg, 1993). In Israel, thanks to improved irrigation management, the crop water-use efficiency has more than doubled from 1955 to 1980: i.e., from 1 to 2.5 kg yield per cubic meter over this period (Hillel, 1994).

However, drip irrigation has some disadvantages; one of its main drawbacks is the big investment that is required for its installation. A comparison of drip irrigation with sub-irrigation and seepage for tomato production in Florida indicated that drip irrigation reduced water needs by 50% but added \$ 328 per ha to the production costs (Pitts and Clark, 1991). In other cases, particularly when advanced technology is not required for the distribution network, a low-cost drip irrigation system for small farmers of developing countries has been promoted (Palak et al., 1997). Instead of an investment of \$2,000 per ha, the cost was reduced by 90% by i) making dripper lines moveable, ii) replacing drippers by simple 0.70 mm holes, iii) and using cheap cloth filters instead of expensive ones. The low-cost system was tested in Nepal and India, where the results of the discounted cash flow technique showed that investment in drip irrigation is economically feasible, even though it is capital-intensive (Narayanamoorthy, 1997).

In Mediterranean countries, the impact of fertigation/chemigation on agricultural production was thoroughly reviewed by an Expert Consultation held in Cairo, Egypt in 1991 (FAO, 1991). This meeting was sponsored by the Food and Agriculture Organisation (FAO) of the United Nations. General conclusions and recommendations were drawn. Among them it was emphasised that: i) Very little fertigation/fertigation research has been conducted in countries of the Near East Region. ii) There is a need to develop multidisciplinary research activities involving international, regional and national institutions as well as the private sector in these activities.

The International Atomic Energy Agency (IAEA) has the mandate (Article III) to “encourage and assist research on, and development and practical application of, atomic energy”. Therefore, a Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture was created in 1964 with the following mission: to strengthen capacity for using nuclear methods to improve technologies for sustainable food security, and to disseminate these through international co-operation in research, training and other outreach activities in Member Countries of FAO and IAEA (IAEA, 1997).

Among the nuclear techniques which are used in agricultural research (IAEA, 1990), two at least are readily applicable to fertigation studies: i) the soil moisture neutron probe which allows an easy monitoring of soil water status and water-balance evaluation (Kirda, 1990), ii) isotopically-labelled mineral fertilisers and to study their fate in the soil-plant system (Papadopolos, 1995, Montonnet et al., 1995).

It is recognized that drip irrigation/fertigation is an effective means to save water and to increase fertiliser-use efficiency. However, although fertigation in the West Asia region was already widely used in the 1990s, insufficient information was available for most of the crops regarding the level of nutrients and the form of fertilisers required. Moreover, in some cases, low fertiliser recoveries, due to the intensive fertilization practised during the last few decades, had created serious agricultural/environmental problems. Treated wastewater is being used in some Middle Eastern countries. Its impact on the environment should be carefully studied, especially when used for drip irrigation/fertigation of crops yielding food that is normally eaten uncooked (Shatanawi and Fayyad, 1996).

An IAEA Regional Technical Co-operation Project (TCP) was launched for the period 1995-1998 on "Water-balance and fertigation for crop improvement (RAW/5/002)". Six countries participated in the research network: Turkey, Cyprus, Syria, Jordan, Lebanon, Iran, Saudi Arabia, and United Arab Emirates, with the aim of applying nuclear techniques to identify best management practices for increased crop yields in such arid and semi-arid zones.

MATERIALS AND METHODS

The main objectives of the Technical Co-operation Project (TCP) are summarised as follows:

1. Compare the conventional fertilization method with fertigation.
2. Evaluate the efficiency of nitrogen (N) applied with conventional and fertigation method.
3. Evaluate water-use efficiency and estimate crop water requirements under conventional fertilization and N fertigation at three different rates.
4. Evaluate potential nitrate ($\text{NO}_3\text{-N}$) pollution with the conventional fertilization method and fertigation.
5. Demonstrate the benefits and transfer the technology to the farmers' level following evaluation of the collected data.

To achieve the above objectives, the following treatments were proposed for both greenhouse and open field conditions:

- $N_0 \equiv$ nil N application.
- $N_1 \equiv 1 \times N$ concentration applied by means of fertigation (50% of N_2).
- $N_2 \equiv 2 \times N$ concentration applied by means of fertigation (100% of the locally recommended rate).
- $N_3 \equiv 3 \times N$ concentration applied by means of fertigation (150% of N_2).
- $N_s \equiv$ soil N application at the same rate as treatment N_2 (which is the locally recommended rate).

In the soil or N_s treatment, the N fertilizer was applied according to the traditional farmers' practice. In some cases, the whole amount was applied at planting, or was split into several applications, with the 1st split applied through the irrigation system and later splits applied to the soil. The overall amount of N fertilizer applied with the N_2 treatment through the irrigation system (fertigation) with every irrigation was equivalent to the amount of the soil N application (N_s treatment). The amount of N applied with the N_s treatment was the amount that is suggested to the farmers for a particular crop with the conventional method of fertilization based on soil fertility. The N_1 and N_3 concentrations were equally spaced from N_2 . For example, if N_2 is 100 mg N/L in the irrigation water, then N_2 is recommended to be 50 mg N/L and N_3 to be 150 mg N/L.

A randomized complete block design consisting of 4–8 randomized blocks (repetitions) was recommended, each divided into five plots. The plots, depending of the crop, contained one, three or five drip-irrigated rows. The length of the rows depended on the space available, but usually ranged from 6–10 m. The spacing between the rows depended on the crop, but was big enough to avoid interference from the rows adjacent to the one where the ^{15}N -labeled fertilizer was applied. In case of insufficient spacing between the rows, plastic/metal barriers were inserted between the rows at the place of the ^{15}N application. In the case of 3–5 rows, the central one or the three central rows, respectively, were used for yield and other data collection. The ^{15}N -labeled fertiliser was applied as follows:

Soil application (N_s treatment): The ^{15}N -labeled fertilizer was applied in the center of the experimental row at a distance which is irrigated by three or five drippers (one or several split applications according to local practice).

Fertigated plots; The ^{15}N -labeled fertilizer was applied through inverted bottles with a dripper or a clip at the cup of each bottle (Papadopoulos, 1995). Where the inverted bottles supplied the ^{15}N -labeled fertilizer, the irrigation line was without drippers. In this way, all plants were irrigated and fertilized through the system; except those fertigated with ^{15}N -labeled fertilizer. The amount of water and the ^{15}N -labeled fertilizer applied through the bottles was equivalent to that amount applied through a single dripper.

Phosphorus (P) and potassium (K) were applied uniformly to all treatments through the irrigation system. The irrigation/fertigation system was composed of two hydraulic injectors, five main lines of plastic tubing into which the five N rates were injected and 1–5 lateral lines for each crop. The drippers were spaced on the laterals at the distance of planting. One hydraulic injector was used for supplying all treatments with uniform concentrations of P and K. To produce the N levels for the three fertigation treatments, N fertilizer was injected by the second hydraulic injector in a ratio of 1:2:3 in the irrigation stream for the N_1 , N_2 and N_3 treatments, respectively (Papadopoulos, 1987).

Water requirements and water-use efficiency were evaluated using a soil moisture neutron probe and several access tubes (# 1.5 m in depth) in all treatments. At least 2–4 replications were observed with one access tube next to the dripper, another one on the line between two drippers and possibly a last one between the two laterals. Two tensiometers, or *tensionics*, were installed beneath drippers in the N_2 treatment for irrigation scheduling and assessment of any nitrate leaching (Moutonnet and Fardeau, 1997).

RESULTS AND DISCUSSION

Iran

Tomatoes were grown with urea fertilizer applied at rates of 0, 150, 300 and 450 mg N/L under drip irrigation (Hobbi et al., 1998). The conventional treatment with surface irrigation received 500 kg N/ha. Drip irrigation saved about 50% of irrigation water (Fig. 1). Yield increased dramatically under drip irrigation, whereas increased rates of N fertilizer, N_1 and N_2 , had no significant effect on fruit dry matter yields. A negative effect on fruit dry matter yield (DMY) was observed in the N_3 treatment (Fig. 2). The N fertilizer-use efficiency was very low under surface irrigation (5%), whereas drip fertigation increased the recovery of N fertilizer to 30% (Fig. 3). In conclusion, drip irrigation significantly increased yields, water-use efficiency, and N fertilizer recovery. However, the crop yield response curve is questionable and further studies are underway.

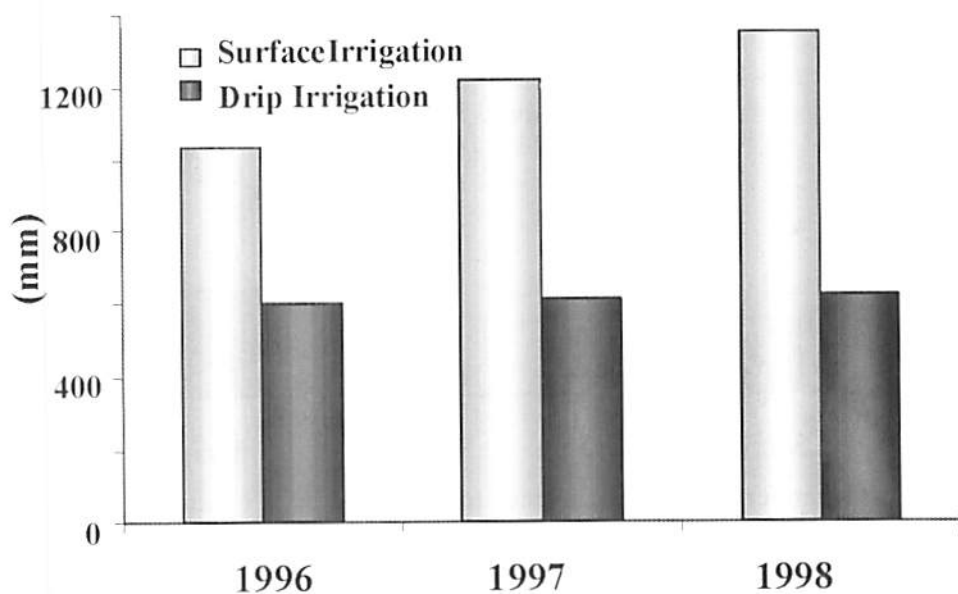


Fig. 1. Amounts or irrigation water applied.

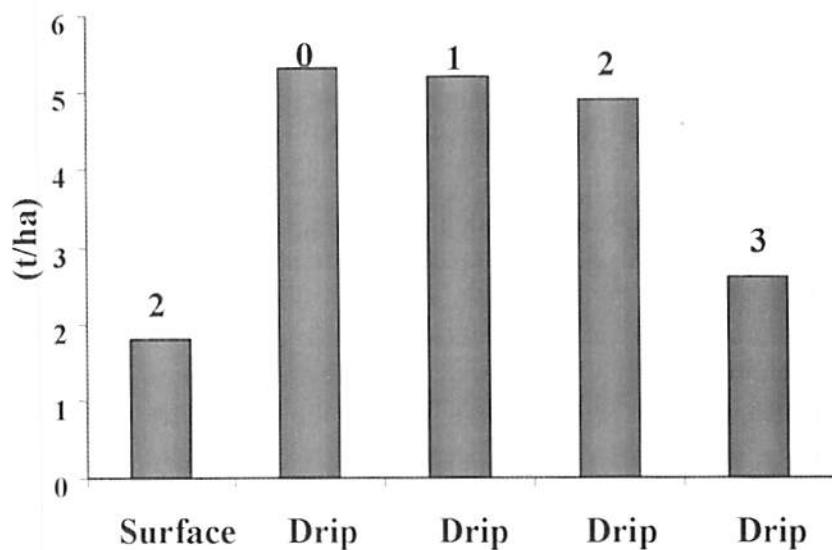


Fig. 2. Fruit dry matter yield vs. surface and drip irrigation treatments.

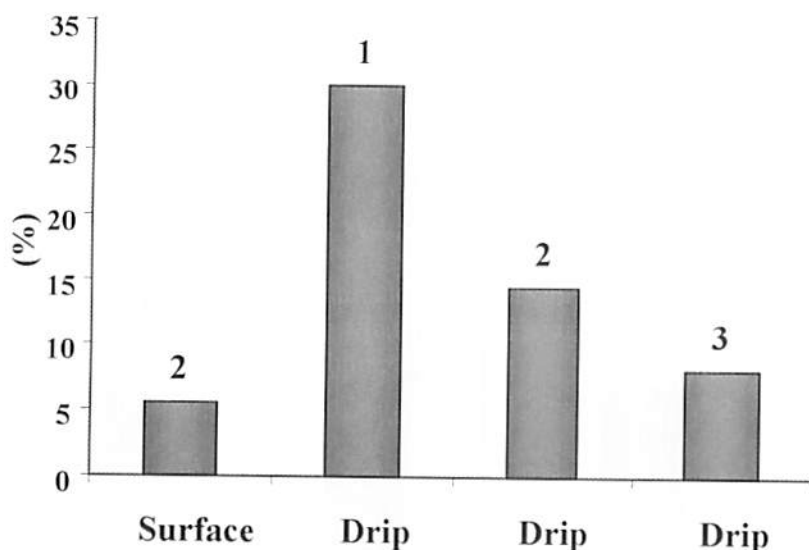


Fig. 3. Nitrogen fertilizer-use efficiency (determined by ^{15}N recovery).

Jordan

Tomatoes were grown with ammonium sulphate fertiliser applied at rates of 0, 50, 100 and 150 mg N/L through fertigation (Al-Zuraiki et al., 1998). The conventional treatment N_s , with 170 kg N/ha, was also drip irrigated. As a consequence, all treatments received the same amount of water (200 mm of irrigation plus 300 mm of rain). Yield increased significantly in treatment N_1 , the first level of N fertilizer application (Fig. 4). At higher N rates, there was no further yield increase. During the 1997-98 season, the N fertilizer applied to the soil (N_s treatment) was significantly less efficient than the corresponding N_2 treatment.

The N fertilizer balance evaluation using ^{15}N recovery for the cropping seasons 1996-97 and 1997-98 are given in Tables 1, and 2 respectively. The N uptake increased significantly with the application of N_1 , but did not increase further at higher rates. It is noteworthy that N fertilizer-use efficiency (NUE) was highest at N_1 and decreased dramatically with higher N rates. In both cropping seasons, the NUE of the N_s treatment was significantly lower than the N_2 treatment.

In conclusion, the crop responded positively to the lowest N fertilizer rate, but not more at higher rates; N fertilizer applied to the soil was not used efficiently; it was recommended to apply relatively low rates of N fertilizer (e.g., 100 kg N/ha) through fertigation, keeping in mind site characteristics.

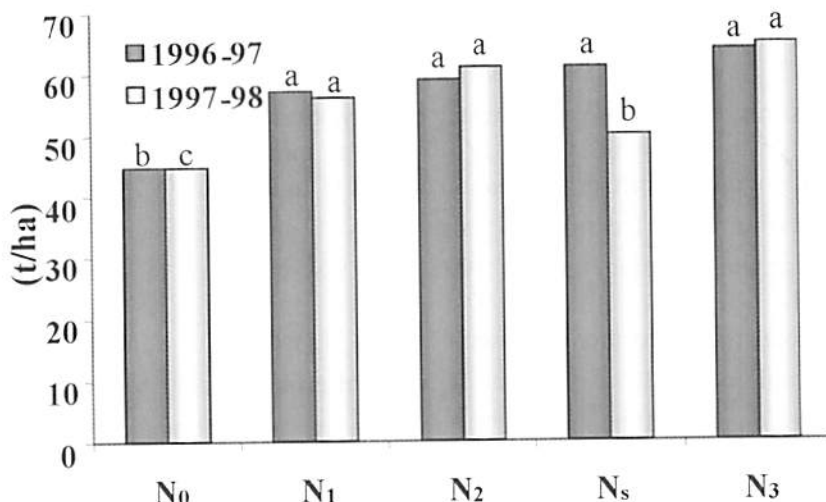


Fig. 4. Tomato marketable yields vs. N fertilizer treatments.

Table 1. Tomato, N fertilizer balance 1996 – 97.

Treatment	Nitrogen	Nitrogen Uptake	Nitrogen Derived from Soil	Nitrogen-Use Efficiency
-kg /ha-	---%---	-----kg/ha-----	-----%-----	
N0 (0)	1.5 b	97 c	—	—
N1 (84)	2.1 a	135 b	29 a	47 a
N2 (168)	2.1 a	135 b	21 a	17 b
NS (168)	2.3 a	125 b	10 b	5 c
N3 (252)	2.0 a	150 a	11 b	7 c

Table 2. Tomato, N fertilizer balance 1997 – 98.

Treatment	Nitrogen	Nitrogen Uptake	Nitrogen Derived from Soil	Nitrogen-Use Efficiency
-kg /ha-	---%---	-----kg/ha-----	-----%-----	
N0 (0)	1.7 b	140 b	—	—
N1 (64)	2.2 a	204 a	15 a	48 a
N2 (128)	1.9 a	201 a	11 b	17 b
NS (175)	1.6 b	166 b	6 c	6 d
N3 (192)	1.9 a	221 a	13 b	11 c

Garlic was grown with ammonium sulphate fertilizer applied at rates of 0, 70, 140 and 210 kg N/ha through fertigation (Mohamad et al., 1998). Two conventional treatments N_{s1} and N_{s2} consisted of surface application of 140 kg N/ha in one or two split doses, respectively. Weekly water consumption ranged from 10 mm at the beginning of the growing season to 40 mm at mid season. Yields increased significantly with N fertilizer application at rates N_1 and N_2 in 1997, and only at rate N_1 in 1998 (Fig. 5, 6). Treatment N_{s2} always gave higher yields than N_{s1} . Fertilizer recovery for the cropping seasons 1997 and 1998 is shown in Tables 3 and 4, respectively.

The total N uptake increased with N_1 and N_2 rates with a mean N fertilizer recovery value of 20–30%. The rate N_3 was not efficient, neither in yields nor in NUE. The conventional treatments, N_{s1} and N_{s2} , were rather low for total N uptake, as well as for N fertilizer recovery, which ranged from 5–10%.

In conclusion, garlic yields increased with N fertilizer rates, especially under fertigation; maximum yields were reached with 80 kg N/ha (fertigation) or 120 kg N/ha (conventional application); the N fertilizer recovery was better under fertigation, while split application is recommended with conventional N application.

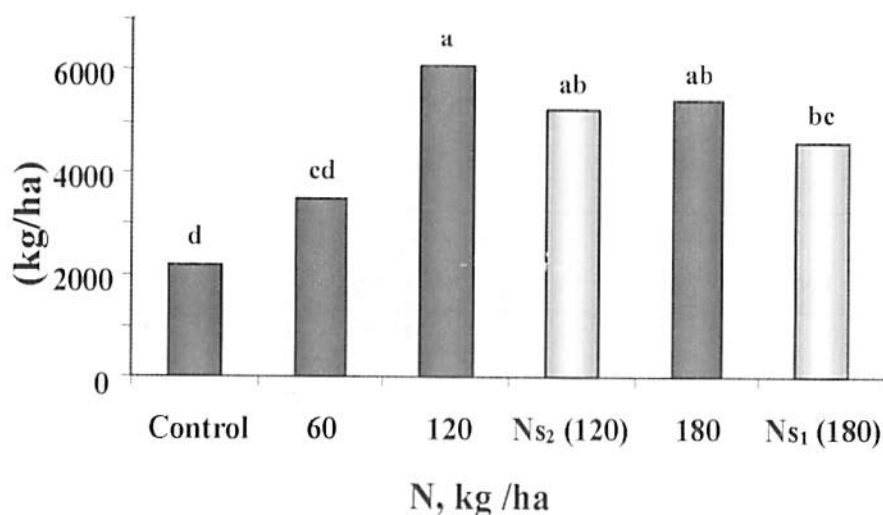


Fig. 5. Yields of garlic in Jordan vs. N fertilizer treatments (1997).

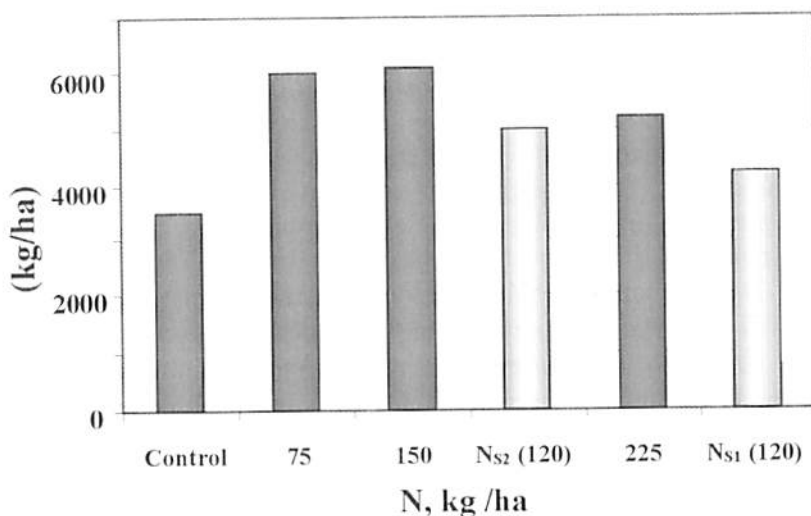


Fig. 6. Garlic yields vs. N fertilizer treatments (1998).

Table 3. Nitrogen fertilizer recovery of garlic (1997).

Rate	Fruit Uptake	Shoot Uptake	N _{diff} Fruit	N _{diff} Shoot	N Fertilizer Recovery
	-----kg N/ha-----		-----%-----		
60	44	7	21	16	17
120	70	14	29	22	20
180	67	19	41	31	18
N _{s2} (120)	55	10	20	20	11
N _{s1} (180)	50	5	12	10	4

Table 4. Nitrogen fertilizer recovery of garlic (1998).

Rate	Fruit Uptake	Shoot Uptake	N _{diff} Fruit	N _{diff} Shoot	N Fertilizer Recovery
	-----kg N/ha-----		-----%-----		
75	71	11	27	25	29
150	78	14	32	30	19
225	69	14	34	33	13
N _{s2} (120)	57	6	23	16	12
N _{s1} (120)	46	5	19	19	8

Lebanon

Field potatoes were grown with rates of urea ranging from 0–480 kg N/ha (1997) and 0–360 kg N/ha (1998) (Darwish et al., 1998). There were six treatments and four replicates. The conventional fertilizer treatments were irrigated either by drip (Ncd) or sprinkler (Ncs). Drip irrigation saved about 50% of irrigation water: 500 mm applied against 860 mm through sprinkler irrigation.

Yield responded positively to N fertilization under drip irrigation at the low rate N1 (Fig. 7). The conventional fertilization was not efficient under sprinkler irrigation; it was improved by drip irrigation. The N fertilizer recovery was around 25% (Fig. 8). Owing to this low level of recovery, a good part of the N fertilizer applied was left in the soil after harvest (Table 5), prone for nitrate leaching during the wet season.

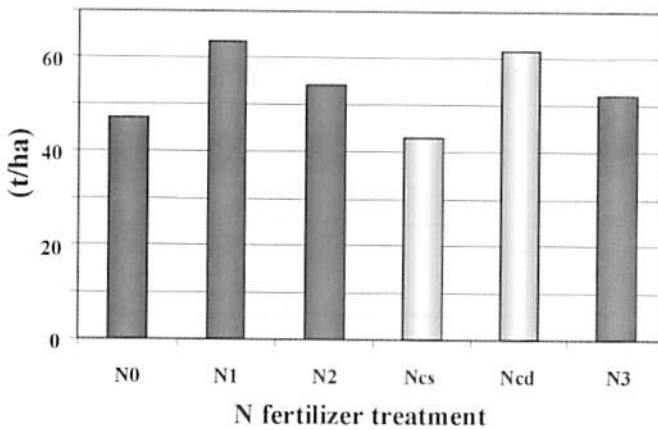


Fig. 7. Spring potato yields (1997).

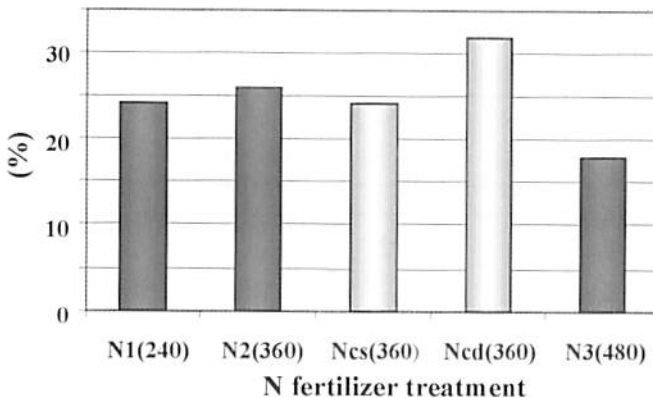


Fig. 8. Nitrogen fertilizer recovery (1997).

Table 6. Soil residual nitrate.

Soil Layer	0 – 20 cm	20 – 40 cm	40 – 60 cm
	-----mg /kg soil-----		
Initially	11	13	12
After			
N0	29	12	12
N1(240)	47	35	16
N2(360)	96	48	27
Ncs(360)	32	59	42
Ncd(360)	36	21	31
N3(480)	122	55	35

Cucumber was grown under greenhouse conditions with two modes of irrigation (every 2 or 3 days) and two modes of fertigation (continuous or discontinuous, every other irrigation). Basic rates of fertilizers were 135 mg N/L as ammonium sulfate, 40 mg P/L as phosphoric acid and 200 mg K/L as potassium sulfate (Attalah et al., 1998; El-Mojabber et al., 1998).

Continuous fertigation, applied every 2 days, gave yields significantly higher than all other treatments (Fig. 9). In terms of N fertilizer-use efficiency, the treatments T2s were significantly better than treatments T3s; otherwise, there was no significant difference between sub-treatments C and D (Fig. 10). Postponing irrigation and fertigation induced a build up of nitrate in the upper soil layers (Table 6). This accumulation could be associated with increased soil electrical conductivity (Table 7).

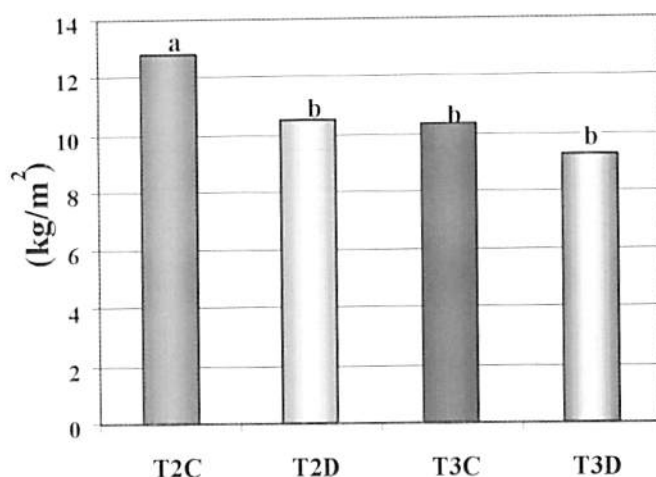


Fig. 9. Fresh weight yields of cucumber vs. treatments.

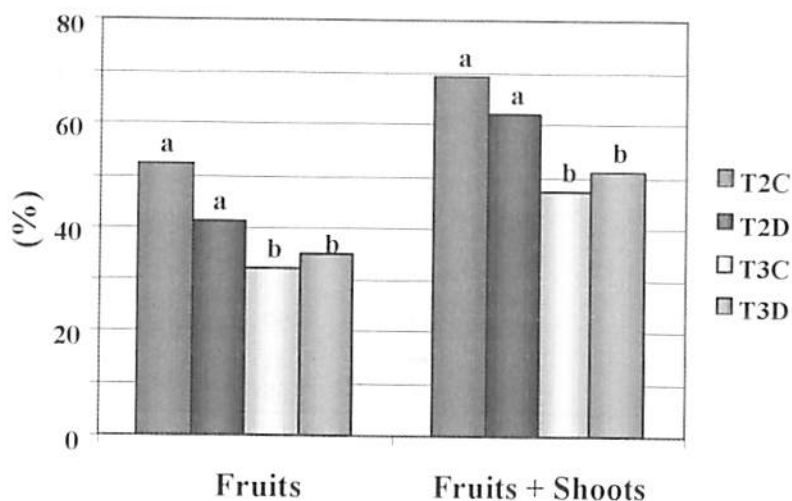


Fig. 10. Nitrogen fertilizer-use efficiency

Table 7. Residual nitrate in the soil at harvest.

Soil Layer	-----NO ₃ -N, ppm-----		
	0 – 20 cm	20 – 40 cm	40 – 60 cm
Beginning	61	54	33
After			
T2C	62 (a)	51	18
T2D	82 (b)	51	23
T3C	126 (b)	62	19
T3D	111 (b)	68	18

Table 8. Soil electrical conductivity.

Soil Layer	-----EC (dS m ⁻¹)-----		
	0 – 20 cm	20 – 40 cm	40 – 60 cm
Beginning	2.2 (a)	1.9	2.1
After			
T2C	2.4 (a)	1.8	1.1
T2D	3.9 (b)	2.2	1.3
T3C	3.8 (b)	2.7	1.4
T3D	3.7 (b)	2.5	1.6

Saudi Arabia

Cucumbers were grown under greenhouse conditions on a typical coarse sandy soil (6–9% field capacity). Five treatments (0–300 kg N/ha; the treatment Ns being the conventional mode of fertilizer application) were imposed with six replicates (Al-Wabel et al., 1998). Yields responded positively to increased rates of N fertilizer (Fig. 11); however, the crop yield response curve did not reach a plateau whereas the optimal N fertilizer rate was 200 kg N/ha. The treatment Ns was less effective than the equivalent rate of N fertilizer used through drip irrigation.

On the other hand, cucumber mineral contents (N, P, and K) increased significantly with increasing N fertilizer rates (Fig. 12). The N recovery data are still pending. Nevertheless, there is much potential for adoption of fertigation practices for increasing production of greenhouse crops.

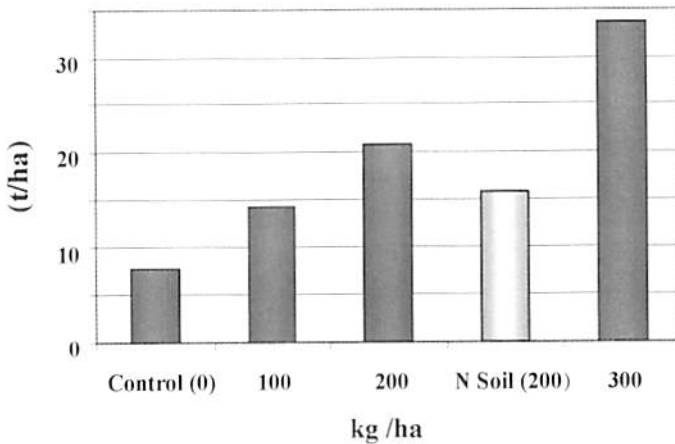


Fig. 11. Cucumber yields vs. nitrogen fertilizer rates.

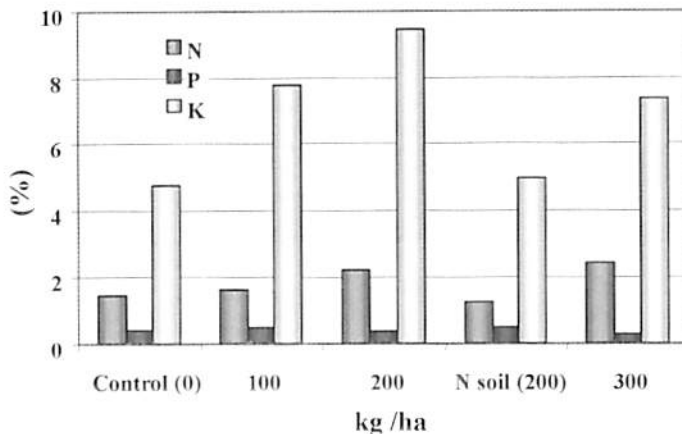


Fig. 12. Mineral contents of cucumber shoots vs. nitrogen fertilizer rates.

Syria

Field experiments were initiated with cotton with the following objectives (Janat and Sami, 1998): i) Assess N fertilizer-use efficiency under conventional (3 split soil surface applications) and fertigation practices, ii) Evaluate N requirements of cotton under fertigation, iii) Study the comparative water-use efficiency of cotton grown under the above conditions.

Irrigation requirements, over the period 1995-98, were about half under drip irrigation compared with furrow irrigation (Fig. 13). Yields increased with N fertilizer rates, reaching a plateau around 120 kg N/ha under fertigation. The conventional treatment always gave significantly lower yields than the corresponding N3 treatment, being often no better than N0 treatment (Fig. 14). The N fertilizer-use efficiency NUE was estimated using the ^{15}N -recovery technique. Over the period 1995-98, the last 2 years are characterized by far higher NUE under all treatments (Fig. 15); one of the possible explanations being a better timing of N fertilizer application and the final irrigation.

The results showed superiority of all fertigated treatments over the surface irrigated treatment. Monitoring of nitrate in the soil solution at increasing depths was done using sets of tensionics. It was shown, specifically under the surface irrigation treatment, that leaching of N fertilizer could be one of the reasons for the ineffectiveness of surface irrigation (Fig. 16).

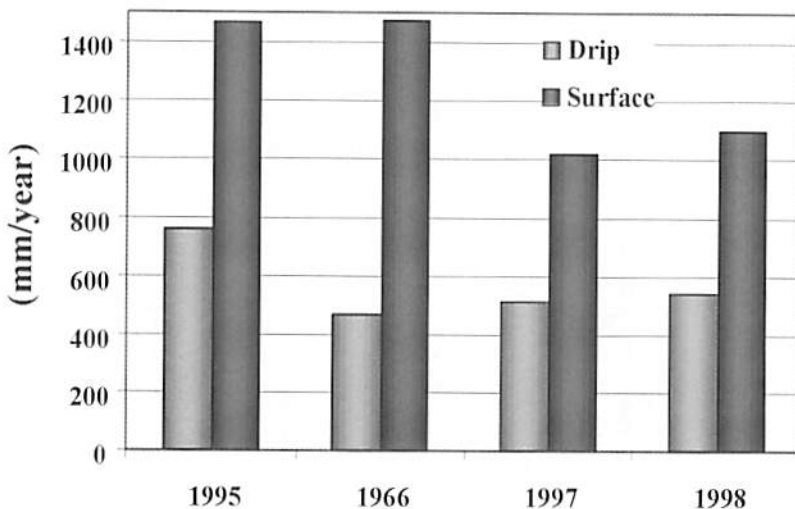


Fig. 13. Irrigation requirements of cotton.

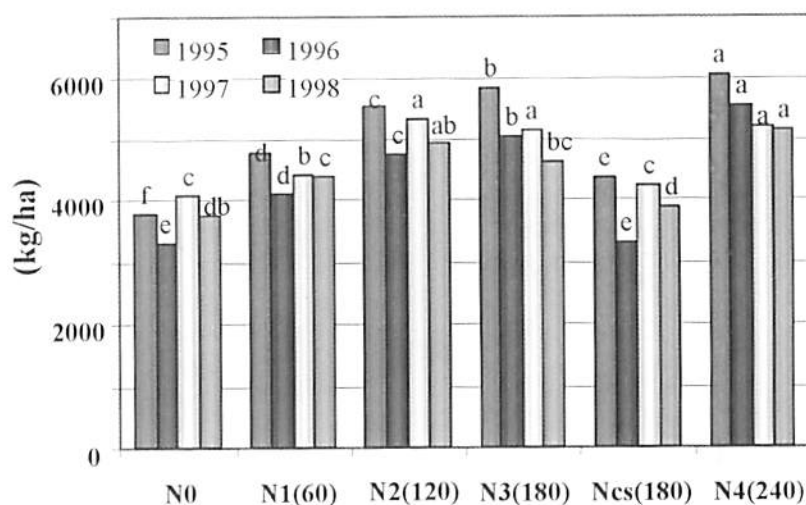


Fig. 14. Seed cotton yields vs. treatments.

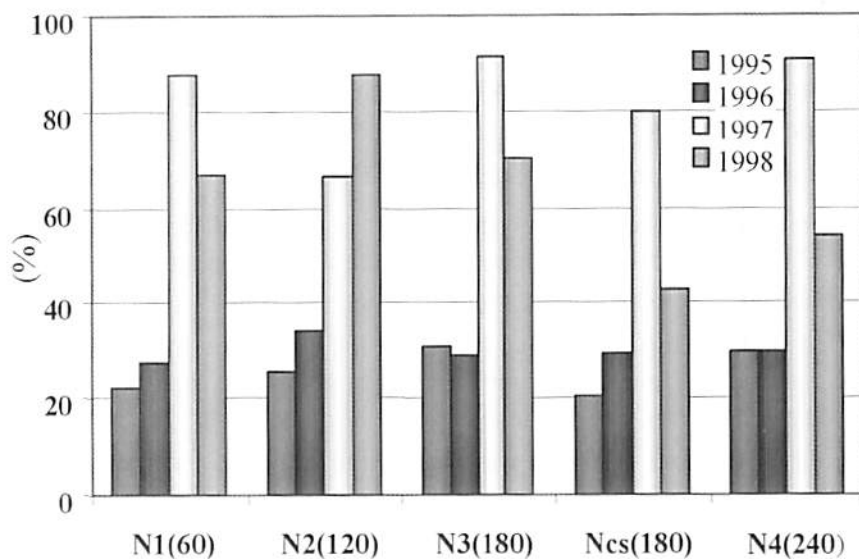


Fig. 15. Nitrogen fertilizer-use efficiency.

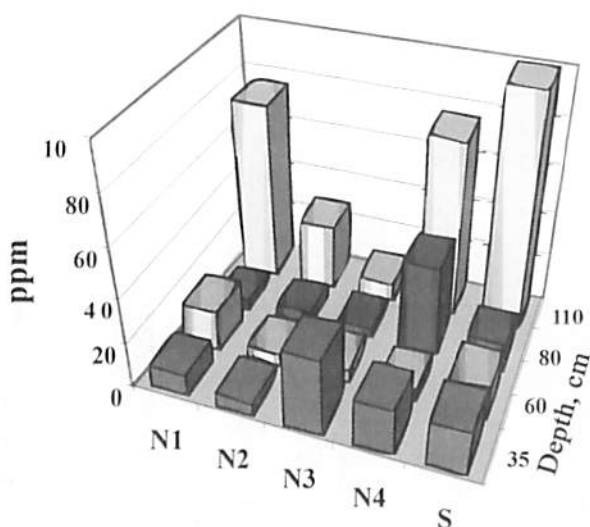


Fig. 16. Nitrate content in soil solution at depths vs. nitrogen application rates (N_1 - N_4) (in fertigation) compared with surface application(s).

Turkey

Eight experiments were conducted under greenhouse conditions with *tomato*, *pepper*, *cucumber*, *melon* and *eggplant* on an "terra rosa" soil near Antalya (Halitligil et al., 1998). Only data obtained with tomatoes (3 trials) are reported here. Fertilizer N rates ranged from 0–150 mg N/L with a conventional treatment corresponding to the N_2 rate which supplied 300 kg N/ha as ammonium sulphate: $1/3$ before planting, and $2/3$ during growth stages.

Yields responded positively to N_1 , the 1st rate of N fertilizer, but not beyond (Fig. 17). In two out of three experiments, the conventional treatment $N_c(300)$ gave significant lower yields than $N_2(300)$ in which the same amount of N fertilizer was applied through drip irrigation. However, the difference in yield was very small owing to the high level of soil fertility and its good field capacity.

The N fertilizer-use efficiency was determined using ^{15}N (Fig. 18); at the N_1 rate, the N fertilizer recovery was rather high (50–70%), decreasing at higher N rates. The recovery of the conventional N fertilizer application was significantly less than with the same amount of N fertilizer applied through fertigation.

A synthesis of the advantages of fertigation is shown in Table 8. Rate N_2 was superior compared with N_0 and N_c in terms of yields, N fertilizer, and water-use efficiencies for the five crops considered. Yields and NUE were always substantially increased.

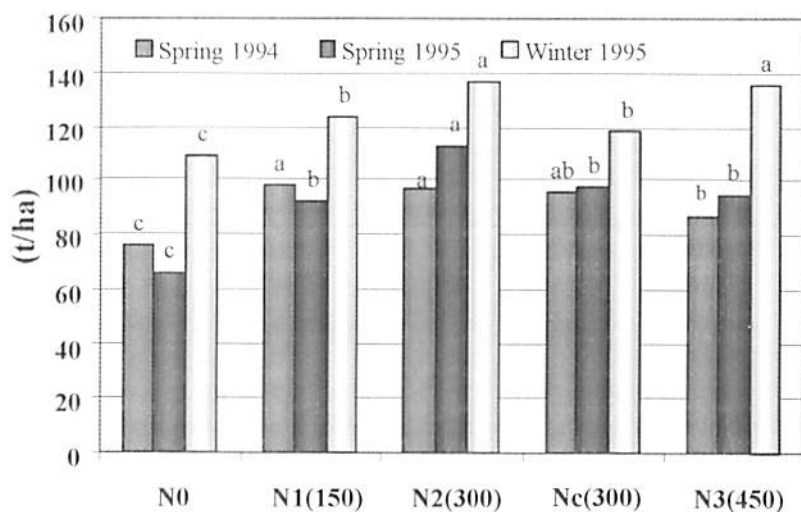


Fig. 17. Tomato yields over the period 1994-95.

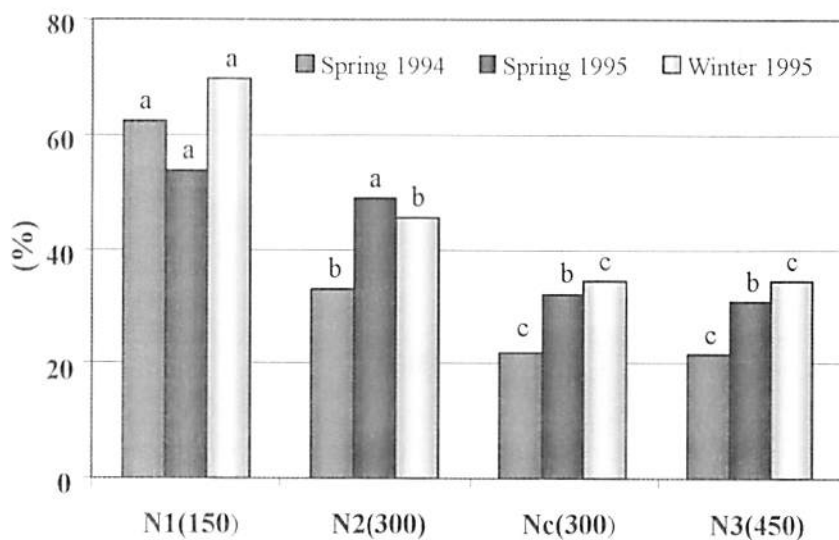


Fig. 18. Nitrogen fertilizer recovery under tomatoes.

Table 8. Advantages of fertigation in this study.

Crop	Yields (N2 vs. N0)	Nitrogen-Use Efficiency (N2 vs. Nc)	Water-Use Efficiency (N2 vs. Nc)
	-----%-----		
Tomato	50	55	10
Pepper	50	55	10
Melon	45	120	80
Cucumber	65	80	10
Eggplant	50	150	20

United Arab Emirates

Cucumber was grown under protected conditions on a saline (~4 dS/m) sandy loam, low in organic matter (Al-Mehrazie et al., 1998). Four rates of N (0, 200, 400, and 600 kg N/ha) were arranged in a CRBD with eight replicates. The plots received 300 and 450 kg/ha of P and K, respectively, as well as 10 t/ha of organic matter.

Yields responded positively to the first rate of N fertilizer but not beyond that (Fig. 19). The low plant density (8130 plants/ha) could partially explain the relatively low yields. Total N uptake (49.8 kg N) was low despite the high inputs i.e., 200 kg N/ha plus 10 t organic matter (Table 9). Nitrogen derived from fertilizer reached the value of 30%; at N2 rate of 200 kg N/ha this represents a N fertilizer recovery of 7%. Further studies are going on for improved crop conditions.

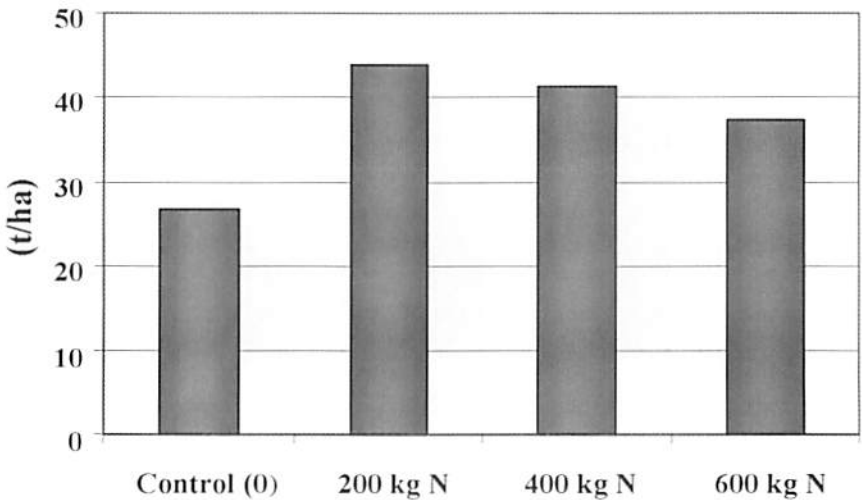


Fig. 19. Cucumber yields vs. nitrogen rates.

Table 9. Nitrogen yield of cucumber plant parts at 200 kg N/ha rate.

Plant Part	Dry Matter Yields	Total Nitrogen	Nitrogen Yield	Nitrogen Derived from Fertilizers	Fertilizer Nitrogen Yield
	---t/ha---	---%---	---kg/ha---	-----%-----	---kg N/ha---
Fruits	1.32	2.76	36.6	29	10.6
Shoots	0.61	2.09	13.0	31	4.1
Roots	0.01	1.58	0.24	31	0.1
Total	1.94		49.8	30	14.8

CONCLUSIONS

Over 4 years (1995-98), the experiments undertaken in eight countries within Europe and the Middle East have *proved that drip irrigation and fertigation are promising techniques in the region*. "On-station" trials were conducted according to the guidelines of the Regional Technical Co-operation Project RAW/5/002 on "Water-balance and fertigation for crop improvement". Experiments benefited from nuclear techniques (soil moisture neutron probe, ¹⁵N-labelled fertilizers) and the support of the FAO/IAEA program in fertigation studies in the Mediterranean region.

The main objective was to quantify the improvement that could be brought to water and N fertilizer-use efficiencies through drip irrigation and fertigation. It was shown that:

1. About 30 to 50% of irrigation water can be saved under drip irrigation.
2. Nitrogen fertilizer application (as well as P and K inputs in most cases) is a necessity for maintaining the productivity of the irrigated crops investigated. Control treatments (N₀) yields were 0–80% lower than N(1–3), depending on the original soil fertility level.
3. The conventional application of N fertilizer to the soil itself (pre-planting plus split applications later on) was not effective whatever the mode of irrigation employed, even if drip irrigation itself gave higher yields compared with conventional techniques.
4. Under fertigation at increasing rates of N fertilizer, the optimal crop yield was very often reached at rate N₁ instead of rate N₂, which corresponded to the "locally recommended rate".

Therefore, fertigation could promote N fertilizer savings at a level which often reached 50% of the recommended inputs under conventional irrigation.

ACKNOWLEDGEMENTS

I would like to thank the researchers who have all been involved in the Regional Technical Co-operation Project RAW/5/002, and their commitment for implementing the experiments is noteworthy. Also, the IAEA Technical Co-operation Department supported the Regional Project: the support of Mr. S. Chaudhri, Section Head of the West Asia Region, and Mr. A. Habjouqa, Project Officer, is gratefully acknowledged.

REFERENCES

- Al-Mehrazi, M.S., H. Sattar, and H. Abu-Alkibash. 1998. Cucumber nitrogen need under protected cultivation using ^{15}N -labelled urea. Progress Report, Karaj, Iran, 31 Oct. – 4 Nov., 1998.
- Al-Wabel, M.I., A.A. Al-Jaloud, G. Hussain, and S. Karimulla, 1998. Study for water-balance and fertigation crop improvement. Progress Report, Karaj, Iran, 31 Oct. – 4 Nov.
- Al-Zuraiqi, S., W. Al-Qawasmi, M.J.R. Mohammad, and I. Al-Deek. 1998. Management of nitrogen fertigation on tomato crop with the use of ^{15}N technology. Progress Report, RAW/5/002. Karaj, Iran, 31 Oct. – 4 Nov.
- Attalah, T., T. Darwish, and M. El-Moujabber. 1998. Modality of fertigation of protected cucumber and Nitrogen use efficiency under field conditions. Progress Report. Karaj, Iran, 31 Oct. – 4 Nov.
- Darwish, T., T. Attalah, S. Hajhasan, and A. Chranek. 1998. Fertigation of spring potatoes utilizing ^{15}N in Central Beqaa, Lebanon: comparative water and N fertilizer utilization in fertigation vs. soil application under drip and macro-sprinkler systems. Progress Report, RAW/5/002. Karaj, Iran, 31 Oct. – 4 Nov.
- El-Moujabber, M., T. Attalah, T. Darwish. 1998. Crop modeling and water-use efficiency of protected cucumber. Progress Report. Karaj, Iran, 31 Oct. – 4 Nov.
- FAO. 1991. Fertigation/chemigation. Proc. "Expert Consultation". Cairo, Egypt, 8-11 Sept. 1991, AGL/MISC/19/91.
- Halitligil, M.B., A.I. Akin, H. Kislal, A. Ozturk, and A. Deviren. 1998. Yields, nitrogen uptakes and nitrogen-use efficiencies of tomato, pepper, cucumber, melon and eggplant as affected by N rates applied with drip irrigation under greenhouse conditions. Progress Report, Karaj, Iran, 31 Oct. – 4 Nov.
- Hardarson, G. 1990. Use of nuclear techniques in studies of soil-plant relationships. IAEA Training Course Series No 2, IAEA, Vienna.
- Hillel, D. 1994. Rivers of Eden, the struggle for water and the quest for peace in the Middle East, Oxford University Press, Oxford, UK.
- Hobbi, M.S., N. Sageb, A. Mousavi Shalmani, A. Khorasani, and H. Abbasalian. 1998. Field evaluation of urea fertilizer and water use efficiency by tomato under trickle irrigation. Progress Report, Karaj, Iran, 31 Oct. – 4 Nov.

- IAEA, Annual Report, Highlights 97. 1997. Food and Agriculture.
- Janat, M., and G. Somi. 1998. Comparative study of nitrogen fertilizer-use efficiency of cotton grown under conventional and fertigation practices using ^{15}N methodology. Progress Report, Karaj, Iran, 31 Oct. – 4 Nov.
- Kemp, P. 1996. New war of words over scarce water. Middle East Economic Digest, 49: 2-7.
- Kirda, C. 1990. Use of neutron water and gamma density gauges in soil water studies. p. 183-223. *In* G. Hardarson (ed.) Use of nuclear techniques in studies of soil-plant relationships 1990. IAEA Training Course Series No 2, Vienna, Austria.
- Mohamad, M.J.R., M. Omari, S. Zuraiqi, and W. Qawasmi. 1998. Nitrogen and water utilization of trickle-fertigated garlic using the neutron gauge and ^{15}N technology. Progress Report, RAW/5/002. Karaj, Iran, 31 Oct. – 4 Nov.
- Moore, J.W. 1988. Balancing the needs of water use. Springer-Verlag, New York, USA.
- Moutonnet, P., G. Guiraud, and C. Marol. 1995. Assessment of inorganic N in soil solution using Tensionic. *In* Nuclear techniques in soil-plant studies for sustainable agriculture and environmental preservation, Proc. Symposium, Vienna, 17-21 Oct. 1994, p. 411-418.
- Moutonnet, P., and J.C.I. Fardeau. 1997. Inorganic nitrogen in soil solution collected with *tensionics* samplers. *Soil Sci. Soc. Am. J.* 61:822-825.
- Narayanamoorthy, A., 1997. Beneficial impact of drip irrigation: a study based on Western India. *Water Resources Journal*, 17-25.
- Papadopoulos, I. 1995. Use of labelled fertilisers in fertigation research. *In* Nuclear techniques in soil-plant studies for sustainable agriculture and environmental preservation, Proc. Symposium, Vienna, 17-21 Oct. 1994, p. 399-410.
- Papadopoulos, I., 1987. A fertigation system for experimental purposes. *Plant Soil* 102: 141-143.
- Pimentel, D., J. Houser, E. Preiss, O. White, H. Fang, L. Mesnik, T. Barsky, S. Tariche, J. Schreck, and S. Alpert. 1997. Water resources: agriculture, the environment, and society. *BioScience*, 47: 97-106.
- Pitts, D.J., and G.A. Clark. 1991. Comparison of drip irrigation for tomato production in South West of Florida. *Applied Engin. Agric.*, 7: 177-184.
- Polak, P., B. Nanes, and D. Addikari. 1997. A low-cost drip irrigation system for small farmers in developing countries. *Water Res. J., ESCAP*, p. 26-31.
- Shatanawi, M., and M. Fayyad. 1996. Effect of Khirbet As-Samra treated effluent on the quality of irrigation water in the central Jordan Valley. *Water Res.* 30(12):2915-2920.
- Tuijl, W. 1993. Improving water use in agriculture: experience in the Middle East and North Africa. World Bank, Washington, DC.

Water Balance for Optimizing Water-Use Efficiency in WANA Region

Abed Al-Nabi Fardous and Ali Al-Shrouf

*National Center of Agricultural Research and Technology
Transfer (NCARTT), Amman, Jordan*

ABSTRACT

Scarcity of water is the most important factor governing agricultural production in the West Asia - North Africa (WANA) region. Knowing the magnitude and dynamics of different components of the crop-water balance is crucial to develop technological options for sustainable production in this region. In addition to precipitation, a thorough knowledge is required on seasonal values of plant *evapotranspiration, runoff, deep drainage, and soil water storage*. Reducing losses including from evaporation, runoff, weed transpiration, and deep drainage will increase the effectiveness of precipitation in crop production. The objective of this paper is to present improved knowledge on water management so as to increase crop water-use efficiency through increasing plant biomass and harvest index.

Many methods of measuring evapotranspiration are known, such as *soil water depletion, lysimeters, water balance, energy balance, and eddy correlation*. While the methods for estimating evapotranspiration (ET) can be determined using alfalfa or *grass-reference combination empirical equations, radiation methods, temperature, and evaporation methods*, research information on climatic data, water balance and soil hydrological characteristics for the region are inadequate. Major problems with available climatic data include *incomplete and insufficient data*. A few lysimetric studies have been conducted to evaluate crop water requirement and water-use efficiency. The water-use efficiency depends on many factors, including *irrigation management (when and how much to irrigate), irrigation method, planting date, soil surface management, and fertilizer application*.

Information on root characteristics and soil water extraction patterns is not available for most of the major crops. A few data had been collected on runoff which was from either small plots or using a rainfall simulator. Few studies had been conducted to measure soil physical and hydrological properties *in situ*. Crop-water budget studies are needed for: (a) estimating plant-available water storage, (b) integration of climatic data with the water budget components, (c) optimizing water use, and (e) establishment of a data bank on water budget components.

INTRODUCTION

Scarcity of water for agriculture is the main constraint to crop production in arid and semi-arid regions. Therefore, water management is crucial to alleviate adverse effects of drought cycles, which seriously reduce crop production in the WANA zone. While drought is a natural phenomenon in this region, its effects and duration can be reduced through implementing appropriate management on soil, crop and water. Although irrigated agricultural areas can produce two to five times more production than rainfed areas, development of the irrigation area in WANA depends on the availability and management of water resources. Long-term and continuous records of scientifically credible climatic and soil data are a necessary pre-requisite for sustainable development of water resources. Data needed include the main components of the water budget and plant growth.

WATER BALANCE

The hydrological cycle can be described quantitatively by applying the principle of conservation of mass, which is often referred to as a water balance or water budget when used in this way. A simple statement of conservation of mass for any particular compartment (usually referred to as a control volume) is that the time rate of change of mass stored within the compartment is equal to the difference between the inflow rate and the outflow rate. For example, if two grams of water are added to a bucket every minute and one gram of water is leaking out each minute, then the mass stored within the bucket is increasing at the rate of one gram per minute. Symbolically, we can write this as:

Where:

M = mass within the control volume [M]; t = time [T]; I' = mass inflow rate

$$\frac{dM}{dt} = I' - O' \dots\dots\dots (1)$$

[M T⁻¹]; and O' = mass outflow rate [M T⁻¹]. The expressions in square brackets are the mass-length-time dimensions associated with the defined quantity; for example, the dimensions of I' are mass per time or M T⁻¹.

The most commonly used crop- water balance model is given as:

$$ET = P + I - S - D - R \dots\dots\dots (2)$$

Where:

ET is evapotranspiration, P is precipitation, I is irrigation, S is change in

soil water storage, D is deep drainage and R is runoff. The components ET, P, and I are always positive, but the others can be positive or negative. If R is negative, it implies runoff from the surrounding area. Negative S indicates depletion of soil-water reserves, and negative D means upward flow from the groundwater. In practical terms, Equation (2) is better expressed as:

$$P - R - E - T_w - T_c - S - D + I = 0 \dots\dots\dots (3)$$

The term ET of Equation (2) has been separated into three components: E is loss by evaporation from the soil, and T_w and T_c refer to transpiration by weeds and crops, respectively. *The objective of soil and crop management practices is to minimize losses by R, E, D, and T_w while maximizing T_c .*

While models illustrated in Equations (2) and (3) are simple, assessment of different components requires careful experimentation and precise measurements. *Measurement of P and I are usually simple and direct, though a sufficient number of rain gauges are needed to obtain reliable estimates over a watershed.* In principle, *assessment of soil water storage* is also simple and direct. In practice, however, obtaining scientifically credible estimates of soil water storage at the field scale is cumbersome, subject to error because of large spatial and temporal variations, and is a challenge. Most methods have their specific advantages and disadvantages. Furthermore, instruments used for measuring soil water content are usually accurate only for changes longer than a week or so unless large amounts of water are added by rainfall or irrigation.

The *gravimetric technique*, though simple and the most basic, is *destructive, laborious and time-consuming, and highly subject to spatial variations* (Campbell and Campbell, 1982). *Non-destructive techniques* (e.g., neutron moderation) are usually expensive and require careful calibration for all soils and major horizons. The neutron samples a large volume, but the maintenance of equipment is a problem to be considered for operations in Jordan and other countries in the world. In addition, Time Domain Reflectometry (TDR), as a non-destructive technique, is used for measuring volumetric soil moisture. Attempts have been made to standardize methods of measurement of TDR (Lal, 1988).

However, from the standpoint of the practitioner, measurement of soil moisture has remained as much an art as a science. Most methods are based on individual judgment, and are subject to budgetary provisions. Measurement of deep drainage (D) requires information on moisture potential profile (ψ), hydraulic conductivity (K), and depth of zero flux. Assessment of these characteristics under field conditions requires careful instrumentation and precise measurements.

Evapotranspiration (ET) estimates from Equation (2) can be obtained by

several methods; it includes all water lost by evaporation from the soil surface and by transpiration from the surfaces of weed and crop plants. Measurement of actual ET can be done by the lysimetric technique (Harold and Dreibelbis, 1951). Lysimeters are useful because they allow direct measurement of D, and S can be accurately evaluated from total weight change over a known time interval.

Nonetheless, direct measurement of ET is difficult. Indirect estimates are obtained by correlating ET with climatic conditions (Ritchie, 1972), and crop yields (Stewart et al., 1977; Hanks, 1974). In general, dry matter production increases with evapotranspiration, the relationship may be linear (Sorenson et al., 1980). The objective of most models is to increase T_c and harvestable plant biomass, two variables, which are highly correlated. Tanner and Sinclair (1983) developed a relationship between dry matter production (Y_t), crop transpiration (T_c) and average vapor deficit of the air during daylight hours (Δe), which is given as Equation (4):

$$Y_t = K T_c / \Delta e \dots\dots\dots (4)$$

Where:

K is a constant and is influenced by several factors, e.g. canopy structure, plant composition, etc. Total dry matter Y_t can be sub-divided into its components, e.g., grain (Y_g), straw (Y_s) and roots (Y_r). Another model by Stewart AND hAGAN, 1973 is designed to correlated yield with ET, i.e.,

$$Y/Y_p = 1 - b (1 - ET/ET_p) \dots\dots\dots (5)$$

Where:

Y is yield associated with a given value of ET, Y_p is potential yield associated with potential evapotranspiration, (ET_p) and b is slope of the relative Yield (Y/Y_p) vs. relative evapotranspiration relation (ET/ET_p). The value of b is empirically determined. For Equations (4) and (5), R is assumed to be zero, D must also be know or assumed zero, and ET_p must be measured or estimated. The model in Equation (5) suits lysimetric studies. Another model proposed by Hanks (1983) can be written as:

$$Y/Y_p = T/T_m \dots\dots\dots (6)$$

Where:

T and T_m refer to actual and potential transpiration associated with the yield Y and Y_p respectively. The practical problem in using Equation (6) is to be able to divide ET into E and T components. Hanks (1985) has described methods to achieve this. The effectiveness of soil and crop management practices in maximizing Y_t and T_c is usually expressed in terms of water-use efficiency (WUE). In agronomic terms, WUE is a seasonal value defined as Equation (7):

$$WUE = \frac{\text{Yield per unit area}}{\text{Total water used}} \dots\dots\dots (7)$$

Quantitatively, WUE is expressed as Equation (8):

$$WUE = \frac{Y_t/T_c}{1 + (E/T_c)} \dots\dots\dots (8)$$

The numerator in Equation (8) (Y_t/T_c) is the transpiration efficiency. Equation (7) is applicable in situations where the summation of terms $E + T$ equals P , and where the R and D components are practically zero (Cooper et al., 1987). If not, the denominator in Equation (8) must contain all components expressed in Equation (2) as follows in Equation (9):

$$WUE = \frac{Y_t/T_c}{1 + (E + R + D + I)/T} \dots\dots\dots (9)$$

Where:

T_c is crop transpiration and T is the total transpiration including that by weeds. Equations (8) and (9) are extremely useful models because they are indicative of ways in which the WUE of a system can be increased.

All the models described in the Equations from (2) to (9) are simple, and each of the quantities described is considered to be a summation over a cropping cycle. Consequently, these models do not apply under transient conditions with reference to crop transpiration and water uptake at a given point in time. More complex water-balance models are available to achieve these objectives.

Water Balance Method

The principle of the water balance method is illustrated in Figure 1. The object is to obtain a balance of incoming and outgoing soil water so that adequate available water is maintained for the plant. Inputs include incoming water in any form, whether from rainfall or irrigation. Outputs include any type of water removal. Water removal is more commonly referred to as evapotranspiration (ET) is usually expressed in depth (mm or inches) per day. It consists of water removal by the plant (transpiration) and water loss due to evaporation from the soil surface. Two variations of the water balance method are used.

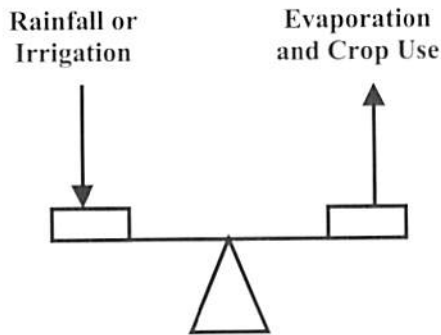


Fig. 1. Principle of the water balance method.

To use either variation soil type and the available water-holding capacity of the soil should be known in addition to the root zone. This zone will vary according to the effective rooting depth of the particular crop. In order to determine the total water available to manage in this zone, it is desirable to try to manage only a percentage of this total water, usually 50 %. As water is removed daily (ET), these amounts are subtracted from the adjusted water available column. When the water available approaches a zero balance it is time to irrigate. The amount to add depends on the soil type, but will usually be the same as the 50 % value calculated earlier plus an added amount to account for application efficiencies less than 100%.

Evapotranspiration may be estimated with a water-balance approach, if the change in storage and all the inputs and outputs except et are known.

$$\frac{dV}{dt} = P(t) + r_{si}(t) + r_{gi}(t) - r_{so}(t) - r_{go}(t) - et(t) \quad \dots\dots\dots (10)$$

Where:

dV/dt : volume of water stored for a given period of time t ; $P(t)$: precipitation rate; $r_{si}(t)$: surface water inflow rate; $r_{gi}(t)$: average groundwater inflow rate; $r_{so}(t)$: surface water outflow rate; $r_{go}(t)$: groundwater outflow rate; and $et(t)$: evapotranspiration rate.

In this equation, the time rate of change in volume of water stored within the control volume (left side) is balanced by the difference between the inputs and the outputs. Each of the terms on the right side of the equation has units of volume per time [$L^3 T^{-1}$], and all are functions of time. Equation (10) may be simplified for some problems, for example, by neglecting r_{gi} and r_{go} when considered unimportant. Once all the terms except et have been measured, then et may be computed as the residual to force a balance that conserves mass in the system.

In many cases, however, the water-balance approach may suffer from the accumulation of errors in the measured variables. It is unrealistic to expect to be able to accurately quantify all the terms in a water balance for a catchment to solve for et , especially over short time periods where storage changes are both significant and very difficult to measure or predict. Furthermore, this is a diagnostic rather than a predictive approach. In many cases, we need to predict the rate of water loss to the atmosphere for certain anticipated conditions.

EVAPOTRANSPIRATION MEASUREMENT

Two methods are used for determining evapotranspiration, *Direct* and *Indirect*.

Direct Measurement of Evapotranspiration

Direct measurement techniques involve isolating a portion of the crop from its surroundings and determining ET by measurement.

Water Balance (Conservation of Mass Technique)

The most widely used direct measurement techniques are based on the conservation of mass principle. The equation defining the conservation of mass principle for the control volume is:

$$\text{Inflow} - \text{Outflow} = \Delta S = D_{rz} (\theta_{vf} - \theta_{vi}) \dots\dots\dots(11)$$

Where:

Inflow and *outflow* equal total flow into and out of the control volume, respectively, during the time interval being considered, cm; S = change in

soil moisture within the control volume during the time interval being considered, cm; D_{rz} = depth of root zone (below soil surface), cm; and θ_{vf} , θ_{vi} = soil moisture contents by volume at end (final) and beginning (initial) of the time interval being considered, respectively.

$$\text{Inflow} = I + P + SFI + LI + GW \dots\dots\dots (12)$$

$$\text{Outflow} = ET + RO + LO + L + DP \dots\dots\dots (13)$$

Where:

I = depth of irrigation, cm; P = precipitation or rainfall, cm; SFI = surface flow into the control volume, cm; LI = subsurface lateral flow into the control volume, cm; GW = ground water seepage into the control volume, cm; ET = evapotranspiration, cm; RO = surface flow out of the control volume, cm; LO = sub-surface lateral flow out of the control volume, cm; L = leaching requirement, cm; and DP = deep percolation, cm. (i.e., downward movement of water from the control volume in excess of that needed for leaching). Combining the inflow and outflow equations gives the final equation:

$$ET = I + P + SFI + LI + GW - RO - LO - L - DP - Drz (\theta_{vf} - \theta_{vi}) \dots (14)$$

The accuracy of ET estimates obtained with this equation is usually low because it is generally difficult to control and/or measure one or more of the terms in the equation.

Energy Balance

The energy balance method of determining E_t can be used for hourly or shorter values, especially during daylight hours. The Bowen ratio approach is the most commonly used method. R_n may be nearly equal to G , and E and H are nearly equal, but with opposite signs. Since the method relies on average gradients determined above the canopy, the calculation of water-vapor flux is independent of stomata or canopy resistance. The accuracy of this method, expressed as a percentage of total flux, as with any method, decreases with decreasing flux of water vapor caused by increasing canopy resistance, low evaporative demand, or both.

Soil-Water Depletion

Soil samples, taken at two different dates and dried in an oven at 105 °C are used to determine the decrease in soil moisture. This is called gravimetric soil moisture sampling. A temperature of 105 °C is used for drying the soil to ensure that only soil water is evaporated. More recently, neutron and other types of soil moisture probes have been used extensively, and generally result in more reliable data.

The major potential error in evapotranspiration determined by this method is caused by drainage from the zone sampled or the upward movement of water from a saturated zone into the zone sampled. These errors are difficult to detect, but they can be minimized with proper precautions. The soil is usually sampled 2 to 4 days after irrigation and again 7 to 15 days later, or just before the next irrigation. The rate of evapotranspiration is calculated using the following equation:

$$E_t = \frac{W_{et}}{\Delta t} = \frac{\sum_{i=1}^{n_s} (\theta_1 - \theta_2)_i \Delta S_i + R_e - W_d}{\Delta t} \dots\dots\dots (15)$$

Where:

$t = (T_2 - T_1)$ time interval between sampling dates (usually days); W_{et} = water used in evapotranspiration, mm; i = an index; n = number of soil layers under consideration; S_i = thickness of the i -th layer, mm; and θ_1 and θ_2 are volumetric water contents on sampling days 1 and 2, respectively, decimal, and R_e is rainfall that does not run off the area in mm, W_d is drainage from the zone sampled in mm (negative for upward flow to the sampling zone).

Determining reliable E_t rates by soil sampling requires adequate precautions such as:

- Using at least six sampling sites representative of general field conditions, a minimum of four may be adequate when using neutron techniques.
- Depth to the water should be much greater than the root zone depth.
- Use only those sampling periods where rainfall is light, all others are questionable because runoff may have occurred and drainage (W_d) may have been excessive.
- Minimize drainage by: (a) applying the pre-plant irrigation at least 10 days before planting, (b) applying less water at each irrigation than the amount that can be retained in the root zone, (c) waiting at least 2 days after a normal light

irrigation before evapotranspiration is small, and (d) using only the active root zone depth for E_r computations.

When using gravimetric sampling procedures, the soil moisture is usually expressed as a percentage on a dry-weight basis, and must be converted to a volumetric basis by multiplying by the bulk density of the soil.

Tanks and Lysimeters

Lysimeters (evapotranspirometers) are tanks filled with soil in which crops are grown under natural conditions to measure the amount of water lost by evaporation and transpiration. The method provides a direct measurement of E_r and is frequently used to study climatic effects on E_r and to evaluate estimating procedures. However, all lysimeter data are not representative of field conditions. Soil conditions inside the lysimeters must be essentially the same crop that is growing in the lysimeter. The lysimeter must be located within a field of the same crop. Studies of advection at edges of fields suggest that locating a lysimeter a distance of at least 100-m from the edge of the field would be desirable. Lysimeters surrounded by sidewalks or gravel will not provide reliable data, nor will lysimeters planted to a tall crop if surrounded by short grass or planted to grass and surrounded by a tall crop.

Differences in growth and maturity between the lysimeter plants and surrounding plants on E_r measured in the lysimeter relative to E_r measured in the surrounding field can be significant (Pruitt and Doorenbos, 1977). Some high crop coefficients reported in previous lysimeter studies may have been the result of such differences in plant growth between the lysimeter and the surrounding field. The ratio of the lysimeter rim-area to lysimeter-area should be less than 0.1. For example, with a 10-mm gap and 5-mm inner and outer walls, this ratio would be 0.08 for a lysimeter that has inside dimension of $1 \times 1_m [4(0.02)(1.02)/1.0]$.

Lysimeters can be grouped into three categories:

- *Non-weighing, constant water-table type*, which provides reliable data in areas where a high water-table normally exists and where the water-table level is maintained essentially at the same level inside as outside the lysimeter.
- *Non weighing, percolation type*, in which changes in water stored in the soil are determined by sampling or neutron methods and the rainfall and percolate are measured (often used in areas of high precipitation).
- *Weighing types*, in which changes in soil water are determined either by weighing the entire unit with a mechanical scale, counter-balanced scale and load cell, or by supporting the lysimeter hydraulically. Weighing lysimeters

provide the most accurate data for short time periods, and E_p can be determined accurately over periods as short as one hour with a mechanical scale, load cell system, or a floating lysimeter. Hydraulically weighed lysimeters are generally not accurate for periods less than 24 hours.

Estimating Evapotranspiration (Indirect Method)

This involves estimating evapotranspiration using historical meteorological and cropping conditions, or predicting future E_p . Both involve meteorological data, but predictions are based on expected meteorological and cropping data. The accuracy of E_p estimates depends primarily on the ability of the equations being used to represent the physical laws governing the processes and the accuracy of the meteorological and cropping data. This also applies to predicted E_p .

Estimates of ET are required in areas where measured ET data are not available. Several theoretical and empirical equations have been developed for computing crop ET. These estimating procedures are based on the correlation of measured ET with one or more climatic factors.

The commonly used methods for ET estimating are:

- Blaney-Criddle,
- Hargreaves,
- Pan Evaporation,
- Penman-Monteith,
- Radiation.

These five methods consider the effect of climate on crop water requirement and use mean daily climatic data for 30 days or smaller periods. ET_0 is expressed in mm per day and represents the mean value over the period chosen for use. The selection of method to use must be based on the type and accuracy of climatic data available and on the accuracy required in determining water needs. Climatic data needed for the different methods are indicated in Table 1.

Soil and Climatic Characteristics of Mediterranean Region

The Mediterranean region is a large area covering semi-arid and wet-dry regions. The region covers the area of West Asia and North Africa (WANA). This zone is characterized by a rainy season of about four to five months (December to April). A short growing season and drought during the crop growth are crucial factors affecting growth and yield. *In situ* conservation of soil and water and

supplementary irrigation, in some years, are important inputs for satisfactory yields. The WANA zone has a growing season length of 4 – 7 months. The mean annual rainfall zone exceeds 700 mm in some areas, and less than 100 mm in the desert area. Up to 10% of the rainfall may occur in a single day, giving very heavy runoff.

Predominant soils of these regions are Entisols, Vertisols, and Inceptisols. Most soils are of low inherent fertility, low in organic matter content, but most of them have high plant - available water capacity. The Vertisols are characterized by swelling during wetting and cracking during drying.

Table 1. Climatic data in relation to ET measurement method.

Method	Temp- erature	Humidity	Wind	Sun- shine	Radiation	Evapo- ration	Enviro- nment
	°C						
Blaney-Cridde	m	+	+	+			+
Hargreaves	m				+		
Pan Evaporation		+	+			m	m
Penman-Monteith	m	*	*	*	x		+
Radiation	m	+	+	*	x		+

(m) measured data, (+) estimated data, (x) used if available, but not essential.

SOIL WATER AND CLIMATIC DATA FOR CROP-WATER BALANCE

The major requirements of water balance studies are: (a) rapid and accurate assessment of changes in water content for the soil profile; (b) measurements of field capacity and permanent wilting point of the root zone, by determination of soil moisture characteristic curves for different depths according to soil layering; (c) assessment of infiltration capacity, runoff rate, and the amount as well as the surface storage capacity; and (d) data on deep percolation, or its estimate, by measuring hydraulic conductivity (K). In addition, detailed measurements are also needed on crop growth and climatic parameters.

Crop growth measurements should include *yield, leaf area index, canopy transpiration rate, and root profile*. Relevant climatic measurements are *daily precipitation and evaporation, net radiation, maximum and minimum temperature, wind speed and relative humidity*. While measurements of crop and climatic parameters are very important, this paper is limited to determination of soil and hydrological characteristic for watersheds and water-use efficiency for some crops grown in Jordan.

A watershed, as a bio-geophysical entity, is an ideal unit to assess crop-water balance. Some examples of the available research information for obtaining

different components of crop water and water-use efficiency balance are briefly described below.

Climatic Data

In Jordan, there are several on-going meteorological stations, which were established during the period between 1920 and 1975. Major problems with the data from these stations are that they are (a) *incomplete* and *insufficient*. Errors in meteorological data can arise from several sources, e.g., *instrument calibration and location, maintenance, reading charts and conversion of units, data management, etc.*

Another major problem is that what information exists has not been adequately and systematically utilized. This is not to say that no attempts have been made to collate the available data and interpret it for land-use planning. Daily and mean monthly records of routinely measured climatic variables were compiled by many researchers and some international organizations, such as FAO. Some examples of the application of the database for planning purposes are available (Samani and Hargreaves, 1988).

While the frequency and intensity of data collection should be strengthened to improve continuity and scientific credibility, it is important that the available information is adequately used. Development of a more detailed daily and weekly climatic database for the agro-ecological zones of the country is strongly recommended. Basic information required includes solar radiation, air temperature, humidity or vapor density, wind speed and precipitation.

The climate data should be used to calculate probabilities and generate data on the onset of assured rains, and occurrence of drought of different duration during the critical stages of crop growth. The information obtained is required for farm management. Many researchers reported that growing season duration, the growing season rainfall and crop yield depend significantly on the onset date of the assured rains. Information of this nature derived from climatic data is a powerful planning tool, and must be used toward planning for sustainable development of land and water resources.

Processes in Plant Canopy

Two factors must be favorable for the canopy to remain alive. *Average net photosynthesis must be positive, and it must remain at non-lethal temperatures.* Net photosynthesis is determined by the environmental factors and by the water balance of the plant. A plant under drought stress exhibits decreased plant water potential and wilting. However, little or no research information exists regarding responses of major crops to drought in the WANA region.

The response can be measured in terms of leaf or root water potential, leaf diffusion resistance for vapor flow, net photosynthesis, plant or canopy temperature, etc. Plant water potential and diffusion resistance for vapor flow change are usually detectable at low soil moisture levels, which can be quickly attained in the coarse-textured soils of low water-holding capacity. Plant response to water deficit is also exhibited in patterns of root growth and water extraction. Root depth must also be known to evaluate the zone of active water extraction. Root distribution is useful parameter that needs to be assessed for a reliable water balance assessment.

Runoff

In many water-balance studies in the rainfed area, runoff (R), deep percolation (D), and upward flow are essentially zero. While this may be true on small plots, they can be major factors under field conditions (watershed). Most soils of the West Asia region are low in organic matter content, contain predominantly high - activity clays and calcium carbonate, and are prone to swelling and crusting and formation of a surface seal. Under high-intensity storms, a large proportion of rain is lost as runoff, especially at the onset of rains when ground cover is scarce and soil surface storage is minimum. The data in Jordan show that the mean annual runoff loss is more than 85% of the total rainfall and in some areas such as Muwaqer, runoff occurs when the rainfall exceeds 3 mm/hr.

Most of the measurements on runoff are made either on small plots or under simulated rains. Although these data are useful, measurements of runoff and deep drainage should be made on agricultural watershed large enough to facilitate normal farm operations. Intensive studies of this nature were conducted at the Center of Water Research and Environmental Studies at the University of Jordan.

Evaporation from Bare Soil

Because vegetation is sparse throughout the WANA regions, evaporation directly from the soil surface represents a major component of the water balance. Even on land that is cropped, soil is likely to contribute at least 40% of the water lost by evaporation during the growing season. Despite the importance of this component, attempts to estimate soil evaporation regionally are very rare.

When after rain, water begins to evaporate from bare soil, it is replenished by the upward diffusion of liquid water from water soil below. Water also diffuses as vapor in a direction determined by gradients of vapor pressure; so, at night, the surface of the soil can be re-wetted by condensation from warmer, deeper soil to a cooler dry surface.

Formal equations for water, vapor, and heat transfer have been used in models that simulate evaporation from soil, but relevant soil parameters are often lacking,

and models become complex when they are extended to take account of processes in the atmosphere as well as in the soil. Initial maximum rate of evaporation determined by weather (E_{s0}) gives way to a rate proportional to the square root of time as well as E_{s0} . Dependence on the square root of time is consistent both with theory for an isothermal column of soil and with field observation on bare soil in the field where vertical gradients of temperature always present.

Figure 2 shows how well the simple theory fits measurements of evaporation from a Vertisol and Alfisol and from a sandy Entisol.

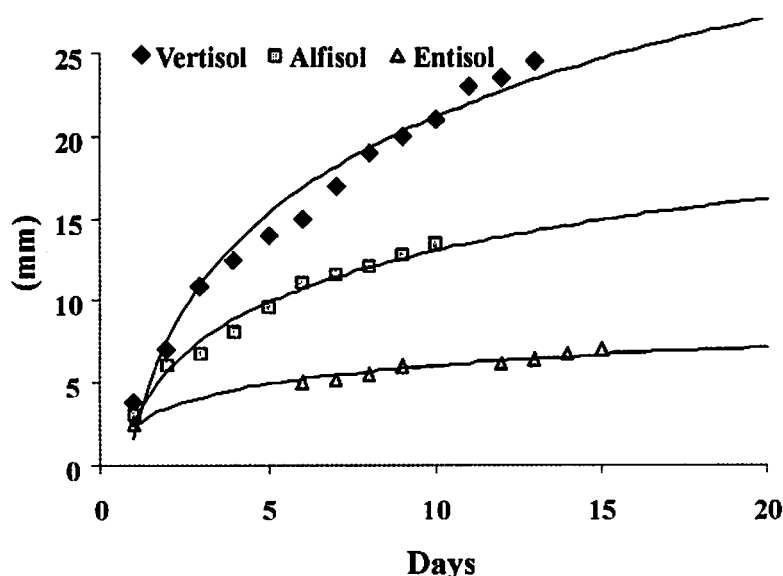


Fig. 2. Cumulative evaporation from three soil types as a function of time after last complete wetting. Points are measurements and curves were fitted using equation with an initial evaporation rate of $ES_0 = 5.0$ mm day.

Evaporation from Vegetation

Potential Transpiration: The term “potential transpiration” is often used to describe the evaporation from a plant stand completely covering the ground and freely supplied with water, a specification drawn up by Penman (1948). A further restriction sometimes imposed is that the vegetation should be “short” because turbulence is more vigorous over a tall crop than over a short one. However, because both latent and sensible heat transfer depend on turbulence and because their sum is constant, one cannot increase without the other decreasing. Commonly, the ratio of the two heat fluxes is such that neither depends strongly either on wind

speed or the aerodynamic roughness of the surface and the turbulence that it generates.

Potential evaporation (E_p), as thus defined, can be determined theoretically or experimentally in a number of ways:

- From the original Penman (1948) formula for evaporation from open water. Penman multiplied this quantity by an empirical season-dependent factor to obtain E_p for vegetation.
- From the Penman-Monteith equation, assuming an arbitrary value for the surface resistance r_s .
- From other physically-based formula, notably that derived by Priestly and Taylor (1972), in which radiation and temperature are the only weather variables, and there is no term equivalent to a surface resistance.
- By direct measurements using lysimeters, by monitoring changes in soil water content, or by measuring fluxes of water vapor in the atmosphere.

The last method is the most reliable but there are few environments in which a uniform stand of vegetation can be readily maintained throughout the year.

Actual Evaporation

The rate of evaporation from a crop stand cannot reach the potential rate, as defined above if :

- The maximum rate of water uptake by roots is less than the demand for water set by the microclimate of the foliage. In this case, leaf cells lose part of their water and stomata close, bringing the rate of transpiration closer to the point at which it matches uptake.
- Ground cover is incomplete so that the amount of radiant energy intercepted by foliage is less than the received on a horizontal surface.
- During dry spell, both these constraints may operate together: reduction of leaf growth and the curling of leaves are mechanisms used by plants to minimize stress during drought.

Soil Physical and Hydrological Characteristics

Soil physical properties exert a dominant effect on soil-water balance, crop production, and water-use efficiency, especially in regions inclined to drought stress. Important soil properties are *infiltration rate*, *water storage capacity* of the soil profile (root zone), *permeability*, and *saturated and unsaturated hydraulic*

conductivity. These properties should be determined either *in situ* or on undisturbed cores. Despite the severe problem of recurring drought, and neglect and mismanagement of soil resources, there is a notable scarcity of reliable data on physical and hydrological characteristics of major soils of the WANA region. Many studies had been conducted in Jordan to determine the soil hydraulic properties including infiltration rate, water-holding capacity, soil-moisture characteristic curve, permeability, and saturated hydraulic conductivity.

Many of these properties had been made *in situ* under field conditions. The *in situ* soil moisture characteristics was measured using a combination of neutron moisture meter or time-domain-reflectometry (TDR) techniques and tensiometric measurements. Although the neutron moisture meter has several advantages, it has limitations for use in heterogeneous soils. For highly variable soils, different calibration curves must be made. The TDR has advantages in measuring volumetric soil water content directly without calibration. Furthermore, obtaining reliable tensiometric measurements can be difficult on gravelly soils, most which are coarse-textured, contain low levels of soil organic matter and are characterized by low levels of water retention.

CONCLUSIONS

While drought is a natural phenomenon in the most area of the WANA zone, the applicability of water conservation problems is severely limited despite available research. The knowledge of the hydrological characteristics of soil, crop, and environment are still limited; the major lack of accurate knowledge is related to soil characteristics due to a large variability within the short distances. In contrast, the rainfall and the conversion rate of solar radiation to sensible and latent heat are relatively uniform process, and, thus, changes in soil moisture content, evaporation, and deep drainage of bare soil profile can be calculated with adequate precision. One difficulty is easily overlooked, i.e., these processes are driven by climatic parameters that are extremely variable from year to year.

It is important to understand rainfall characteristic, e.g., probability of occurrences of a certain amount of assured rains at a given time. Evaluation of different components of water balance is a necessary pre-requisite to maximize crop-water use and minimize losses due to evaporation, weed competition, and surface runoff. Hydrological studies, preferably on well-defined agricultural watersheds as bio-geophysical units, are needed for the following:

- Agro-climatic analysis to determine plant-available water reserves for different soils, regions and cropping systems;
- Integration of climatic data with soil characteristics, and strengthening of databases by the systematic evaluation of soil properties and climatic characteristics;

- Assessment and application of hydrological and soil water theory to benchmark soils, predominant ecological environments and major crops of the region;
- Evaluation of the components of the water balance (e.g., runoff, soil-water storage, soil evaporation, crop transpiration) in relation to cultural practices of soil and crop management; and
- Establishment of databanks based on long-term, continuous and scientifically credible climatic records.

In Jordan, where agronomists continue to examine the value of optimizing water use through field experiments, theory dictates that they should work more on measuring soil and weather data in detail. In addition, they must also collect data on crop leaf-area index development, root system development and activity, and dry matter accumulation rates.

REFERENCES

- Cooper, P.J.M., P.J. Gregory, D. Tully, and H.C. Harris. 1987. Improving water use efficiency of annual crops in the rainfed farming systems of West Asia and North Africa.. *Exp. Agric.* 23: 113–158.
- Campbell, G.S., and M.D. Campbell. 1982. Irrigation scheduling using soil moisture measurements: Theory and practice. *In* D. Hillel (ed.) *Advances in Irrigation*, New York, Academic Press. 8: 25–42.
- Hanks, J. 1974. Model for predicting plant yield as influenced by water use. *Agron. J.* 66: 660–665.
- Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. *Proc. Roy. Soc., London*, 193: 120–146.
- Pruitt, W.O. and J. Doorenbos. 1977. Guidelines for predicting crop water requirements. *FAO Irrigation and Drainage Paper No. 24*. FAO, Rome, Italy.
- Ritchie, J. 1972. Model for predicting evaporation from a row crop with incomplete cover. *Water Resources Res.* 8: 1204–1213.
- Stewart, J.I., and R.M. Hagan. 1973. Functions to predict crop effects of crop water deficits. *ASCE J. Irrigation and Drain.* DW. 99 (IR4): 421–439.

Plant Nutrient Management under Pressurized Irrigation System in the Mediterranean Region: Crop Water Requirements

Pasquale Steduto

The International Center for Advanced Mediterranean Agronomic Studies (CIHEAM), Bari, Italy

ABSTRACT

The determination of the crop-water requirements (ET_c) under irrigated agriculture still relies on the so-called “two-step” approach. The first step consists of deriving the evapotranspiration of a reference crop (ET_o), and the second one consists of utilizing a crop coefficient (K_c) which is supposed to account for the specific crop, stage of development, conditions of soil surface wetness and crop-atmosphere interaction, so that ET_c is the product of such two parameters ET_o and K_c . This approach has been shown to be robust, practical and effective, but also to be prone to some significant uncertainties in its application, particularly in the Mediterranean region.

In this paper, some of the most relevant issues for the correct determination of crop-water requirements are discussed in order to highlight the related risks of errors. The discussion, developed both on theoretical and practical grounds, focuses on: the influence of soil wetness when groundcover by the crop canopy is incomplete (the evaporation component of the evapotranspiration process); the impact of macro-advection on ET_o and K_c ; the way the crop coefficients (K_c) are derived; and the problems encountered when working on tree crops. All these aspects deserve special consideration when operating in arid and semi-arid environments of the Mediterranean region.

INTRODUCTION

Most of the water used by crops (98 to 99%) is lost to the atmosphere as water vapor by evapotranspiration, i.e., the sum of *evaporation*, mostly from the soil, and *transpiration*, the evaporation of water passing through the plant interior and undergoing some physiological control. Strictly speaking, the whole water consumption of crops includes the water used for physiological needs (e.g., protein

synthesis, CO_2 assimilation, etc.). However, the amount of water used for physiological needs is within the same order of magnitude of the errors for the determination of evapotranspiration. Consequently, "crop-water requirement" (CWR) is simply defined as "the amount of water required to compensate the evapotranspiration loss from a cropped field", i.e., the amount of water needed to match crops evapotranspiration (ET_c).

When talking about ET_c , we need to distinguish an *actual* ET_c from a *standard* ET_c , since the first term refers to the evapotranspiration of the crop under the existing conditions (including possible stresses, nutritional unbalances and diseases), and the second term refers to "the evapotranspiration of the crop which is disease-free, well fertilized, grown in a large field, under optimum soil water conditions, and achieving full production under the given climatic conditions". Under irrigated agriculture, where crops are generally not undergoing water stress, we refer mainly to *standard* ET_c .

Another distinction to highlight is the difference between CWR for *planning* purposes and CWR for *management* purposes, since the first refers to the requirement of a crop in a *typical* season (generally considering an average climate or a climate with a certain probability of occurrence) and the second refers to the requirement of a crop during the *on-going* season (the actual climate).

To determine ET_c , either *actual* or *standard*, for planning or for management purposes, there are only two alternatives: *measurements* or *estimates*. For practical applications under irrigated agriculture, the determination of ET_c relies heavily on the *estimates*. Nevertheless, *measurements* of ET_c (generally carried out in research and experimentation) are necessary to derive the parameters to be used in the estimation (e.g., factors, coefficients, etc.). The most widespread criteria to estimate ET_c is represented by the so-called "two-step" approach.

The first step consists of deriving the evapotranspiration of a reference crop (ET_0), and the second step consists of utilizing a crop coefficient (K_c) which is supposed to account for specific crops, stages of development, conditions of soil surface wetness and crop-atmosphere interaction, so that ET_c is the product of such two parameters ET_0 and K_c .

The most relevant publication on this issue was represented by the FAO *Irrigation and Drainage* Paper N°. 24 (Doorenbos and Pruitt, 1977). The "two-step" approach is quite known worldwide, sometimes criticized, but never surpassed by any other approach when dealing with crop water requirements under irrigated agriculture. Even after more than 20 years of progress, the FAO *Irrigation and Drainage* Paper N°. 56 (Allen et. al., 1998), the upgraded version of N°. 24, in fact still relies on the "two-step" approach. This is because the "two-step" approach has shown to be *robust*, *practical*, and *effective*. Unfortunately, it has also shown to

be prone to some significant uncertainties in its application.

Such uncertainties include: the impact of macro-advection on ET_o and K_c ; the influence of the soil wetness when ground cover by the crop canopy is limiting (the evaporation component of the evapotranspiration process); the consequences of improper boundary conditions within which the crop coefficients (K_c) are derived (e.g., fetch problems); and the limitations pertaining the evapotranspiration estimates of tree crops, etc. All these aspects deserve special consideration when operating in arid and semi-arid environments of the Mediterranean region.

This paper will try to elaborate each of these features to give adequate insight to reduce approximation in the estimates, while the reader is referred to other papers for an extended treatment of the two-step approach (e.g., Allen et al., 1998). The discussion will first be developed on theoretical grounds and then be translated into practical applications to improve the estimates.

EVAPOTRANSPIRATION

The Two-Step Approach

The most basic formulation of the evapotranspiration process from a homogeneous and extended cropped surface is represented by the so-called Penman-Monteith "big-leaf" model (Monteith, 1965, 1973) and is expressed by the following equation:

$$\lambda E = \frac{s(R_n - G) + \rho_a c_p g_a (e_s - e_a)}{s + \gamma \left(1 + \frac{g_a}{g_c} \right)} \dots\dots\dots(1)$$

Where:

- λE = latent heat flux density,
- R_n = net radiation at the crop surface,
- G = soil heat flux density,
- ρ_a = air density,
- c_p = specific heat capacity of air at constant pressure,
- e_s = saturation water vapor pressure,
- e_a = actual water vapor pressure,

- Δ = slope of the water vapor pressure curve,
 γ = psychrometric constant,
 g_a = aerodynamic conductance,
 g_c = canopy surface conductance.

By knowing the reflectance characteristics (albedo) of the surface, its aerodynamic parameters (the roughness length z_0 and the equivalent plane, where the kinetic energy of the momentum exerted by the wind motion is extinguished, or zero-plane displacement d), and the canopy conductance, Eq. (1) can be solved straightforwardly.

When the evapotranspiration of the cropped surface (ET_c) is calculated directly through Eq. (1), one is actually using what is named as the “one-step” approach. Thus, in principle, the one-step approach can be used by adjusting the albedo, the aerodynamic and the canopy surface conductance to the characteristics of the specific crop. These adjustments, however, are difficult to make, and they may vary continuously during the growing season. Furthermore, the canopy conductance will be influenced also by the water status of the soil. As there is still considerable lack of information on these aspects, the one-step approach cannot be reliable to calculate ET_c . Then, a more reliable criterion to estimate ET_c remains the “two-step” approach that separates the integrative measure of the atmospheric capacity to supply energy and carry away the water vapor (ET_o) from the crop/field component of the evapotranspiration process (K_c). While ET_o is an expression of the effect of the weather on ET_c , K_c is a measure of the “wetness” and “roughness” of the field (Hsiao, 1990), so that:

$$ET_c = ET_o \times K_c \dots\dots\dots (2)$$

Eq. (1) is used to calculate ET_o , as it represents the ET_c of a specific crop, which remains the same everywhere and all the time, and K_c is derived experimentally. We will now examine the insight features pertaining to the terms of Eq. (2).

The Determination of ET_o and the Advection Problem

The climatic demand for water (or evaporative demand) by the atmosphere, can be

expressed as the evapotranspiration of a specific crop that can be taken as a *reference*. In this case, we refer to the *reference crop evapotranspiration* (ET_0). The most convenient *reference crop* would be one which is able to keep full groundcover all the year around to avoid the complication introduced by the soil evaporation. Originally, ET_0 has been defined as “the rate of evapotranspiration from an extensive surface of 8 to 15-cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short in water” (Doorenbos and Pruitt, 1977).

Thus, a cool-season grass (i.e., *Lolium perenne*, L.) or a tall grass (i.e., *Festuca arundinacea*, L.) became the most spread *reference crops* for ET_0 . In some arid climates, alfalfa (*Medicago sativa*, L.) was used in place of grasses for its higher ability to withstand drought conditions. Whatever *reference crop* is adopted, the choice was, anyway, for a *real* or *living* crop, which needed perfect management (irrigation, fertilization, cuttings, health-care, etc.) in order to properly match the definition. Furthermore, a *living* crop could suffer in particular climatic conditions, notwithstanding the availability of water.

Typically, ET_0 was measured, as ET_c , by lysimeters (e.g., drainage, constant water-table, weighing, etc.) to test the various “equations”, “models” or “methods” of estimating ET_0 . The FAO Paper 24 (Doorenbos and Pruitt, 1977) suggested four methods as most suitable for estimating ET_0 : *Blaney-Criddle*, *Radiation*, *Pan evaporation*, and *Penman*. In the cited order, they represent an evolutionary trend where the process of evapotranspiration accounts for more and more factors entering into play, i.e., temperature, radiation, vapor pressure deficit of the atmosphere, and wind. Unfortunately these methods needed rigorous local calibrations, and the resulting calibration factors proved to have limited global validity, i.e., they behaved differently in different locations.

For instance, the radiation method shows good results in humid climates while tending to underestimate ET_0 in arid climates. The FAO-Penman, on the other hand, frequently tends to overestimate ET_0 . The Pan-evaporation method reflects the shortcomings of predicting evapotranspiration from a free-water surface, and it is susceptible to the micro-climatic conditions under which the pan is operating and to the rigor of the station maintenance.

Nevertheless, the Penman equation was the most mechanistic method to model the evapotranspiration process that could be proposed at that time. Its weakness, though, derived from the wind function which empirically attempted to account for both aerodynamic and canopy conductances. Thus, after a long world-wide experimentation and the recognition of the limitations shown by the various methods, the Penman-Monteith (PM) method was introduced by FAO for the estimation of ET_0 (Allen et al., 1994a, 1994b; 1998).

The PM equation is the natural extension of the Penman equation where the

previous weaknesses were overcome, since the aerodynamic conductance is expressed on the basic theory of fluid dynamics and the canopy conductance is parameterized according to a physiological expression of the reference crop. Furthermore, the reference crop can be abstracted from a *living* form to take a *hypothetical* form.

In fact, according to the new FAO Paper N° 56 (Allen et al., 1998), the actual definition of ET_0 is “the rate of evapotranspiration from a *reference surface*, i.e., a *hypothetical* grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23. The *reference surface* closely resembles an extensive surface of green, well-watered grass of uniform height actively growing and completely shading the ground”.

In the *hypothetical* reference crop, the inconveniences related to the management, maintenance, and response under different climate, pertaining to a living crop, have been avoided so that the FAO Penman-Monteith method (FAO-PM) is recommended as the sole standard method to compute ET_0 (Allen et al., 1998). The standard equation to use is:

$$ET_0 = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{900}{T + 273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)} \dots\dots\dots (3)$$

Where:

- ET_0 = reference evapotranspiration (mm day^{-1}).
- R_n = net radiation at the crop surface ($\text{MJ m}^{-2} \text{ day}^{-1}$).
- G = soil heat flux density ($\text{MJ m}^{-2} \text{ day}^{-1}$).
- T = mean daily temperature at 2-m height ($^{\circ}\text{C}$).
- u_2 = mean daily wind speed at 2-m height ($^{\circ}\text{C}$).
- e_s = saturation water vapor pressure (kPa).
- e_a = actual water vapor pressure (kPa).
- Δ = slope of the vapor pressure curve, also indicated with s , ($\text{kPa } ^{\circ}\text{C}^{-1}$).
- γ = psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$).

The calculation procedure for R_n , G , e_s , e_a , Δ and γ are reported in Allen et al. (1998).

Similar to the previous methods, the FAO-PM equation is also being tested widely to observe its performance under different climatic conditions. According to some studies in the US (Jensen et al., 1990) and in Europe (Choisnel et al., 1992), the FAO-PM proved to be relatively accurate and consistent in both arid and humid climates. A relatively conflicting result appears, instead, for a study in the Mediterranean (Steduto et al., 1996) and in Southern Spain (Berengena and Fereres, personal communication) where a fairly evident underestimation of ET_o was observed when compared with lysimeter data. One of the major causes for such underestimation is attributed to the macro, or regional, advection which occurs in some arid regions of the Mediterranean, where a sort of oasis-effect prevails due to the low ratio between irrigated and arid surface areas.

To better appreciate the issue of advection, one should have a measure of the energy balance at the surface, which can be expressed as:

$$R_n + H + \lambda E + G = 0 \dots\dots\dots (4)$$

Where:

R_n , H , λE and G are the net radiation, the sensible heat, the latent heat and soil heat fluxes (in $W\ m^{-2}$), respectively.

Figure 1 shows the examples of diurnal changes in the principal components of the energy balance (R_n , λE , H and G) for three different surfaces having particular boundary conditions. Clearly, the major driving force in each case is radiation, but the responses of λE , H and G are quite different in each case. Note that, to have clearer plots in these diagrams, the sign convention is positive, when R_n is directed downward and negative when R_n is directed upward, while the sign is positive upward and negative downward for the other terms (λE , H and G).

The upper and lower plots (Fig. 1a, 1c) are examples from a well watered cropped surface and from an almost dry surface, respectively. For the case of Fig. 1a, the net radiation curve suggests clear skies throughout the 24-hour period, with net radiation having a value of about $-90Wm^{-2}$ throughout the nocturnal period of radiation cooling, switching sign about one hour after sunrise, peaking at solar noon at a little more than $500\ Wm^{-2}$, and reversing sign again about an hour before sunset.

During the daytime, when $R_n > 0$, most of the radiant energy absorbed by the surface (a grass crop) is consumed by the evaporation process (λE), while smaller amounts contribute to heating the air (H) and soil (G). At night, the radiant energy lost by the surface is replaced by fluxes from both the subsoil and from the air as the surface temperature decreases below air and sub-surface values, and also, in part, by condensation in the form of dew (presumably) in the early morning hours.

In sharp contrast is the example of Fig. 1c, where measurements were made over a bare and dry soil. Here, with hardly any moisture in the soil, the rate of evaporation is barely measurable and all of the incoming radiation during the daytime serves to heat the air and the soil. In the early part of the day, G exceeds H while, for the remainder of the daylight hours, their roles are reversed. Figure 1b, instead, shows the energy balance for a grass surface that responds in a quite different manner from the other two examples.

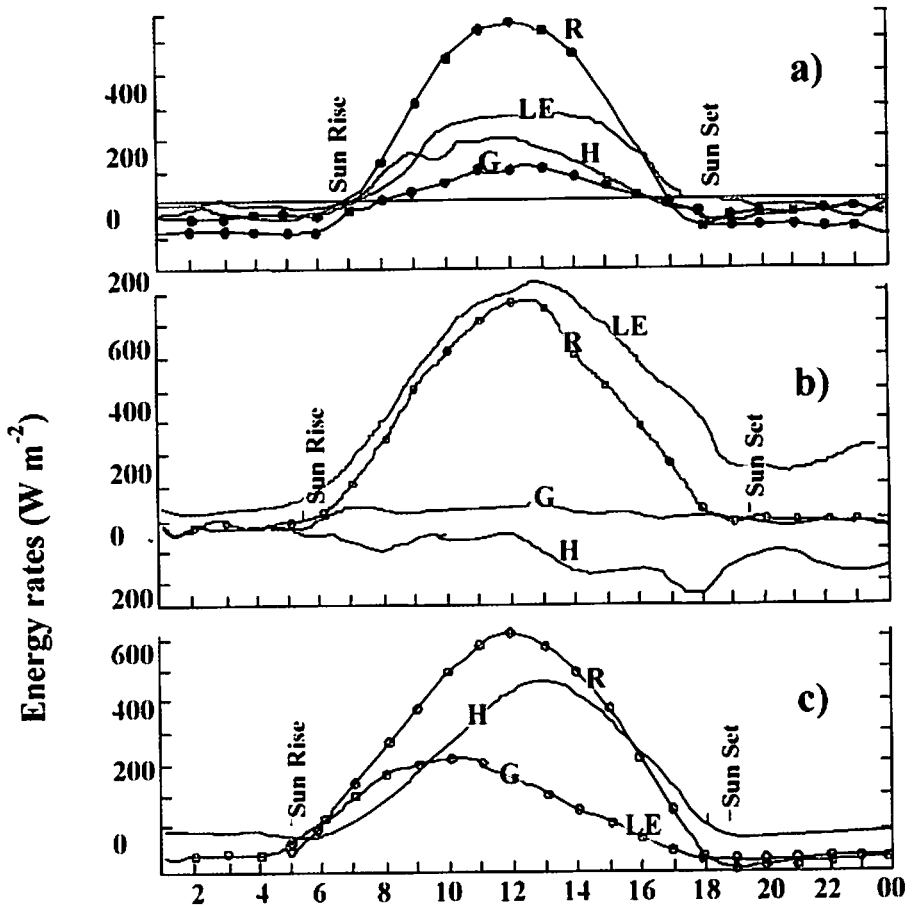


Fig. 1. Examples of diurnal changes in the energy balance of surfaces having different boundary conditions (See text for explanation).

It no longer appears to be a question of partitioning R_n between H , λE and G , since λE now exceeds the net radiation throughout the 24-hour period, although λE and R_n are clearly in phase. Nearly all of the available radiant energy is consumed in the evaporative process, but there is an additional energy source that allows λE

to exceed R_n . This energy is taken from the air (H occurs as a downward heat flux), which is maintained by horizontal advection of warm dry air from the surrounding land. This is typical of irrigated agriculture where evapotranspiration from irrigated vegetation keeps the surface temperature below air temperature causing heat exchange from the air to the surface.

All of the land sites we have looked at so far can be explained primarily by the partitioning of the available radiant energy between H , λE and G according to surface and sub-surface properties. Heat stored in the subsoil is not readily available because of its poor conductivity, indicating that the surface and subsoil are poorly coupled. In such a case, the surface temperature, as well as the vapor pressure, if the surface is moist, responds strongly to incoming solar radiation. This is not necessarily the case with large bodies of water, since the heat storage is generally large and vertical mixing within the water body is effective, so that diurnal changes in surface temperature are minimal. Thus, evaporation from the surface is driven by a vapor-pressure gradient which is not strongly related to solar input. Another difference arises because currents are capable of transporting large quantities of heat into and out of a volume fixed in space.

The case of Fig. 1b is expected in quite a few situations of the Mediterranean region in which the FAO-PM appears to underestimate ET_0 . Why, then, should the FAO-PM equation underestimate under regional advection? There are at least four reasons:

1. Determination of water vapor-pressure deficit (VPD) from minimum and maximum, rather than from hourly integrations of air temperature (T) and relative humidity (RH).
2. Fictitious increases in net long-wave radiation (R_{nl}) under advection.
3. Canopy resistance is considered constant under different climatic conditions.
4. Dissimilarity between aerodynamic conductance for water vapor and sensible heat under stable conditions.

Concerning Point 1, it should not be overlooked that while VPD is derived from the min and max T over 24-h data, the reference crop's evapotranspiration is dominated by the energy and mass exchange experienced during daylight hours. It is interesting to note how the evolution of the ET_0 formulas moved toward the actual physiology of a crop, reaching its highest evolution with the Monteith introduction of the canopy resistance term, while the climatic variables entering the equation are still bounded to the 24-h average, min and max values.

In dry climates, the daily excursion of temperature can significantly influence the VPD derivation. The lower the value of T_{min} , in fact, the lower the

value of VPD for the same $T_{\max}$ and relative humidity (RH). This can be seen in Fig. 2, where the VPD is calculated according to a $T_{\max}$ of 35 °C, $RH_{\max}$ of 80% and $RH_{\min}$ of 40%, while $T_{\min}$ is made variable. It is quite evident that this effect may play a variable role in the calculation of evapotranspiration.

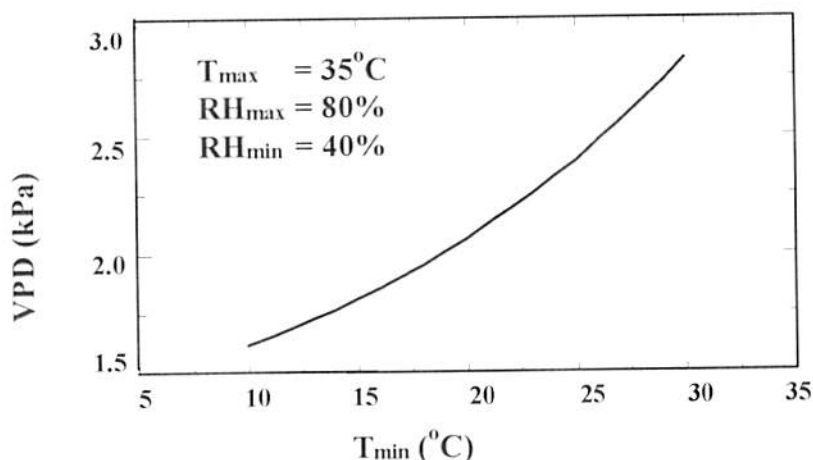


Fig. 2. Variation of vapor pressure deficit (VPD) with variable temperature excursion obtained by keeping constant max at 35 oC, RHmax at 80%, RHmin at 40%, and changing Tmin.

Concerning Point 2, it should be recognized that the net long wave radiation is calculated as:

$$R_{nl} = \sigma \cdot \left[\frac{T_{\max,K}^4 + T_{\min,K}^4}{2} \right] \cdot (0.34 - 0.14 \cdot \sqrt{e_a}) \cdot \left(1.35 \frac{R_s}{R_{so}} - 0.35 \right) \dots\dots(5)$$

Where:

- R_{nl} = net outgoing long-wave radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$).
- σ = Stefan-Boltzman constant ($4.903 \cdot 10^{-9} \text{ MJ K}^{-4} \text{ m}^{-2} \text{ day}^{-1}$).
- $T_{\max,K}$ = max air temperature over the 24 hr period ($K = ^\circ\text{C} + 273.16$).
- $T_{\min,K}$ = min air temperature over the 24 hr period ($K = ^\circ\text{C} + 273.16$).
- e_a = actual atmospheric vapor pressure (kPa).

R_s = actual solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$).

R_{so} = calculated clear-sky solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$).

Since the temperature excursion makes a large change in $T_{\max}$ and $T_{\min}$, and since these values in Eq. (5) are risen to the fourth power, it can be easily noticed how the R_{nl} can also take, in this case, variable figures depending on $T_{\max}$ and $T_{\min}$ of the day. This can also be seen in Fig. 3 where the same conditions of Fig. 2 are utilized. Since the net radiation (R_n) is calculated as difference between net short-wave radiation (R_{ns}) and net longwave radiation (R_{nl}), it is evident the impact of the temperature excursion on R_n .

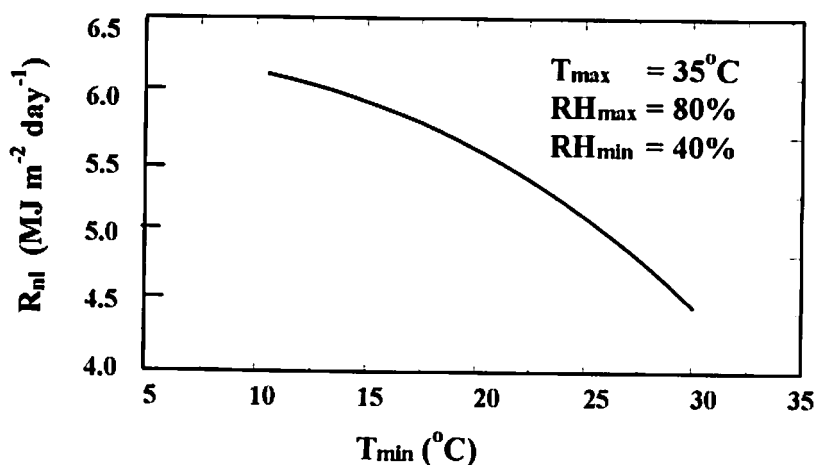


Fig. 3. Variation of net long-wave radiation (R_{nl}) with variable temperature excursion obtained, as in Fig. 2, by keeping constant $T_{\max}$ at 35°C , $\text{RH}_{\max}$ at 80%, $\text{RH}_{\min}$ at 40%, and changing $T_{\min}$.

Furthermore, it should also be recognized that, under regional advection, the air temperature is higher than the actual surface temperature of a full transpiring crop by several degrees and that this overestimates the R_{nl} . In Fig. 4 is shown the percentage overestimate in R_{nl} according to the difference between air and surface temperature.

Concerning Point 3, it should be recognized that the canopy resistance, more properly called surface resistance, does not represent a purely physiological term (Baldocchi et al., 1991; Finnigan and Raupach, 1987) in that it includes additional climatic components (e.g., radiation load). In other words, the partitioning of the available energy into latent and sensible heat depends not only on the aerodynamic

and canopy resistance but also on the general nature of the prevailing climatic and weather conditions of the location (Verma et al., 1986). The canopy resistance can then assume different values depending on such prevailing conditions and, under regional advection, low values are expected. The impact of climate on the canopy resistance and, in turn, of the canopy resistance on evapotranspiration is currently under study (Rana et al., 1994; Steduto et al., 1999).

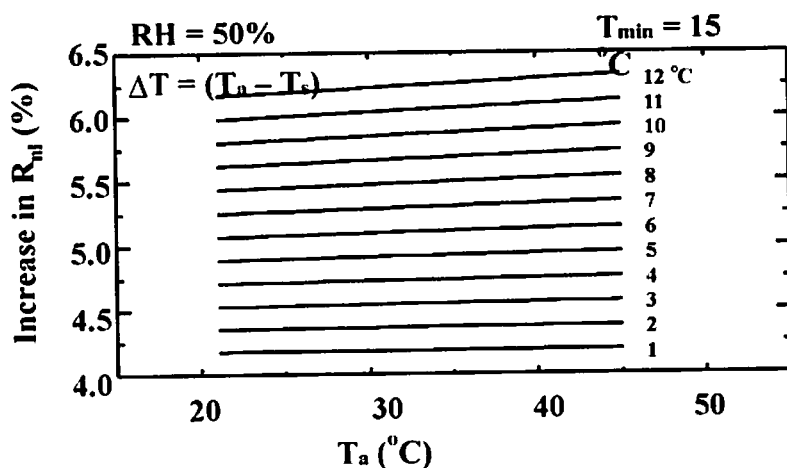


Fig. 4. Percentage overestimation of net long-wave radiation (R_{nl}) at different air temperature (T_a) and variable difference in air-to-surface temperature (ΔT) for a case of $RH=50\%$ and $T_{min}=15^\circ\text{C}$.

Concerning Point 4, it should be recognized that the calculation of the aerodynamic conductance assumes the conditions of neutral stability of the atmosphere, i.e., temperature, water vapor and wind velocity distributions follow nearly adiabatic conditions (sensible heat = 0). Although the conditions of stability do not occur for long periods of time during the day, stability correction is generally not required under well-watered conditions provided the heat exchange between the crop surface and the atmosphere is small. This can be the case for unstable conditions (heat exchange from the surface toward the atmosphere) but not for stable conditions (heat exchange from the atmosphere toward the surface), as in the case of regional advection.

While the bulk of available evidence indicates that the eddy-transfer coefficients (an expression of g_a) for water and heat are about the same under both neutral and unstable atmospheric stability (Dyer, 1974), there is experimental evidence of eddy-transfer coefficients for heat being larger than the one for water under stable conditions (Motha et al., 1979; Verma et al., 1978), with underestimation of latent heat flux (measured with a micro-meteorological method)

by about 20% compared to the lysimeter (Blad and Rosenberg, 1974) under large regional advection. This is an issue that deserves further independent study. Thus, all previous points may play a variable role in the underestimation of ET_0 by the FAO-PM equation.

The Determination of K_c and the Fetch Requirement

I would like to draw the attention also on a second feature of the CWR in relation to the two-step approach. When looking at the definition of ET_0 and ET_c , there is one very important qualification that is frequently overlooked, i.e., the evapotranspiration under consideration must come from an “extensive surface” or “large field”. In other words, the issue of an adequate fetch (the distance between the measurement site and the border of the field, in the upper-wind direction) must be properly considered.

Since in agriculture we generally confine the flux exchange between a crop surface and the atmosphere to a one-dimensional (vertical) treatment, a basic requirement for a correct approach to the problem is that all measurements have to be made within the adjusted and equilibrated internal boundary-layer.

Abrupt changes introduced at the edge of a surface produce a discontinuity in the stratification of various scalars above the surface. The impact of such discontinuity is not negligible when the surface is of limited extent. Due to this change in stratification, the wind velocity profile and the turbulent structure of the air are not in equilibrium with the changed surface conditions. The region of the atmosphere above the surface affected by such a change is referred to as the internal boundary layer (Brutsaert, 1982). A schematic view of the boundary layers establishing over a crop is shown in Fig. 5.

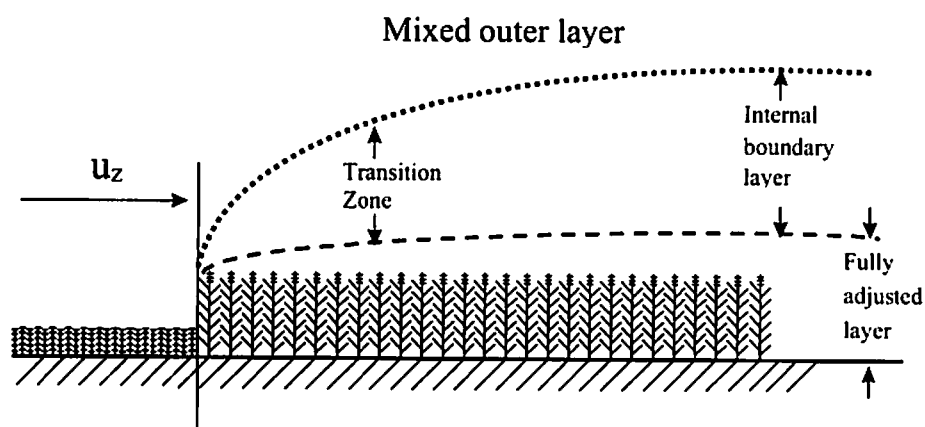


Fig. 5. Schematic representation of the boundary layers establishing over a crop.

Experimental studies in fluid dynamics showed that the internal boundary layer over a surface, after an abrupt change in surface roughness, grows according to the 4/5 power of the distance from the upwind edge. Munro and Oke (1975) suggested, for neutral conditions, that the thickness of the internal boundary layer (δ) over a crop surface is a function of the fetch from the upwind edge (x) and the roughness parameter (z_0) of the surface, according to:

$$\delta = x \left(\frac{4}{5} \right) z_0 \left(\frac{1}{5} \right) \dots\dots\dots(6)$$

The lower portion of this region, where wind velocity profiles are considered to be in full equilibrium with the surface, is indicated as an internal equilibrium sub-layer (Brutsaert, 1982). Peterson (1969), Shir (1972), and Rao et al. (1974), using higher-order closure models, found that the equilibrium sub-layer is only about 10% of the internal boundary layer thickness (δ), for a transition from smooth-to-rough surface, and only about 5%, for a transition from rough-to-smooth surface.

Fetch-to-height ratios have been derived from experimental results, to provide practical estimates of the relative thickness of the equilibrium sub-layer, with values ranging from 10:1 (Panofsky and Townsend, 1964) to 200:1 (Dyer, 1965), and an overall suggested average of 100:1 (Monteith, 1973; Rosenberg et al., 1983).

If we consider that agrometeorological stations have sensors typically placed at two meters, this means that it would be needed a fetch of about 200 m in order to be in the equilibrated boundary layer above the crop surface (say, grass) on which the station is standing. If wind has variable direction, to be safe, the 200 m should be considered as the radius of the surface where the station is at the center. This results in a surface area of about 12.5 ha. When the meteorological stations are surrounded by a large uniform cropped area, there is no significant problem of representativeness.

However, this is not the case for many actual situations where the agrometeorological stations are surrounded by different, non-uniform crops, not necessarily all under irrigation. Even worse is the case when we are growing the crops on the lysimeter to determine ET_c . The fetch in such cases is absolutely inadequate for 90% (or more) of the situations. This poses a great problem in the derivation of the K_c value since these are a ratio ET_c/ET_o . In fact, if ET_o is derived by FAO-PM (making use of the agrometeorological station with its own fetch, plus the possible problem of advection) and ET_c is derived by the lysimeters (having a completely different fetch and with generally enhanced evapotranspiration due to the micro-advective conditions), the resulting ratio can be fairly high as consequence of the inadequate boundary conditions of the corresponding measurements.

The Climatic Influence on K_C

We will now consider the theoretical expectation of the maximum K_C values under proper boundary conditions and how they may change under different climatic conditions. A dimensional analysis of the expected maximum K_C can be evaluated making use of the PM equation for both the actual crop evapotranspiration (ET_C) and the reference crop evapotranspiration (ET_0) so that:

$$K_C = \frac{ET_C}{ET_0} = \frac{s(Rn-G)_{[crop]} + \rho_a c_p g_{a[crop]} (e_s - e_a)}{s + \gamma \left(1 + \frac{g_{a[grass]}}{g_{e[grass]}} \right)} \cdot \frac{s(Rn-G)_{[grass]} + \rho_a c_p g_{a[grass]} (e_s - e_a)}{s + \gamma \left(1 + \frac{g_{a[crop]}}{g_{e[crop]}} \right)} \dots (7)$$

Where:

The different terms are already defined.

Considering to be under full ground cover and maximum vegetative crop development, the following inferences can be drawn:

1. The variation of $Rn-G$ over green vegetation coming from any field crop is negligible, so that no difference in $(Rn-G)$ can be really important in the difference observed as evapotranspiration between the grass and the actual crop.
2. The variation of g_c between a grass and another field crop can be actually relevant, though the impact of g_c on evapotranspiration, when the crops are at full ground cover and under well water conditions, is also negligible since the limiting factor for evapotranspiration in this case is the climatic demand and not the resistance of the crop to the water vapor flux.

This can be seen in Fig. 6, where the variation of actual to maximum ET_C of a maize crop is reported as function of g_c (Steduto and Hsiao, 1998). After g_c reaches the value of 15 mm s^{-1} , the further increase of g_c has a sharp decreased impact on ET_C . This value is about the same value of g_c suggested for grass in the FAO-PM. Then, the conclusion is that, under well-watered conditions, the difference in g_c between grass and actual crop can also be considered negligible.

3. A noticeable difference between the grass and the actual crops, instead, is definitely in their height and architecture of the vegetative habits, which makes a difference in the zero-plane displacement (d) and roughness of the

surface (z_0), which, in turn influence the magnitude of the aerodynamic conductance (g_a). The impact of a different habits of the crops (height and roughness) on the ratio ET_c/ET_0 is, however, of the order of 20%. Then, it should be clear that the maximum expected K_c should not be more than 1.2 – 1.25, even under large advective conditions. In fact, the advective conditions should be considered for both reference and actual crops.

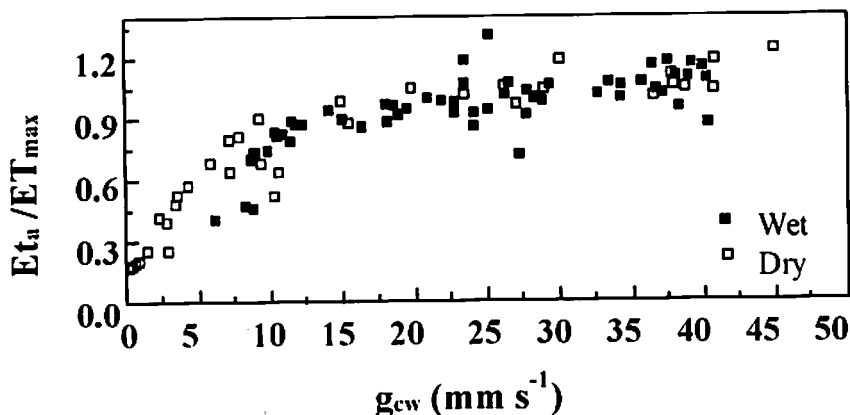


Fig. 6. Daily ET_a/ET_{max} versus midday canopy conductance (g_{cw}) for the irrigated (WET) and non irrigated (DRY) maize crop (Steduto and Hsiao, 1998).

A variable impact, instead, can come from the atmospheric humidity conditions. If the humidity conditions of the atmosphere would be close to 100% (saturated conditions or $VPD=0$), there would not be any difference between the evapotranspiration of the reference and the actual crop, regardless as the differences in height and roughness, because the aerodynamic conductance have no impact (we have equilibrium evaporation). In this case, indeed, the K_c would be equal to 1.

The magnitude of the effect of wind speed (and thus g_a) on the evapotranspiration, under warm and humid and under dry and hot weather conditions, is shown in Fig. 7.

From this, it can be easily seen that the aerodynamic effect on evapotranspiration is damped with the increase in vapor pressure of the atmosphere. Such expression of the weather on the evapotranspiration thus reflects on the K_c and explains the variability observed with crop coefficients in different environments.

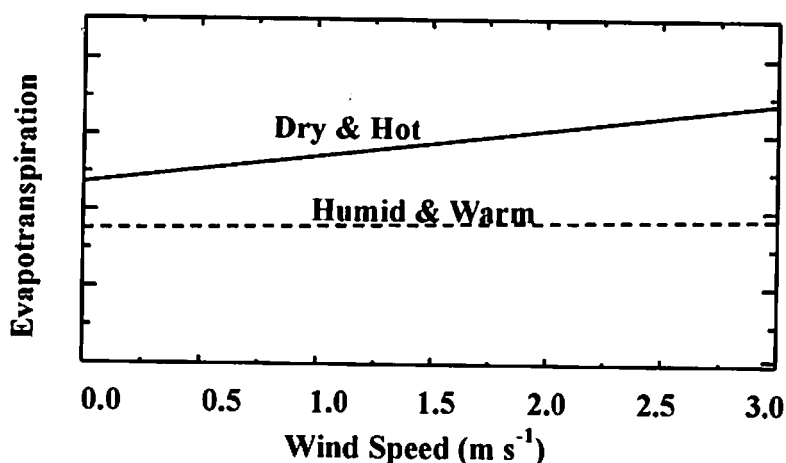


Fig. 7. Influence of wind speed on the magnitude of evapotranspiration in dry and hot conditions, as compared to humid and warm conditions.

However, from the above analysis, it must be recognized that there is an upper limit for the crop coefficients that should be no more than 1.25. When K_c values larger than this value are observed in experimental conditions, one should be aware that some boundary conditions of the system under study are not appropriate. It may happen that the ET_c is well measured, but the ET_o is underestimated (e.g., as a result of the FAO-PM equation under regional advective conditions), or that the ET_o is measured correctly but ET_c is overestimated (e.g., due to micro-advection coming from the lysimeter surrounding).

The K_c under Incomplete Ground Cover

We have considered how air moving over an aerodynamically rough field is more turbulent than that over a smooth field, and hence is more effective in carrying energy to and remove water vapor from the field. For herbaceous crops, this effect is not major. The evapotranspiration from a tall row crop such as maize is only about 15% or 20% greater than evapotranspiration from a smooth short grass when both are well supplied with water, fully covering the ground, and actively growing. On the other hand, evapotranspiration can be influenced markedly by the “wetness” of the field. For a field of bare soil, its “wetness” would be determined by the water status of the soil surface and its temperature, which affects water vapor pressure at the surface. Soil evaporation (E_s) can be separated into three stages (Fig. 8).

Neglecting the third stage, because of the low contribution to the whole evaporation process, we can distinguish: *Stage I*, when the soil surface is fully wet

and E_s is determined by the atmospheric evaporative demand; *Stage II*, when, due to drying of the surface, water vapor pressure at the surface (and consequently water vapor-pressure gradient from the surface to the air above) is reduced sufficiently to depress evaporation. During *Stage II*, E_s declines continuously with time, first rapidly and then more and more slowly, as the surface dries out (thus entering *Stage III*). When rain or irrigation wets the surface again, the cycle is repeated, starting with the *Stage I* rate.

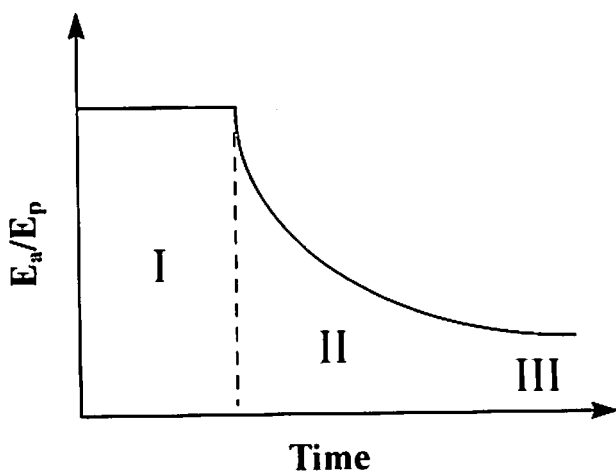


Fig. 8. Relationship of relative evapotranspiration rate (E_a/E_p) to time, indicating the three stages of soil-drying process. Stage I, $E_a/E_p=1$; Stage II, there is a rapid decline of E_a/E_p ; Stage III, E_a/E_p proceeds with minimum values and does not change much with time.

For a field fully covered by foliage canopy of the crop, its “wetness” would be determined by the temperature of the leaves and the extent of opening of their stomata. Open stomata permit the ready diffusion of water vapor from the leaf interior to outside, making the surface of the crop canopy essentially “wet”, much like the wet surface of a soil. Partly closed stomata conduct water vapor less readily, making the canopy surface less wet, and hence restricting transpiration.

The occurrence most encountered in the practice of agricultural systems does not lie at the two extremes of complete bare soil or complete ground cover by crops, but rather in dynamic intermediate conditions where incomplete ground cover may persist (e.g., tree crops) or a transition from bare soil to partial or full ground cover (e.g., annual field crops) may develop over a period of time.

Then, if the crop canopy covers the soil only partially, e.g., as is the case when a field crop is young and canopy still developing, the “wetness” of the field would be the combined wetness of the soil and of the crop canopy, approximately in

proportion to the relative land areas occupied by them. The climatic factors and the roughness of the field determine the rate of evapotranspiration as long as the surface of the field is effectively fully wet. When the soil surface begins to dry out, and when the stomata of the crop begin to close sufficiently, the surface of the field would be less than fully wet, and evapotranspiration then slows below the potential rate.

Even when well supplied with water, ET_c is below potential, and K_c is less than 1.0, in the early growth stages. As mentioned, that is because the field is less than fully "wet" for much of the time due to the incomplete canopy cover of the ground and the drying out of the soil surface. Customarily, K_c for that period is determined empirically, and is often taken to be rising linearly with time. This approximation recognizes that much of the change in ET_c is the result of the growth and enlargement of canopy cover, but obscures the fact that ET_c is also a function of the wetting of soil surface, as discussed below.

During the canopy development stage, transpiration (T) increases as the result of the enlargement of the canopy or transpiring surface area. Equally important is the fact that an enlarging canopy intercepts more and more radiation and hence absorbs more energy for transpiration. Also, the radiation intercepted by the canopy does not reach the soil, so evaporation from the shaded part of the soil is greatly reduced.

As a first approximation, soil evaporation (E_s) can be assumed to be confined to the unshaded portion and T can be assumed to be at the potential rate but confined to the fraction of the land area covered by the canopy. Of course, this assumes that soil water supply to the roots is ample and stomata remain open. To better visualize the separate effects of soil wetting and canopy development, a computer simulation of E_s and T separately and their sum, ET , for an average daily weather at middle latitude, is presented in Fig. 9. The simulation is derived and modified from Ritchie (1972) and is based on the aforementioned assumptions of Stage I and Stage II evaporation. In Fig. 9, the peaks of soil evaporation are the result of irrigation water wetting the soil surface.

The decline in E_s after the initial wetting is the result of shifting from Stage I to Stage II evaporation after the first day, when the soil surface begins to dry. With time, the maximum peak height of this "irrigation spikes" decreases because a greater proportion of the soil surface is shaded by the enlarging canopy. Transpiration is very low at the beginning because of the very small leaf area of the plants and canopy cover, and increases with time as the canopy develops. The sum of E_s and T , ET , shows the combined effect of wetting and drying of the soil surface and of canopy development. The differences in the pattern and cumulative amount of ET due to different frequencies of soil wetting and rates of canopy development can be seen by comparing part A and B of Figure 9.

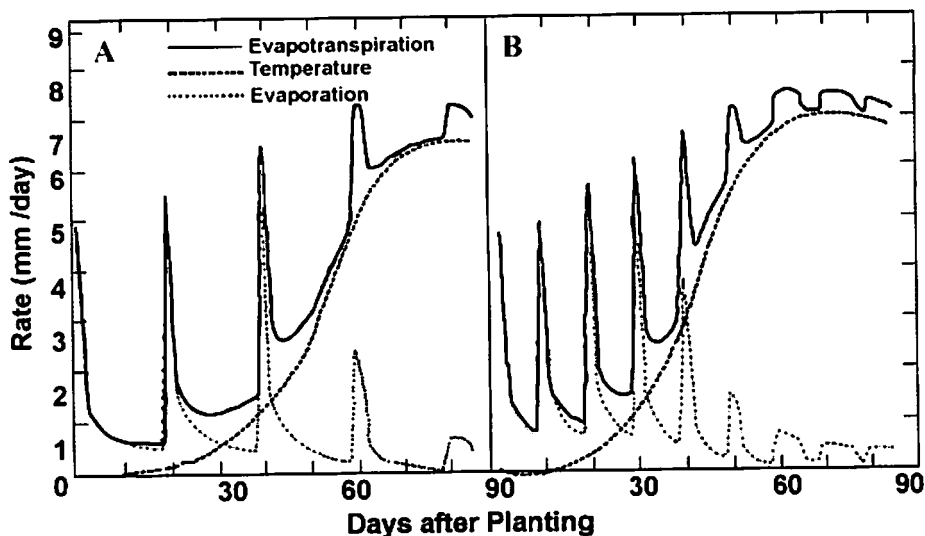


Fig. 9. Computer simulated soil evaporation (ES), crop transpiration (T) and their sum (ET) of a row crop with slow canopy development and irrigated every 20 days (A), and a crop with fast canopy development and irrigated every 10 days (B). Redrawn from Hsiao (1990).

As mentioned before, K_c is often approximated by a straight line of several segments of straight lines over the canopy development stage. Consequently, the effect of wetting the unshaded soil surface is frequently not recognized. The simulation reemphasizes the dependence of K_c on the frequency of irrigation or rain and on the extent of canopy cover. It also points to the possibility of saving some water through a reduction in irrigation frequency to minimize E_s .

Another point is that fast canopy development, accompanied by faster water use and a higher rate of productivity, allows a higher proportion of the consumed water to be used productively (in exchange for CO_2 assimilated) and a smaller proportion wasted through soil evaporation. To separate the contribution due to the crop transpiration from the contribution due to the soil evaporation, to the whole evapotranspiration process, the K_c can be split in two terms: the “basal” crop coefficient (K_{cb}) and the “soil evaporation” coefficient (K_e) (Allen et al., 1996, 1997, 1998), so that:

$$K_c = K_{cb} + K_e \dots\dots\dots (8)$$

The basal crop coefficient (K_{cb}) is defined as the ratio of ET_c to ET_o when the soil surface layer is dry but where the average soil water content of the root zone is adequate to sustain full plant transpiration. In other words, K_{cb} represents the baseline potential K_c in the absence of the additional effects of soil wetting by irrigation or precipitation. The soil evaporation coefficient (K_e) describes the evaporation component from the soil surface and can be defined as the ratio of cumulated E_s to cumulated ET_o from the starting of the wetting event.

The dual coefficient has great importance for the initial stage of the field crops, for the period until crops do not reach full ground cover and for the tree crops during their whole irrigation season. The approach of the dual coefficient is more complicated and more demanding in terms of computation, so that it is recommended to be used for daily estimates and for actual irrigation scheduling.

While the reader is referred to the tables reported in the FAO Paper N°. 56 (Allen et al., 1998) for the derivation of the basal crop coefficients (K_{cb}), here we are illustrating a criterion to calculate the crop coefficient for soil evaporation (K_e) which is a compromise between the more rigorous framework reported by Ritchie (1972) and the more simplified derivation suggested by the FAO source.

Following the previous definition, the soil evaporation coefficient (K_e) for a period of time from the first day after the wetting occurrence ($d1$) to the day of interest (dn), before next wetting event, can be derived as:

$$K_e = \frac{\sum_{d1}^{dn} E_s}{\sum_{d1}^{dn} ET_o} \cdot f_{ew} \dots\dots\dots (9)$$

Where:

f_{ew} is the fraction of the soil that is both exposed and wetted.

We already know how to calculate ET_o , so that now we'll see how to calculate E_s making the distinction between stage I and stage II, as well as for the day of the transition between the two stages, that might occur during the whole period considered.

(a) During Stage I

$$\sum_{d1}^{d-end-I} E_{S(I)} = \sum_{d1}^{d-end-I} ET_o \quad \text{for } \sum E_{S(I)} \leq U \quad \dots\dots\dots(10)$$

Where:

U is the threshold cumulative soil evaporation, for the different soil types, during the stage I evaporation (or upper limit). Values of U can be derived locally, by experiments, for the different soils and climatic conditions, or from the literature. In Table 1, the most common U values are reported for typical soil types.

Table 1. Estimated figures of the upper limit of Stage I cumulative evaporation (U) and of the coefficient α for four soil types (after Ritchie, 1972).

Soil Type	Cumulative Evaporation	α
	-----mm-----	-----mm day ^{-1/2} -----
Clay Loam	12	5.08
Loam	9	4.04
Black Clay	6	3.50
Sand	6	3.34

To extend the U estimates to all types of soil whose texture is known, the following equations can be adopted:

$$U = 8 + 0.08 \cdot \text{clay} [\%] \text{ for sand } < 80\% \text{ and clay } < 50\%$$

$$U = 5 + 0.15 \cdot (100 - \text{sand} [\%]) \text{ for sand } > 80\%$$

$$U = 5 + 0.06 \cdot (100 - \text{clay} [\%]) \text{ for clay } > 50\%$$

(b) For the day of transition between the two stages

$$E_{s(I-II)} = 0.6 \cdot ET_o \quad \dots\dots\dots (11)$$

(c) During Stage II

$$\sum_{d_start_II}^t E_{S(II)} = \alpha \cdot \sqrt{t} \dots\dots\dots(12)$$

Where:

α is dependent on the hydraulic properties of the soil and “t” the number of days from the starting of Stage II. Again, values of α can be derived experimentally or estimated from the literature (e.g., Table 1). The values of α reported in Table 1, however, are quite sufficient for practical purpose, and where no information is available on the soil type, a suggested value of 3.5 mm day^{1/2} has been proven valid for many soils. Furthermore, it should be recognized that errors in Stage II have less impact on the whole E_s estimate.

Now, the soil evaporation from both stages, and the day of transition between them, needs to be attributed to the fraction of the soil that is both exposed and wetted (f_{ew}), i.e., the fraction of the soil surface from which most of the evaporation occurs. Integratively, then, the K_e at any day after the wetting event (irrigation or rain), and before the next wetting event, can be estimated as:

$$K_e = \frac{\sum_{d1}^{dn} E_s}{\sum_{d1}^{dn} ET_o} \cdot f_{ew} = \frac{\sum_{d1}^{d_end-1} E_{S(I)} + E_{S(I_II)} + \sum_{d_start_II}^t E_{S(II)}}{\sum_{d1}^{dn} ET_o} \cdot f_{ew} \dots\dots\dots(13)$$

One more aspect to consider is when the crop is undergoing to some degree of water stress, as a result imposed by the actual management. In this case, direct measurements of evapotranspiration (e.g., by water balance or micro-meteorological methods) remain the best performing approach as compared to models. Nevertheless, using the two-step approach, a possible water deficit imposed to consider quality aspects of yield (e.g., in grape) and/or economic aspects as well (e.g., in olive) can be accounted for by introducing a deficit coefficient (K_d), so that Eq. (8) can be rewritten as:

$$Kc = (K_{cb} + K_e) \times K_d \dots\dots\dots(14)$$

Although crop coefficients are rough in their parameterization of the evapotranspiration process, they still represent the most practical approach for estimating crop water use under irrigated conditions.

THE K_c OF TREE CROPS

Tree crops represent a very special case in the K_c determination for different reasons: the actual determination of ET_c is extremely complex and difficult; the quite significant three-dimensionality of the individual trees should require a different approach to the treatment of K_c parameterization as compared to field crops; having almost always conditions of non-complete ground cover, the shaded and non-shaded areas of the soil surface are variable depending on the period of the year, making more complicated the estimation of the soil evaporation contribution to the whole ET_c .

Most of the K_c reported in the literature can be considered as “educated guesses” rather than actual results from experimentation. What can be done to improve the estimates of what is already available in the literature? First of all, we should identify the essential structure and boundary conditions of our orchard.

In a simple way, this can be considered by: (a) distinguishing deciduous trees from evergreen's; (b) evaluating the actual plant density; (c) estimating the vertical projected area of the tree crown on the ground surface at the stage of full leaf area development (for deciduous trees) or at the actual stage (valid for the whole season) for evergreen trees; (d) evaluating the height of the mid-crown from the ground and the distance between mid-crowns of adjacent trees (both on the row and between rows); and (e) defining the irrigation method and system used in the orchard.

The deciduous trees are characterized by having the initial, development, mid-season and late season stages in a similar fashion to the annual field crops. The perennial trees are, instead, characterized by having essentially one vegetative stage for the whole season % length. The plant density, along with the projected area of the crown at full leaf area development will allow us an estimate of the maximum ground cover which will be taken as reference for max ET_c of the orchard. The height and inter-distances of the tree mid-crown are parameters that can be used to attribute some adjustment for the three-dimensionality of the system. The irrigation methods and systems affect the wetting pattern of the soil surface (area, frequency, etc.) which will be further subdivided in the shade and non-shaded (wetted) area.

The actual conditions are, of course, more complex than what the parameters indicated above can represent, but they are an attempt to better frame the tree-crop system and to adjust what are the general K_c values found in the literature. The starting K_c still remains the one reported in review papers such as FAO Irrigation and Drainage N°. 56 (Allen et al., 1998); these values, then, can be adjusted following a simple approach as the one described below.

Once derived, the reference crop coefficient for the season (K_{C_ref}) from the literature or local information, the first adjustment factor should be done for the ground cover fraction (GC), and this can be done in a direct proportional way (i.e., $K_{C_GC} = K_{C_ref} \cdot GC$), where GC is obtained from the previous Point b and c. In the case of GC estimates for the deciduous trees, the projected area of the crown should consider the actual leaf area developmental stage (e.g., the ratio of the projected green area to the whole projected crown area). Considering the largest distance between on-the-row and between-row, for a mid-crown inter-distance larger than 1 m and less than 3 m, there should be an increase of the K_C by 0.1 for each meter of inter-distance. Beyond 3 m (if occurring), the max adjustment of 0.3 remains constant.

Considering, in the proper way, the irrigation methods and systems, the wetting pattern and the shaded and non-shaded area of the wetted area, better values of the parameter for the estimates of the evaporation from the bare soil (as illustrated in the previous section) can be used. Of course, the cases presented are limited to the bare soil underneath the crown and not in grassed conditions since we are considering the case of Mediterranean regions where the dominant limiting factor is water.

There is much greater need for research and experimentation that addresses the evaluation of the crop water requirements of tree crops under different stages of development and different management systems.

CONCLUSIONS

Notwithstanding the progress in agricultural research, the determination of crop water requirements (CWR) remains a difficult task to perform. It seems that the "two-step" approach has for a long time represented the most reliable criteria for estimating the CWR for both planning and management purposes. It is also likely that the "two-step" approach will continue for a while at least not to be surpassed by any other approach.

However, the approach is too simplistic to be applied to the variable and complex cropping systems found in agriculture. An apparent paradox is that the approximations of the "two-step" approach are considered too large when compared to the value of a scarce resource such as water, and, at the same time, the best achievable approximation when compared to the available alternatives. Probably, an appropriate attitude to maintain when dealing with CWR is to avoid the use of the two-step approach in a sort "recipe" mode and be more aware of the assumptions, boundary conditions and problems that can raise with the actual cropping system under investigation. With such an attitude, perhaps, adjustments of the estimates can be adopted with a saving in the water use.

The particular conditions of the Mediterranean regions point to the regional advection as one of the probable cause of uncertainty in estimates of CWR. The

methods recommended in the literature may be prone to deviations from the correct estimates when large daily temperature fluctuations occurs affecting the calculation of VPD and R_n . Mismatch in fetch requirements between agro-meteorological stations (used to estimate ET_0) and lysimeters (used to determine ET_c) may yield erroneous K_c values. Particular attention should be paid to the contribution of the soil evaporation (E_s) to the whole field evapotranspiration under incomplete ground cover. The knowledge of the irrigation methods and systems, along with proper management, can allow a better framework for estimating and reducing E_s . The CWR of tree crops represent the most difficult case to solve. The progress in this field, in fact, is lagging very much beyond the progress obtained for field crops.

What appears as an old subject for study and research is instead something that requires a big effort to be understood first and properly applied after. It is then needed to continue to work hard on the various issues affecting CWR to make an effective and efficient use of the water, which has a value considerably higher than what is expressed by its costs and prices.

REFERENCES

- Allen, R.G., M. Smith, A. Perrier, and L. S. Pereira. 1994a. An update for the definition of reference evapotranspiration. *ICID Bull.*, 43,(2):1–34.
- Allen, R.G., M. Smith, L. S. Pereira, and A. Perrier. 1994b. An update for the calculation of reference evapotranspiration. *ICID Bull.*, 43, (2):35–92.
- Allen, R.G., M. Smith, W.O. Pruitt, and L. S. Pereira. 1996. Modification of the FAO crop coefficient approach. p. 124–132. “International Conference on Evapotranspiration and Irrigation Scheduling”, ASAE, San Antonio, Texas, 3–6 Nov. 1996.
- Allen, R.G., M. Smith, L. S. Pereira, and W. O. Pruitt. 1997. Proposed revision to FAO procedure for estimating crop water requirements: 17–33. Second Intern. Symposium on Irrigation of Horticultural Crops. China, Crete, ISHS, 9–13 Sept., 1996.
- Allen, R.G., L. S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. *Irrigation and Drainage Paper N°56, FAO, Rome*.
- Baldocchi, D. D., R. J. Luxmoore, J. L. Hatfield. 1991. Discerning the forest from the trees: an essay on scaling canopy stomatal conductance. *Agric. For. Meteorol.*, 54:197–226.
- Blad, B.L., and N.J. Rosenberg. 1974. Lysimetric calibration of the Bowen-ratio energy balance method for evapotranspiration estimation in the central Great Plains.
- Brutsaert, W. 1982. Evaporation into the atmosphere. Theory, history, and applications. *Reidel D. Publ. Co., Dordrecht, The Netherlands*.

- Choisnel, E., O. de Villele, and F. Lacroze. 1992. Une approche uniformisée du calcul de l'évapotranspiration potentielle pour l'ensemble des pays de la Communauté Européenne. *Com. Commun. Européennes*, EUR 14223 FR, Luxembourg.
- Doorenbos, J., and W.O. Pruitt. 1977. Crop water requirements. *Irrigation and Drainage Paper No.24, FAO, Rome*.
- Dyer, A.J. 1965. Discussion on change of terrain roughness and the wind profile by H. A. and A.A. Townsend. *Quart. J. Roy. Meteorol. Soc.*, 91:241.
- Dyer, A.J. 1974. A review of flux-profile relationships. *Boundary-Layer Meteorol.*, 7:363-372.
- Finnigan, J.J., and M. R. Raupach. 1987. Modern theory of transfer in plant canopies in relation to stomatal characteristics, p. 385-429. In: Stomatal function. E. Zeiger, G.D. Farquhar, I.R. Cowan (ed). *Stanford University Press*, Stanford, Calif. USA.
- Hsiao, T.C. 1990. Plant-atmosphere interactions, evapotranspiration and irrigation scheduling. *Acta Hort.*, 278:55-66.
- Jensen, M.E., R. D. Burman, and R.G. Allen. 1990. *Evapotranspiration and Irrigation Water Requirements. ASCE Manuals and Reports on Engineering Practices No. 70*. ASCE, New York.
- Monteith, J.L. 1965. Evaporation and environment, pp. 205-234. In: G.E. Fogg (ed). The state and movement of water in living organisms. Symposium of the Society for Experimental Biology, 19. *Academic Press*, New York.
- Monteith, J.L. (Ed.) 1973. Principles of Environmental Physics. *Edward Arnold*, London.
- Motha, R. P., S. B. Verma, and N. J. Rosenberg. 1979. Exchange coefficients under sensible heat advection determined by eddy correlation. *Agric. Meteorol.*, 20:273-280.
- Munro, D.S., and T.R. Oke. 1975. Aerodynamic boundary-layer adjustment over a crop in neutral stability. *Boundary-Layer Meteorol.*, 9:53-61.
- Panofsky, H.A., and A.A. Townsend 1964. Change of terrain roughness and wind profile. *Quart. J. Roy. Meteorol. Soc.*, 91:147-155.
- Peterson, E.W. 1969. Modification of mean flow and turbulent energy by a change in surface roughness under conditions of neutral stability. *Quart. J. Roy. Meteorol. Soc.*, 95:561-575.
- Rana, G., N. Katerji, M. Mastrorilli , and M. El Moujabber. 1994. Evapotranspiration and canopy resistance of grass in a Mediterranean region. *Theor. Appl. Climate.*, 50:61-71.
- Rao, K.S., J.C. Wyngaard, and O.R. Cote'. 1974. The structure of the two dimensional internal boundary layer over a sudden change of surface roughness. *J. Atmos. Sci.*, 31:738-746.
- Ritchie, J.T. 1972. Model for predicting evaporation from a row crop with incomplete cover. *Water Resour. Res.* 8(5):1204-1213.

- Rosemberg, N.J., B.L. Blad, and S.B. Verma. 1983. Microclimate: the biological environment. John Wiley & Sons, New York.
- Shir, C.C., 1972. A numerical computation of air flow over sudden change of surface roughness. *J. Atmos. Sci.*, 29:304–310.
- Steduto, P., A. Caliendo, P. Rubino, N. Ben Mechlia, M. Masmoudi, A. Martinez-Cob, M.J. Faci, G. Rana, M. Mastrorilli, M. El Mourid, M. Karrou, R. Kanber, C. Kirda, D. El-Quosy, K. El-Askari, M. Ait Ali, D. Zareb, and R.L. Snyder. 1996. Penman-Monteith reference evapotranspiration estimates in the Mediterranean region, p. 357–364. “*Intern. Conf. on Evapotranspiration and Irrigation Scheduling*”, 6–9 Nov., San Antonio, Texas.
- Steduto, P., and T.C. Hsiao. 1998. Maize canopies under two soil water regimes II. Seasonal trends of evapotranspiration, carbon dioxide assimilation and canopy conductance, and as related to leaf area index. *Agric. For. Meteorol.*, 89:185–200.
- Steduto, P., 1999. Insights on the *physiological* and *climatological* components of g_c in the Penman-Monteith equation. *Plant Cell Envir.* (in preparation).
- Verma, S.B., N.J. Rosenberg, and B.L. Blad. 1978. Turbulent exchange coefficients for sensible heat and water vapor under advective conditions. *J. Appl. Meteorol.*, 17:330–338.
- Verma, S.B., D.D. Baldocchi, D.E. Anderson, D.R. Matt, and R.J. Clement. 1986. Eddy fluxes of CO₂, water vapor, and sensible heat over a deciduous forest. *Boundary-Layer Meteorol.*, 36:71–91.

Approaches for Using Climatic Data to Improve Water-Use Efficiency

Ayman F. Abou Hadid

*Central Laboratory for Agricultural Climate (CLAC),
Agricultural Research Center, Cairo, Egypt*

ABSTRACT

This paper covers the various concepts related to irrigation and water-use efficiency. Methods to improve the utilization of water and reduce water losses during application are discussed. Finally, a presentation of innovative systems that depend on the use of climatic data to accurately estimate water and nutritional needs for crop production is presented.

The general concept of irrigation or water-use efficiency is the ratio between the input of water to the water utilized in the next step of the agricultural system. This covers the irrigation practices from the *conveyance efficiency*, *delivery efficiency*, and *system efficiency*. Another concept is that related to water-use efficiency, which is expressed as the ratio between the amount of irrigation water to the amount of biomass, edible plant organs, or even cash return from the commodity produced.

Several management practices and technologies were developed in the past to improve water-use efficiency; these include irrigation systems, ranging from field surface irrigation to pressurized irrigation in protected agriculture, agricultural systems that vary from the rainfed field production of cereals to production of cash crops in hydroponics, and management systems that vary from flood irrigation to computer-based precision agriculture.

The paper describes examples of such systems starting from the surface irrigation design to the modern computer-based water management packages. The experience of Egypt in the utilization of climatic data to improve water-use efficiency by means of mathematical models and computer expert systems will be illustrated.

CONCEPTS OF WATER-USE EFFICIENCY

Irrigation Efficiency

The original concept of water-use efficiency started with the term "irrigation efficiency", which was identified by Doneen and Westcot (1988) to be the *application of the least amount of water required for wetting the root zone to field capacity*. If the amount of water applied grossly exceeds that actually needed for replenishment, the irrigation efficiency is very low. The method of calculating irrigation efficiency or water application efficiency was using the formula:

$$E_a \% = E_t / I_d \dots\dots\dots (1)$$

Where:

E_a is application efficiency, E_t is evapotranspiration, and I_d is irrigation water delivered at the farm gate.

Irrigation application efficiency (the ratio of water delivered at the farm gate to the amount stored in the active root zone) could vary from extremely low values to values approaching 100% (Israelsen and Hansen, 1962). However, in normal irrigation practices, surface irrigation efficiencies of application are in the range of 60%, whereas well designed sprinkler irrigation systems are generally considered to be at least 75% efficient. Drip irrigation application efficiency could be up to 90 %.

Water-Use Efficiency

Water resource problems are often associated with lack of efficiency related to water-use in agriculture, industrial, and domestic supply. Agriculture is by far the most important water-use activity (Hamdy and Lacirignola, 1999). It is also probably the sector least efficient in water-use. Low irrigation efficiency can be primarily attributed to *water mismanagement*, in addition to technical problems of *conveyance, distribution*, or on-farm application as well as *poor maintenance of irrigation structures*, often caused by *inadequate investments for operation and maintenance*. In order to raise irrigation efficiency, it is necessary to improve system water management and on-farm water management, where the former must be a prerequisite for the latter.

Irrigation efficiency was developed to accommodate the needs of the land and water-use, especially for agronomic purposes. Tanner and Sinclair (1983) presented a detailed and comprehensive review for different methods and models of calculating water-use efficiency. The phrases efficient water-use or water-use efficiency, are intrinsically ambiguous in relation to crop production. It may mean

saving water from a given supply for crop use, or increasing production per hectare per unit of water evaporated from the soil and/or transpired from the plants in the field.

The term water-use efficiency has been employed very loosely by plant scientists and agronomists to refer to observations ranging from gas exchange by individual leaves for a few minutes to grain yield response to irrigation treatments through an entire season (Sinclair, 1984). For agronomists, water-use efficiency is commonly defined as:

$$WUE = \text{Yield per unit area} / \text{water volume used to produce yield.}$$

The quantity of water used to produce yield may be expressed by different ways according to Gregory (1991). The simplified way of calculating water-use efficiency was reported to be as follows:

$$WUE = (N/T) / (1 + (E/T)) \dots\dots\dots (2)$$

Where:

E is evaporation, N/T is transpiration efficiency, N is dry matter production, and T is transpiration.

Tanner and Sinclair (1983) concluded that the analysis of crop water-use efficiency results in a rather pessimistic view of substantially improving it by either plant breeding or local agronomic practices. Yet in a broader geographical sense, substantial improvements in water-use efficiency can be achieved by matching crop production with areas of low vapor-pressure deficits. In general, solar radiation, saturation deficits, and evapotranspirational demand in a region increase as precipitation and cloudiness decrease. Climatic divisions for regional aridity of the contiguous United States was reported in areas in which saturation deficits and evapotranspiration increase. Although potential productivity under irrigation can also increase with aridity because of increased sunshine and growing period, advection adds to the evapotranspiration of irrigated fields without a concomitant increase in productivity.

Since irrigation often produces yield increases in the humid regions, Tanner and Sinclair (1983) concluded that the greatest gains in improving crop water-use efficiency for the entire USA would be to put greater emphasis on *water management* and *irrigation technology* in these humid areas. In addition, these gains in yield could be achieved in the humid regions with much smaller water input than in the more arid areas. Rainfall would still provide much of the required water, and the transpiration losses are smaller in humid regions. Finally, salinization is not

a problem in the humid regions where there is a much greater availability of water, which is usually of high quality.

Irrigation research has suffered neglect in the humid regions, where unpredictable rainfall imposes considerably different technical problems than those experienced in the dry regions, where most irrigation technology has been developed. The soil fertilizing practices in humid regions have been developed with little regard to the interaction between water-use efficiency and irrigation efficiency. Considerable research must be done to develop sound fertilizer/irrigation practice that recognizes this interaction, and minimizes leaching while maintaining an adequate soil water supply for the crop. This becomes increasingly important with shallow-rooted crops and sandy soils. This research, which involves irrigation that does not bring the root zone to full water supply, is essential to reduce the energy use in irrigation and to avoid nitrate contamination of groundwater (Tanner and Sinclair, 1983).

Irrigation practices on sloping land must be researched to integrate them with sound conservation measures. Erosion hazards are greater in humid regions where unpredicted precipitation can follow irrigation. Plant disease, insects, and weeds pose problems under irrigation in humid regions, which are not found in dry regions. Trafficability for field operations is often a problem on fine-textured soils under natural rainfall, and the problem worsens when crops are irrigated. Increasing energy costs will change the feasibility of irrigation in both arid and humid regions. The impact in humid regions will vary greatly depending on availability of water supply and probability of yield increase; this needs assessment. Electric power use for pumping is seasonal, and with the weather-induced uncertainties on timing irrigation in humid regions, management of power generation and distribution for load peaks is an increasing problem.

In short, scheduling irrigation must help optimize fertilizer use, soil conservation, pest control, power requirement, electric load management, and other crop management practices for high productivity and minimal environmental damage (ground water pollution, soil loss) in the presence of unpredictable rainfall. Better medium-scale forecasting of rainfall would help to improve water-use efficiency, but in view of forecasting advances since 1900, it offers small hope.

Factors Affecting Water-Use Efficiency

Factors influencing water-use efficiency may be summarized as follows:

Water-Delivery Systems

Open canals, lined ditches or the pipelines are different in the ability to convey water with different losses. On the macro level, water conveyance system will be a major factor in determining water-use efficiency.

Irrigation Systems and Water-Delivery Systems

These are generally the methods for making more water available to the transpiration processes. It also include methods to improve water movement in the soils, its absorption by roots, and its movements through the plant are considered in detail as possible approaches to maximizing the availability of water to crops.

Crop Shape and Morphology

Crops with closed leaf canopies and when soil evaporation is small are better in water-use efficiency.

Climatic Factors

These mainly affect the physical processes controlling crop evapotranspiration are considered as keys to managing and minimizing water loss. The problem of water deficits developing in crops, causing severe limitation in the ability of crops to produce an economic yield.

Management Options

These aim to increase the amount of water available for crop production and to improve crop-growth characteristics for increasing the economic yield.

Economic Considerations

The cash return of the unit of yield is of a major importance for improving efficient water-use.

Techniques for Predicting Yield

These involve the economic component of the crop for the water invested. This includes the productivity of crop per unit area of land with the consumption of water per unit of yield. It help in selection of the crop to be cultivated in a giver are to produce the maximum cash return from the unit volume of water.

Social and Political Factors

These set the priority for increased efficient water-use in crop production in a given area.

Efficient Water Management Systems

Information related to on-farm water-use is available in a wide range of publications. It is quite difficult to sum it in few lines. Nevertheless, this section will shed some light on the methods and approaches to improve water-use efficiency in agriculture.

Irrigated agriculture

Irrigation systems vary in their water-use efficiency. The amount of water required for irrigation may be approximated by sampling the soil at several places in the field and estimating the moisture deficit (Doneen and Westcot, 1988). The water application is then calculated on this basis, allowing for the possible losses. The irrigation efficiency for sprinkler irrigation could vary from 60 to 70%, improving to about 80% for localized irrigation, ranging between 45 and 75% in basin irrigation, and between 40 to 65% in furrow irrigation.

Guide to Efficient Application of Water

When to irrigate during the hot dry season can be estimated if the consumptive use is known. If the maximum consumptive use rates are known for the crop and area, divide the millimeters of available moisture held in the rooting depth of the soil by the consumptive use rate in millimeters per day to estimate the number of days between irrigations. This procedure should not be used for early-season irrigations. Neither does it apply to young plants with incomplete root development, or to special applications, such as pre-planting or leaching irrigations.

For any irrigation method used, it can be assumed that a uniform soil will absorb about the same amount of water in one location in a field as in another part if the water is in contact with the soil for the same length of time in each place. In other words, if intake "opportunity time" is the same at all points in the field, then a uniform application of water would be expected over the entire field. Most irrigation methods do not permit water to be applied for exactly the same length of time at one place as at all others, but all irrigation methods can be made to approach this ideal goal.

The following are some guidelines to be used in improving irrigation practice and to increase irrigation efficiency:

1. Before irrigating, check the soil moisture in the root zone at several locations. Estimate the amount of water needed to bring the soil to field capacity. About 2 or 3 days after an irrigation, check the soil moisture again. The moisture should be close to field capacity throughout the rooting depth. There should be no dry spots or dry layers in the field.

2. Determine the depth of water (in centimeters) applied to the field during irrigation. This will require the measurement of the stream size and the period of time the water was delivered to the field, then calculate the depth applied. For sprinklers, multiply the application rate, in millimeters per hour, by the length of time in hours that the sprinklers have operated at one setting.
3. How does the estimation of the amount of water needed compare with the amount delivered to the field? What efficiency of irrigation was obtained? Note that high efficiency can be achieved, but a poor irrigation may result if only a small amount of water is put on the dry soil.
4. During irrigation, watch to see whether the intake opportunity time is about the same throughout the field. When irrigating by the border method, does the water stand about as long at the lower end and middle of the field as it does at the upper end? If furrows are used, does the water reach the lower end at about one-fourth of the total time that it is on the upper end? Are basins and level borders filled quickly?
5. Observe the amount of irrigation water running off the surface of the field as waste. A large amount of surface run-off from a border indicates the stream is too large or that water has been run into the border strip for too long a time. When the water in a well-designed border (not a level border) approaches the lower end of the strip, the stream may be reduced or cut off, at the upper end. In this way, an even distribution will be obtained with little or no run-off.

The stream size must be properly adjusted to the soil-intake rate and to the border length if the border is to be evenly irrigated without excessive run-off. If furrow run-off is excessive, the furrow stream should be reduced to about one-third to two-thirds of the initial flow after the water reaches the lower end.

6. Watch for evidence of too much water being used, as it may be as costly as using too little. Losses may occur in four different ways from over-irrigation: (a) water costs more than when it is used efficiently; (b) leaching some plant nutrients below the root zone of the crop plants; (c) water-logging some or all of the farm land; and (d) the yield of some crops is reduced when too much water is applied.

The above discussion has been concerned with efficient use of irrigation water and an even spread over the field in the right amount to fill the soil reservoir or water-adsorption capacity. In the final analysis, it is the amount of crop produced

with the water supply available that determines the real efficiency of water-use. Crops can be efficiently irrigated once or twice during the season and still fail to yield well because of the lack of moisture during part of the growing season. Also, water cannot be used efficiently unless good farming methods as well as good irrigation practices are followed.

Protected Cultivation

The use of greenhouse and plastic house techniques had contributed substantially to the improvement of water-use efficiency. The plastic or glass cover creates a special microclimate in which radiation and wind movement are lower than its value in the open field, while air relative humidity is higher than the open field air humidity (Abou Hadid and El-Beltagy, 1991). These factors favor a reduction in evapotranspiration (Eissa et al., 1992). On the other hand, the higher temperature promotes increased plant growth rate and consequently more yield per unit area of the cultivated land. The increase in yield and reduction in water consumption under protected cultivation was reported by Abou Hadid et al (1992).

The end-result of this situation is larger yields under protected cultivation that use less water, which improves water-use efficiency (Abou Hadid and El-Beltagy, 1992). The efficient use of water in greenhouses is also reflected on the efficient use of fertilizers. Many reports on this subject (Ismail et al., 1996; El Behairy et al., 1996; Abd El-Moniem et al., 1996) indicated that protected cultivation and soilless culture techniques help in improving nutritional conditions in plastic houses and to solve nutritional problems that could not easily be solved under open field conditions.

Soilless Culture

A remarkable example on the efficient use of water resources is the use of substrates in soilless culture for better vegetable quality and as a means for improving the water-use efficiency. To clarify the relation between substrate culture and water-use efficiency, it is noticed that field grown tomato produce 3 kg of tomato fruits per cubic meter of water while, plastic house soil-grown tomato produces 17 kg per cubic meter of water. Tomatoes grown in substrate under plastic house conditions in Egypt produce up to 45 kg of tomato fruits per cubic meter of water.

Soilless culture techniques were developed under glass houses in order to overcome major agricultural problems such as nutrition, plant diseases and environmental pollution. Later, it was seen as to be one of the most efficient tools for water saving. The development of simple low-cost systems for hydroponics was the main challenge to make soilless culture possible. Several attempts to design and implement the different techniques of soilless culture were followed, and proved to be economically viable and environmentally safe.

Such techniques resulted in improving water-use efficiency to a great extent and helped reduce the amount of chemicals used for both nutrition and pest and disease control to a acceptably low level. Production cost is relatively high, but future research may be promising to reduce the cost and hence improve the applicability of these systems on a large scale in arid lands.

The limited water resources and rapid increase in population were the major factors that drew the attention towards the use of intensive agriculture in Egypt. Protected cultivation was the first step, which started initially in the late seventies and intensified at mid eighties. Maximizing crop yield per square meter of soil, as well as per cubic meter of water, could be achieved through the use of hydroponics systems. (Zayed et al., 1989).

Several possibilities and options of soilless culture are available for use in Egypt. Nutrient film technique (NFT) and rock-wool are the most expanded systems, even though the rock-wool should be replaced every other years, involving another additional costs compared to the nutrient film technique. Several efforts have been made to introduce the nutrient film technique in Egypt, initially in the tourist villages where the soil could not cultivated successfully. Nevertheless, there still be a good opportunity to increase the water-use efficiency by using other systems such as the aeroponic systems (El Shinawy et al., 1996).

USE OF CLIMATIC DATA TO IMPROVE WATER-USE EFFICIENCY

The old land in Egypt, which has been cultivated for millennia, is characterized by uneven field surface, short furrows and small basins, deep percolation, water and fertilizer losses, soil profile heterogeneity, and other soil characteristics that all affect water and fertilizer distribution. Early planting is one of the options for summer cultivated crops in order to get the maximum economical yield at harvesting. Early prediction for diseases and insects is important to help farmers avoiding heavy spray of pesticides and take the necessary actions to avoid dangerous diseases.

Proper management nowadays depends on accurate irrigation scheduling that reduces the cost of irrigation and minimizes problems related to the misuse of water. Early pest, disease forecast, and warnings allow suitable time for taking necessary actions to avoid chemical spraying. Proper calculation of sowing dates for several crops ensures uniform plantation and reduces the cost of sowing seeds. The above - mentioned agro-management practices require a real-time weather data system covering the country.

The Agricultural Research Center in Egypt has established the Irrigation Requirement Information System (IRIS) within the activities of the Central Laboratory for Agricultural Climate (CLAC). The system covers more than 30

agro-meteorological stations. Dissemination of information is one of the CLAC efforts that occur through different mass media facilities. Computer modeling is used to calculate water and fertilizer requirements, disease and insect prediction, and planting dates. Planting dates of vegetable crops are determined according to agro-meteorological data, especially soil temperature at different depths. Research is being conducted to establish the precise soil temperature for each cultivar of different vegetable species. This is important for selecting the proper cultivation time and area, as in case of newly reclaimed lands, in order to achieve the best germination and avoid the major diseases and/or pests.

Water resource management and water availability are among the most important political, social and economical issues of the 21st century (Harsh et al., 1989; Krug, 1989; Medany et al., 1997). In Egypt, the misuse of limited water resources creates serious yield reduction in the traditional agro-management systems. On the other hand, control of insects is the outcome of dynamic processes that can be conceptualized as a system depending on weather conditions, the pest and its natural enemies and the host plant as interrelated components.

If mathematical models designed to simulate integrated pest management (IPM) events are to be realistic, they must include insect phenology and behavior, host-plant growth rate, attractiveness, period of vulnerability and response to injury, and the impact of weather conditions on all of these components (Berger, 1977; Fry, 1982; Jones et al., 1984; Royer and Russo, 1989).

Planting in an accurate date prevents plant's damage caused either by insects or diseases, in addition to better planning that improves growth and yield, both at the level of growers and the country in general. Studies concerning improving or changing technologies to maximize crop production and transfer of knowledge gained from such studies involve large amounts of information from different areas (Bilbro, 1975; Lichev, 1965; Makram et al., 1995; Nelson, 1968).

Engineering practices and system management are required before recommendations are made for selecting the proper irrigation system, IPM and planting dates. From an agronomic standpoint, all irrigation methods that maximize crop production are equally important. However, particular soil type, crop species and climatological status may affect efficiency of irrigation water. Poor IPM, planting dates, and delivery systems will inevitably lead to yield reduction.

There are several studies in Egypt on developing and modifying utilization of climatic data in crop management. The Laboratory for Agricultural Climate is investing in these studies to foster agricultural development. As Egypt is divided to several climatic regions, in combination with water availability, soil types, and demographic factors, those regions can be modified to three major agroclimatic zones as follows:

- **The Nile Delta and Old Valley:** This area is characterized by clay soil, available fresh water and mild climate, with high population density.

- **The “New” Lands:** This term is generally referring to new land reclamation projects surrounding the Delta and the Old Valley with similar climate, but with sandy soil and lower population density.
- **North Coast:** This embraces a 50-km strip of land parallel to the Mediterranean Sea. The climate is quite mild with relatively higher rainfall, by Egyptian standards (180–200 mm/yr.), and sandy soil.

OBJECTIVES OF THE WEATHER DATA SYSTEM

The main objective of the Central Laboratory for Agricultural Climate weather data system is to develop water and fertilizer, integrated pests and diseases, planting date management techniques for selected crops in both the old and new lands. This is to be achieved through introduction of the proper design of modified or improved irrigation system of uniform water distribution, highly insects and diseases prediction systems and accurate planting dates of vegetable crops to maximize yields. Finally, to provide information on the chilling requirement of deciduous fruit trees to allow the growers starting management practices timely with the fulfillment of chilling hours. Long-term objectives includes information related to:

- *Green house heating, ventilation and cooling systems.*
- *Animal and poultry farm information, including expected heat waves, possible flux of diseases and water consumption in relation to animal-farm management.*
- *Aquaculture information systems that provide temperature, humidity, radiation and other factors affecting fish production.*
- *Policy-making information system, this will cover the information related to the best possible use of land and water resources for agricultural production.*

Data Collection and Processing

The interaction between the Climate Laboratory, as a research and development unit, and other research institutions, ongoing training activities, universities and ongoing research projects to produce services for growers, investors, extensionists, scientists and policy-makers is illustrated (Fig. 1). The services may be provided in the form of recommendations and technological packages.

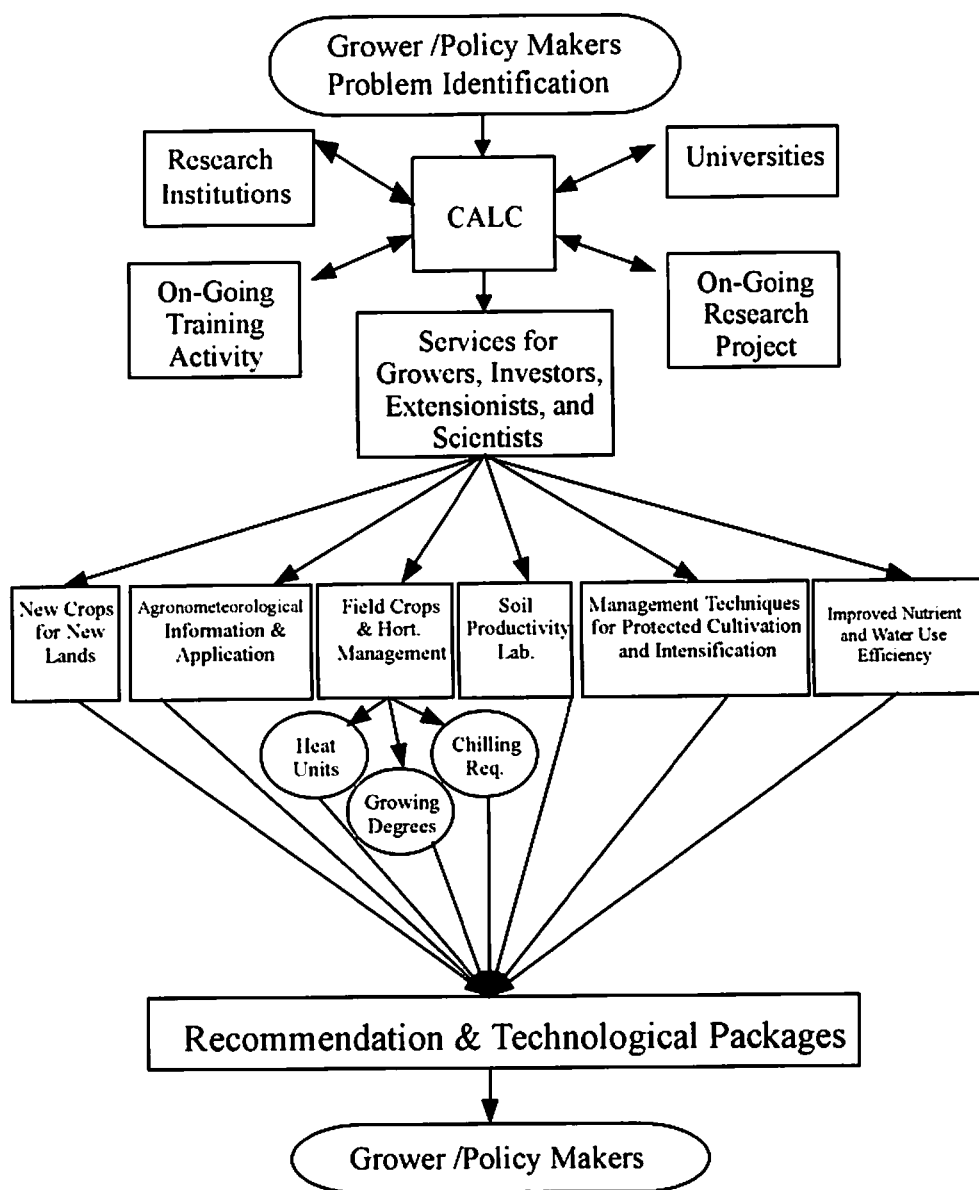


Fig. 1. The interaction between the Laboratory for Agricultural Climate and other organizations to produce recommendations and technological packages for growers.

Historical data are retrieved from the Egyptian Meteorological Authority (EMA) as well as daily data of some locations; real-time data are logged by the agro-meteorological stations belonging to CLAC, while manual stations of the Ministry of Agriculture provide daily data for several other locations. These are the main three data sources and main input for the daily weather data. Besides, some information at the regional levels is retrieved from the INTERNET and satellite images. Historical data are used as an alternative source in case of any shortage in the real-time data.

Data collected from different sources have different formats and cannot always be utilized as they are. In any case, all data are subjected to a series of data processing to produce uniform data file as shown in Fig. 2. For example, relative humidity could be calculated from air temperature and dew-point temperatures, or from wet and dry bulb temperatures using specific equations. Hourly and synoptic 3-hour interval data are processed to produce daily averages for some applications. On the other hand, synoptic data are processed to calculate hourly data for other applications. Automatically received data are handled through specific software to produce the same uniform outputs to be used for different applications.

Application

As illustrated in Fig. 2, the uniform data are utilized by four main activities that perform the necessary data processing according to each application. Fig. 3 illustrates the logical flow of the integrated pest management, while Fig. 4 illustrates the utilization of daily data for the calculation of irrigation scheduling. The uniform data file is used to calculate daily potential evapotranspiration (ET), chilling requirements for fruit trees, growth rates and yield from the daily weather data using computer models.

The main model used to estimate crop water requirements is based on the Penman-Montieth equation. Plant growth is directly related to the climatic conditions that affects canopy area index (CAI) and leaf area index (LAI). Estimating plant growth according to prevailing weather conditions dramatically improves the quality of estimated crop water requirements. There are several growth models that are currently utilized in this aspect.

Growing degree-days (GDD) is estimated from the hourly temperature and two thresholds (upper and lower), and is used for the prediction of the development rate of any biological organism, providing the upper and lower threshold temperatures. It is currently used for some insects of economic consequence. Units (GDU) are calculated using the equation:

$$(T-B)*(T_i/1.440)=DD \dots\dots\dots (3)$$

Where:

T = Temperature at time (t), B = Base temperature, Ti = Time interval in minutes between temperature readings.

Daily GDU data are calculated at CLAC and send to the Plant Protection Research Institute (PPRI), thus knowing lower and upper thresholds of each insect, we can build a good prediction for development the pest and planting dates.

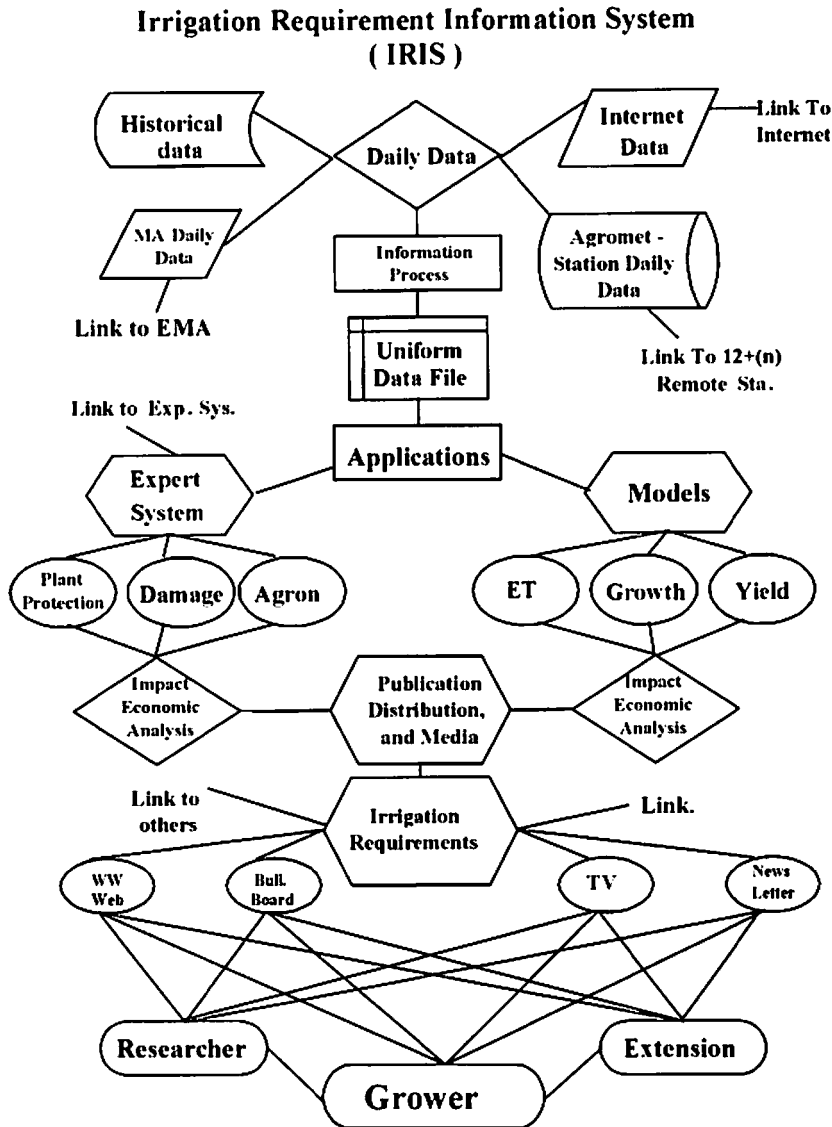


Fig. 2. Data collection, processing and applications.

Distribution

Information which is produced is disseminated to the growers via several channels; faxing to ten local broadcasting stations, inclusion in the daily news programs, and daily distribution to the direct customer as specifically needed is also possible by fax upon request.

The Laboratory produces a newsletter at 10-day intervals, including meteorological information and agricultural applications in the form of extension recommendations. It is distributed to a mailing list including all universities, research organizations, agricultural offices in the Ministry of Agriculture, and governorates, and also to growers on demand. The Laboratory is now preparing a Web page that includes current activities and available data and information.

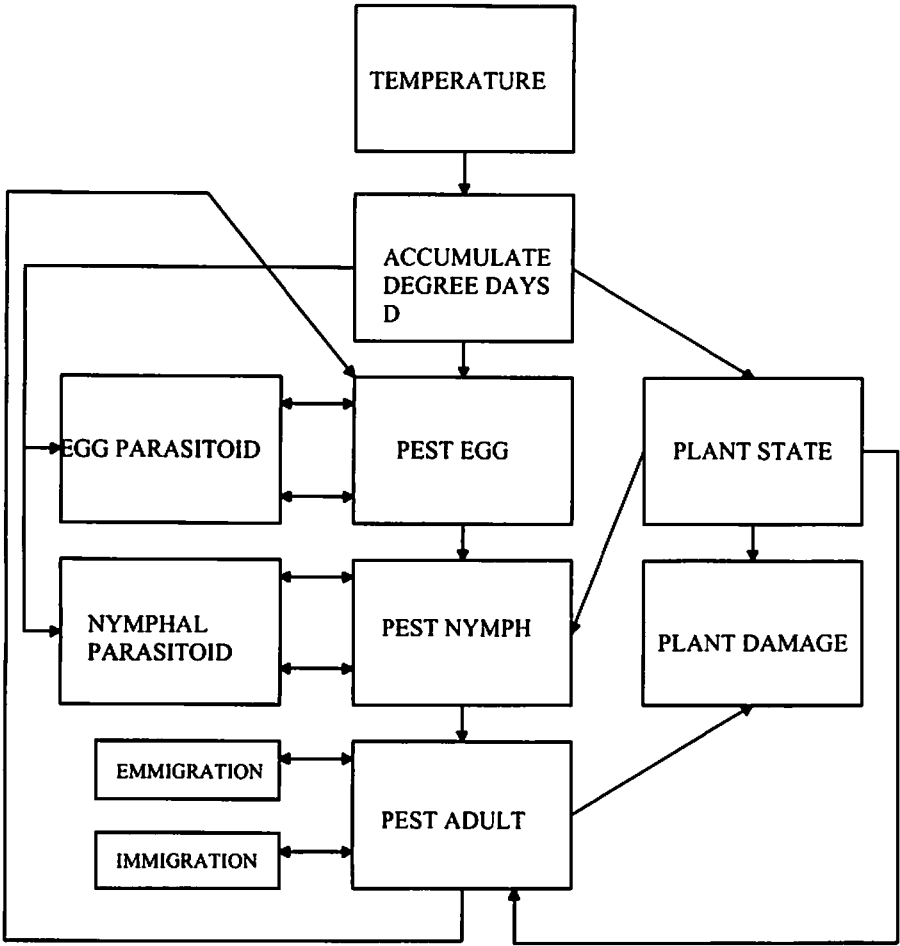


Fig. 3. Logical flow of integrated pest management.

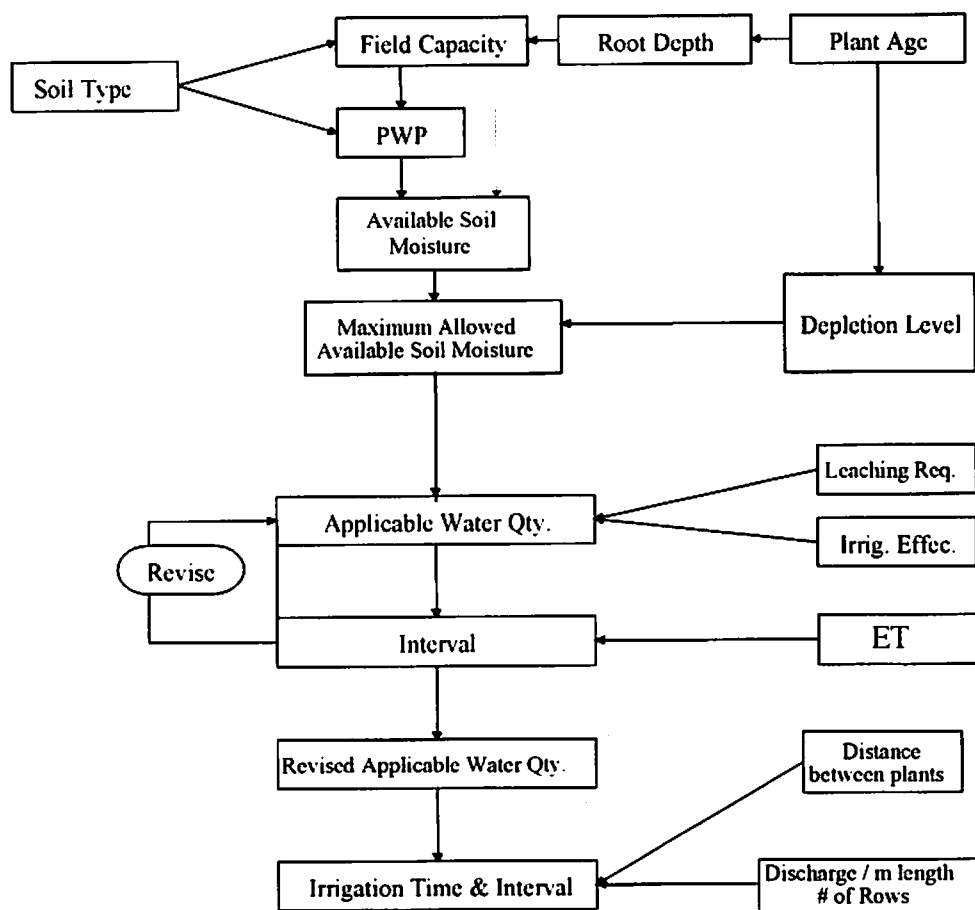


Fig. 4. Flow of data for estimating of irrigation scheduling.

NEW MODELS FOR EFFICIENT WATER AND NUTRIENTS USE

IRRICLAC

A software developed by the Laboratory (CLAC) aims at calculating either daily irrigation requirement or irrigation scheduling for a growing season. The software is divided into three major screens. The first deals with four major crop groups; i.e., *vegetables*, *fruits*, *field crops*, and *greenhouse crops*. Selecting a crop-group, the user can select the desired crop from a drop list. Almost all crops grown in Egypt

are included. From the plant age, or planting date, the program selects a crop coefficient (K_c) and root depth as a function of time.

The program uses the Penman-Montieth equation. The new version of the program will be able to offer a selection list of more than ten different equations depending on the availability of climatic data.

The second screen is related to location, and includes the farm area to select the nearest weather station to calculate the potential evapotranspiration (ET_o) for that location. It also includes soil types, which allows the program to select soil field capacity and permanent wilting point. The program then calculates the maximum amount of water that could be given to saturate the soil down to the active root depth. The program can estimate the frequency and amount of water that should be given to a certain crop at a certain location according to plant soil and crop age.

The last screen offers a menu related to the irrigation system type, efficiency and discharge per unit length, as well as distance between laterals. This section allows the program to estimate the duration of irrigation time.

FERTICLAC

A software developed by the Laboratory aims at estimating fertilizer scheduling, mainly nitrogen, potassium, phosphorus and magnesium, as well as iron and manganese. The program has several forms, including crop, location and soil (as in IRRICLAC), in addition to previous crop, soil problems (salinity, alkalinity and carbonates), fertilizers available (organic and inorganic), and nutrient response curves. The user has the option to select from a drop list the available fertilizers and estimate units of each individual nutrient as well as its physical and chemical properties. The user also is capable of editing the response curve for the above mentioned nutrients once such information is available locally. The program calculates the fertilization schedule according to the crop type and age, soil type, location, and available fertilizers. The software has options to run basically in Arabic or English, with capabilities to be used to any other languages after translating a list of words from English during installation.

REFERENCES

- Abd El-Moniem, E.M., M.Z. El-Shinawy, A. F. Abou Hadid, A.M. Eissa, and A.S. El-Beltagy. 1996. Effect of nitrogen form on lettuce plant grown in hydroponic system. *Acta Hort.* 434: 47–52.
- Abou Hadid, A.F., and A.S. El-Beltagy. 1991. Pan evaporation as affected by plastic house-microclimate. *Acta., Hort.*, 287: 35–46.
- Abou Hadid, A.F., and A.S. El-Beltagy. 1992. Water balance under plastic house conditions in Egypt. *Acta Hort.*, 303: 61–69

- Abou-Hadid, A.F., M.Z. El-Shinawy, A.S. El-Beltagy, and S.W. Burrage. 1992. Relation between water-use efficiency of sweet pepper grown under Nutrient Film Technique and rock-wool under protected cultivation. *Act Hort.*, 323: 89–96.
- Bilbro, J.D. 1975. Relationship of air temperature to first bloom dates of cotton. *Texas Agric. Exp. Sta. Misc. Pub. No. 1186*. College Station, Tx., USA.
- Doneen, L.D., and D.W. Westcot. 1988. Irrigation practices and water management. *Oxford and IBH Publ. Co. PVT.*, New Delhi, India.
- Eissa, M.M., A.F. Abou-Hadid, A.S. El-Beltagy, and A.A. Omara. 1991. Relationship between Class “A” Pan evaporation and water vapor pressure deficit under plastic house. *Egypt. J. Hort.* 18: 131–139.
- El-Behairy, U. A., A. F. Abou-Hadid, A. El-Asdoudi, and S. Burrage. 1996. Effect of phosphorus application on mineral contents of cucumber grown in NFT. *Acta Hort.* 434: 21–27.
- El-Shinawy, M.Z., M. A. Medany, A.F. Abou-Hadid, E.M. Soliman, and A.S. El-Beltagy. 1996. Lettuce plant growing: comparative water-use efficiencies of production systems. *Acta Hort.* 434: 53–57
- Fry, W.E. 1982. Principles of plant disease. Academic Press , New York. USA.
- Hamdy, A., and C. Lacirignola, 1999. Mediterranean water resources: Major challenges towards the 21st century. Tecnomarek, Bari, Italy.
- Harsh, S. B. , J. W. Lloyd, and L. R. Borton. 1989. Models as an aid to decision-making. *Acta Hort.* 248 : 27 – 48.
- Ismail, A.S., A.M. Eissa, A.S. El-Beltagy, and A.F. Abou-Hadid. 1996. Iron-zinc and phosphorus relationship in nutritional of tomato seedlings grown on sandy soil. *Acta Hort.* 434: 77-84.
- Israelson, O.W., and V. E. Hansen. 1962. Irrigation principals and practices (3 ed), Wiley, New York, USA.
- Jones, A. L., P. D. Fisher, and L. Seem. 1984. Development and commercialization of an in-field microcomputer delivery system for weather - driven predictive models. *Plant Dis.* 68: 458–463.
- Krug, H. 1989. Growth models as an aid for planning vegetable production in greenhouses. *Acta Hort.* 260 : 391 – 400.
- Lichev, S. 1965. Effect of the weather condition on the emergence and development of cotton. (Bulg.) *Rast. Nauki* (1964), 1, No. 10: 93–101. (Cited after Field Crop Labs., 18, No. 4).
- Gregory, P.J. 1991. Concepts of water-use efficiency. p. 9 – 20. *In*: H.G. Harris, P.J.M. Cooper, M. Pala (ed) Soil and crop Management for improved water-use efficiency in rainfed areas, ICARDA, Aleppo, Syria.
- Makram, E. A., K. A. Ziadah, and W.M. El-Shazly. 1995. The proper soil temperature for sowing cotton early. *J. Agric. Sci. Mansoura Univ.* 20(7):3191.
- Medany , M. A., M. M. Wadid, and A. F. Abou Hadid. 1997. New extension system

- for modern irrigation management in Egypt. 3rd Int. Symposium on Sensors in Horticulture, Aug. 17 – 21, 1997, Tiberius, Israel.
- Nelson, L.E. 1968. Effect of root temperature variation on growth and transpiration of cotton (*Gossypium hirsutum* L) seedlings. *Agron. J.* 1967, 59, 395. (Bibl. 14, Mississippi Agric. Exp. Stn. State College).
- Royer, M.H., and J. M. Russo, 1989. Plant disease predication using a meso-scale weather forecasting technique. *Plant Dis.* 73: 618 – 624.
- Tanner, C.B., and T.R. Sinclair. 1983. Efficient water-use in crop production: research or re-search? Cited in *Limitations to Efficient Water-Use in Crop Production*. Taylor et al, Amer. Soc. Agron., 1 – 25.
- Sinclair, T.R., C.B. Tanner, and J.M.Bennett. 1984. Water-use efficiency in crop production. *Bio. Sci.* 34: 36 – 40.
- Zayed, A., A.F. Abou-Hadid, U. El-Behairy, and A.S. El-Beltagy. 1989. The use of Nutrient Film Technique for the commercial production of greenhouse tomato in Egypt. *Egypt. J. Hort.* 16: 101 – 110.

Water Quality for Pressurized Irrigation Systems

Fawzi Karajeh

*International Center for Agricultural Research in the Dry
Areas (ICARDA), Aleppo, Syria*

ABSTRACT

Pressurized irrigation systems, if designed and managed properly, can conserve water and fertilizer and improve yields by precisely controlling water and nutrient applications to plants, such as in the case of drip and micro-irrigation systems. Emitters with small micro-outlets (0.2–0.5 mm in diameter for drip, and 0.5–1.5 mm in micro-sprinklers) are used to deliver the required flow rates. The combination of *slow application rates, low pressure, and small openings create serious clogging problems* when using water with high pH levels which contains high concentrations of calcium, magnesium, and carbonate. Clogging of emitters reduces the emission uniformity, which causes excessive variability in emitter discharge rates, in turn, lowers yield and/or reduces water and fertilizer-use efficiency. The paper covers criteria to assess irrigation water quality for its clogging potential and the water treatments required, if such water alone is used for irrigation or for fertigation, to prevent clogging in low-flow pressurized irrigation systems.

INTRODUCTION

Micro-irrigation systems can be profitable if the right steps are taken to prevent clogging through the use of proper management and system design, and optimum plant growth can be attained.

The quality of water resources in a country is controlled primarily by the interaction/reaction of the water molecules with geophysical, geo-biological, geo-chemical, human intervention processes of the hydrological system. After all, the quality of a water system affects the suitability of a farming system and the associated natural resource base. Water availability without appropriate quality criteria may not be available for certain uses, or may not be useable at all. Therefore, water quality is a measure of the availability of a water resource for a particular use. Agriculture is the main water-demand sector in most countries, particularly in arid and semi-arid regions. Water quality means different things to different water sectors. For irrigation, water suitability is related to its effect on soils, crops, irrigation system, and on irrigation management.

Water suitable for surface irrigation may not be recommended for overhead sprinkler irrigation. Leaf burn is caused by sodium and chloride absorption when the rate of evaporation is high. Conditions such as low humidity, high temperature, and winds can increase the concentration of these ions in the applied water on the leaves between irrigation events. Furthermore, not all water suitable for overhead sprinklers can be used safely in micro-irrigation or drip irrigation systems.

The small outlets of micro-irrigation or drip irrigation systems can be readily clogged by poor water quality. Clogged emitters reduce the uniformity of water and nutrient applications, and therefore decrease the yield. The success of pressurized irrigation systems, particularly drip, and micro-irrigation depends on the ability of the system manager to prevent emitter clogging. Emitter clogging can be attributed to the following causes: particulate matter, biological growth, chemical precipitates, poor system design and management, or combinations of these factors.

WATER QUALITY FOR IRRIGATION

Irrigation water quality should be assessed to determine its suitability for irrigation. Knowledge of the chemical characteristics of water should be established to design a water management scheme to overcome potential soil salinity buildup problems, infiltration rate reduction problem, ion toxicities from using the water, and fertilizer solubility and compatibility.

Table 1 provides the guideline for evaluation of water quality for irrigation. The guideline is based on assumptions; for detailed information about these assumptions, refer to FAO publication (1989). It is reported that the guideline is being used successfully in general irrigated agriculture, groundwater, drainage water, and treated wastewater. Table 2 shows relative clogging potential of irrigation water when using pressurized low-flow irrigation systems.

These guidelines are the first step toward understanding the limitation associated with using irrigation water for agriculture production using such irrigation systems. However, from irrigation management point of view, these guidelines alone may not be sufficient to guarantee a successful agricultural operation. Knowledge regarding soil type, depth, fertility level, crop type, crop placement in the ground, crop rotation, management skills of the irrigation system operators are also factors that help to facilitate a successful use of irrigation water with various quality to produce agronomic output in a sustainable way.

Water Quality and Fertigation (i.e., Phosphorus)

Fertigation is the application of both water and nutrients through water lines to small emitters in precisely measured amount. Fertigation claims many advantages, including less labor required, uses less energy, the nutrients are precisely applied

Table 1. Guidelines for interpretation of water quality for irrigation.

Water Characteristics	Degree of Problem		
	None	Increasing	Severe
<u>Salinity</u>			
(affects water availability to crop)			
Total dissolved salts, (TDS), (mg/l)	500	500 – 2000	> 2000
Electrical conductivity of irrigation water, (Ecw), (dS/m)	0.75	0.75 – 3.0	> 3.0
<u>Permeability</u>			
(affects infiltration rate of water into soil)			
Adjusted Sodium Adsorption Ratio, (SAR) = $0 - 3$ and EC_w (dS/m) =	> 0.7	0.7 – 0.2	< 0.2
= $3 - 6$ =	> 1.2	1.2 – 0.3	< 0.3
= $6 - 12$ =	> 1.9	1.9 – 0.5	< 0.5
= $12 - 20$ =	> 2.9	2.9 – 1.3	< 1.3
= $20 - 40$ =	> 5.0	5.0 – 2.9	< 2.9
<u>Specific Toxicities</u>			
(affects only sensitive crops, trees, vines)			
Sodium (mg/l)			
Surface irrigation	< 70	70 – 200	
Sprinkler irrigation	< 70	> 70	> 200
Chloride (mg/l)			
Surface irrigation	< 140	140 – 350	
Sprinkler irrigation	< 100	> 100	> 350
Boron (mg/l)			
Suitable for all crops (except lemon and blackberry)	< 0.5	> 0.5	
Suitable for most vegetable and field crop	0.5 – 0.75	> 0.75	
Suitable for some vegetable and field crop (tomato, Alfalfa, sugar beets, celery)	0.75 – 2.0	> 2.0	
<u>Miscellaneous Effects</u>			
(affects only susceptible crops)			
Nitrate – N (NO_3N) or Ammonium – N (NH_4N), (mg/l)	< 5	5 – 30	> 30
Bicarbonate (HCO_3), (mg/l)	< 190	90 – 500	> 500
{overhead sprinkling}	6.5 – 8.4		
PH			

Source: Compiled from FAO (1989); Hanson et al. (1993).

and regulated, using less fertilizers, nutrients are distributed more evenly throughout the entire root zone, and fertilizers being applied any time with irrigation water.

Table 2. Relative clogging potential of irrigation water in drip irrigation systems.

Water Characteristics	Degree of Problem		
	Minor	Moderate	Severe
pH	< 7.0	7.0 – 8.0	> 8.0
Bacterial Population (Maximum number per ml)	< 10,000	10,000 – 50,000	> 50,000
(Units)	(mg/l)	(mg/l)	(mg/l)
Maximum			
Suspended Solids	< 50	50 – 100	> 100
Total Dissolved Solid	< 500	500 – 2000	> 2000
Manganese Concentration	< 0.1	0.1 – 1.5	> 1.5
Iron Concentration	< 0.2	0.2 – 1.5	> 1.5
Hydrogen Sulfide Concentration	< 0.2	0.2 – 1.5	> 2.0

Source: Schwankl et al., (1995).

Most dry phosphorus (P) fertilizers produced for general agricultural application should not be injected into irrigation water because there are insoluble. Monoammonium phosphate (12–61–0), diammonium phosphate (21–53–0), monobasic potassium phosphate (0–52–34), phosphoric acid, urea phosphate, liquid ammonium polyphosphate (10–34–0), and long-chain linear polyphosphates represent water-soluble phosphate fertilizers that can be used on fertigation (Burt et al., 1995). Nevertheless, these fertilizer grades and types, if injected to irrigation water containing high level of water hardness ($\{[Ca] + [Mg]\}/[HCO_3]$), may still have precipitate problems.

Generally speaking, for fertigation, growers should use acidic form of P fertilizers rather than neutral forms (Burt et al., 1995). Solution acidity of pH is an important factor in P solubility. The ideal pH for P solubility is between 6 to 7. At pH below 6, P reacts with iron (3+), aluminum (3+), and manganese (2+). While at pH above 7, P precipitates with calcium and magnesium. Water temperature is another water quality parameter that influences the solubility of P fertilizes. Generally speaking, the solubility of P fertilizer decrease as water temperature decreases. Fertilizer solution pH has some effects on irrigation water, soil, and soilless culture. High pH values (> 7.5) in the irrigation water are undesirable because calcium and magnesium carbonate and orthophosphate precipitation may occur in the irrigation line and emitters. High soil pH may reduce zinc, iron, and P

availability to plants. However, nitric or phosphoric acids can be used to reduce the pH of the irrigation water to 5.0, while a lower pH value is not recommended to avoid negative impact on the plant's root development (Fraser, 1998).

Table 3 provides useful information for some injected P fertilizers. However, some fertilizers or other agriculture material may decrease the solubility of the material being used, and might detract from the data provided from the table. As reported by Burts et al., (1995), the following are general rules regarding P compatibility:

1. Phosphorus and calcium coming from fertilizer or irrigation water, when in solution together, form di-and tri-calcium phosphate, which are *insoluble phosphates*. These precipitated forms can clog irrigation emitters and lines.
2. Phosphorus, ammonium-nitrogen, and magnesium (from fertilizer or irrigation water), when in solution together, sometimes can form magnesium phosphates or magnesium ammonium phosphates, which are *insoluble and clog irrigation lines*.
3. Phosphorus and iron, when in solution together, can form *iron phosphates, which are insoluble*.
4. Ammonium ortho-polyphosphate materials (10-34-0 and 11-37-0) and monoammonium and diammonium phosphate (12-61-0 and 21-53-0) dissolved in hard water ($\text{Ca} + \text{Mg} > 50 \text{ mg/l}$ and bicarbonate $> 150 \text{ mg/l}$ or $\text{Ca} + \text{Mg} > 75$ and bicarbonate $> 100 \text{ mg/l}$) form precipitates that cause plugging in low-flow pressurized irrigation system.

Table 3. Solubility information on various phosphorus fertilizer commonly used to prepare fertilizer solutions and/or for application through irrigation water.

Phosphate Fertilizers	Grade	Form	Solubility
			----gm/100 ml----
Ammonium Phosphate	8-24-0	$\text{NH}_4\text{H}_2\text{PO}_4$	Moderate
Ammonium Polyphosphate	10-34-0	$(\text{NH}_4)_5\text{P}_3\text{O}_{10}$ & others	High
Ammonium Polyphosphate	11-37-0	$(\text{NH}_4)_5\text{P}_7\text{O}_{16}$ & others	High
Phosphoric Acid, green	0-52-0	H_3PO_4	45.7
Phosphoric Acid, white	0-54-0	H_3PO_4	45.7

Source: California Fertilizer Association (1980).

Management Aspects

All chemical compounds should be compatible with water quality, including fertilizers, acids or other chemicals to prevent corrosion and deterioration of the irrigation systems' components. Also all components must be properly installed and managed. A regular maintenance schedule should be developed and adjusted as field experience is gained. *A maintenance schedule should include flushing of the filters, chemical injections, flushing of the pipelines and routine system inspections, checks of flow rates, pressures, and emitter performance.* Routine system inspections should be conducted to ensure that all components are functioning as designed and that clogging does not occur. This requires visual inspections for leaks or other component failures, and the reading of pressure gauges and flow meters to ensure that design flow rates are being met.

To prevent emitter clogging, micro-irrigation systems must be properly designed and emitter must be properly selected. Turbulent-flow emitters have very desirable flow characteristics with respect to emitter clogging. However, if the water available for use contains constituents that have potential for chemical or biological precipitates alone or in combination (Table 2), treatment must be considered. Inorganic constituents of water, particularly calcium carbonate (lime), iron, and manganese can cause chemical precipitation that causes emitter clogging. The presence of organic material and such bacteria that uses such chemical as a source of energy may even further complicate the precipitation processes. Table 4 summarizes recommended treatments for various types of chemical and biological clogging.

To improve fertigation efficiency, the users are asked to perform the "jar test" before fertilizer-use in pressurized irrigation systems. According (Burt, 1995) "a jar test involves putting some of the fertilizer solution into a jar of irrigation water, and watching for any precipitate or milkiness which may occur within two hours. If cloudiness does occur, there is a chance that injection of that chemical will cause line or emitter plugging. If different fertilizer solutions are to be injected simultaneously into the irrigation system, mix the two in a jar. When testing the compatibility or acceptability of any fertilizer solution or combination of solutions, use the approximate dilution rate that would be expected when the product are injected into the irrigation system."

Water-use efficiency is being discussed again and again as a mean of producing more food with less water. Ways to improve it are already established in the form of plant selection and management, better water utilization, or by adaptation to more appropriate irrigation technologies. Although it is important to continue searching for ways to encourage farmers to improve water-use efficiency, we should realize that any changes to the existing system or adoption of new technology that improves water saving may entail some risk to the growers from their point of view. The risk is mainly an economic one.

Table 4. Water treatments to prevent clogging in drip irrigation system.

Problem	Recommended Treatment Option
Carbonate precipitation (white precipitate) HCO_3 greater than 100 mg/l and pH greater than 7.5	1. Continuous injection: maintain pH between 5 and 7. 2. Slug injection: maintain pH at under 4 for 30–60 minutes daily.
Iron precipitation (reddish precipitate) Fe concentrations greater than 0.1 mg/l	1. Aeration and settling to oxidize iron. (Best treatment for high concentrations 10 mg/l or more.) 2. Chlorine precipitation–injecting chlorine to precipitate iron: a) Use an injection rate of 1 mg/l of chlorine per 0.7 mg/l of iron. b) Inject in front of the filter so that the precipitate is filtered out.
Manganese precipitation (black precipitate) Mn concentrations greater than 0.1 mg/l	1. Inject 1 mg/l of chlorine per 1.3 mg/l of manganese in front of the filter.
Iron bacteria (reddish slime) Fe concentrations greater than 0.1 mg/l	1. Inject chlorine at a rate of 1 mg/l of free chlorine continuously or 10 to 20 mg/l for 30 to 60 minutes daily.
Sulfur bacteria (white cotton–like slime) Sulfide concentrations greater than 0.1 mg/l	1. Inject chlorine continuously at a rate of 1 mg/l per 4 to 8 mg/l of hydrogen sulfide, or inject chlorine 2. intermittently at 1 mg/l free available chlorine for 30 to 60 minutes daily.
Algae, slime	1. Inject chlorine at a rate of 0.5 to 1 mg/l continuously or 20 mg/l for 20 minutes at the end of each irrigation cycle.
Iron sulfide (black sand–like material) Fe and sulfide concentrations greater than 0.1 mg/l	1. Dissolve iron by injecting acid continuously to lower pH to between 5 and 7.

Source: Schwankl et al. (1995).

Therefore, one way to approach growers not only from water conservation angle, but instead from improving resources efficacy that includes most agronomic inputs. When one optimizes the production system to include costs of water delivery and maintenance, fertilizers and fertility application, pesticides, energy, soil quality maintenance, etc. By doing that, a better understanding of economic outputs can be achieved and, in turn, improve growers' acceptability. As a result, a better argument could be put to the growers to adopt new technologies that improve resources management, the author believes that without an adequate profit margin, farmers cannot justify soil and water conservation. One has to prove that efficient irrigation practices produces additional return to the growers, then and only then growers will be willing to voluntarily adopt recommended technologies.

In addition to increased research and development to improve water-management efficiency and fertigation efficiency, a need exists, to name few, for:

1. More large-scale and on-farm demonstrations of improved techniques and systems in order to accelerate their early and widespread adoption.
2. More research on different water quality and fertilizers solubility and compatibility in the region. Testing different water quality and the different P fertilizers available in the market recommended for fertigation. Also testing with any other fertilizers that are being recommended to be used in combination or in simultaneously with P fertigation.
3. Develop an optimization model to focus on resource efficiency and growers' profit.
4. Improved coordination and cooperation among private and public sources for research support. Private support for research through colleges, universities, and research centers should continue and increased.
5. A formation of technology transfer and adoption strategies through qualified agriculture extension service agents.
6. Help/encourage the development of on-farm Water Management Mobile Laboratory to address the issue of soil and water conservation, fertigation technologies, energy conservation, and natural resources base protection and management.

CONCLUSIONS

Water availability in any country is measured not only by the volume of available water resources but also by the quality of that water. Depending on the water sector

uses the water, one water quality criterion is different from one uses to another. Drinking water criteria are usually more stringent than water quality criteria for irrigation. Furthermore, water quality for pressurized irrigation systems is required to have less impurities than the one used for surface irrigation.

Salinity is a major water quality criterion for irrigation; the presence of Ca, Mg, and HCO_3 concentration at high level in irrigation water may require special treatment to avoid interaction/reaction which leads to precipitates that cause clogging problem in low-flow pressurized irrigation systems. The high pH water (more than 7) in this case may also lead to precipitates, particularly if the water is used for fertigation. Water temperature in relation to fertigation has also an impact on the fertilizer-use efficiency and irrigation system performance.

Irrigation efficiency improvement is part of resource efficiency strategy that leads to a positive economic increase to the bottom line of a grower, and is the most convincing way to advance growers adoption to improved water and nutrient management strategy.

REFERENCES

- Burt, C., K. O'Connor, and T. Ruehr. 1995. Fertigation. *Publ.*, Irrigation Training and Research Center, Calif. Polytechnic State Univ., San Luis Obispo, Ca., USA.
- California Fertilizer Association. 1980. *Western Fertilizer Handbook*, 7th Ed. The Interstate Printers and Publ., San Luis Obispo, Ca., USA.
- Hanson, B., S. Grattan, and A. Fulton. 1993. Agricultural salinity and drainage. *Publ.* Univ. Calif. Irrigation Program, Univ. Calif. Davis. Ca., USA.
- Hoffman, G., J. Rhoades, J. Letey, and F. Sheng. 1992. Salinity management, management of farm irrigation systems. Amer. Soc. Agric. Engin., Hoffman, Howell, and Solomon. St. Joseph, MI.
- FAO. 1989. Water quality for agriculture. *FAO Irrigation and Drainage Paper* N°. 29, Rev.1., FAO, Rome, Italy.
- Fraser, D. 1998. The lowdown on fertigation. *Irrigation J.* 48(5): 20–22.
- Scwankl, L., B. Hanson, and T. Prichard. 1995. Micro-irrigation of trees and vines. *Publ.* Univ. of Calif. Irrigation Program, Univ. Calif., Davis, Ca., USA.

SECTION II:

NUTRIENT MANAGEMENT REQUIREMENTS AND INTERACTIONS

Crop Nutrient Requirements

Mohamed M. El-Fouly

*Botany Department, National Research Centre, Dokki,
Cairo, Egypt*

ABSTRACT

Pressurized irrigation systems provide a good tool for optimizing nutrient management. This can be only achieved by determining the accurate crop nutrient requirements, and applying fertilizers based on the requirements. Methods used for the determination of nutrient requirements are: *deficiency symptoms, soil tests, plant analysis, field trials, and the balance method*. The balance method is based on estimating the amount of nutrients removed by a target yield of a crop and what is provided by the soil and other inputs, and providing the difference through fertilizers. Crop nutrient requirements are influenced by expected yield quantity and it's quality. To determine the nutrients to be provided through fertilizers, the appropriate crop nutrient requirements and the efficiency of use of the fertilizers should be taken into consideration. Irrigation system, water quality and the economics are also important factors in this respect.

INTRODUCTION

Pressurized irrigation systems offer an excellent opportunity to provide water to the crop at narrow and regular intervals and in well measured quantities based on the actual plant needs and considering environmental conditions. Using the irrigation system to provide nutrients to the crop is becoming a common practice (*fertigation*). Fertigation is a better way of nutrient management than the other traditional ways of applying nutrients (Rolston et al., 1981 ; Lelkes, 1996), and it helps a lot in reaching the goal of good nutrient management, which should aim to provide the crop with the needed nutrients at each growth stage with maximum efficiency possible for *economically, environmentally optimum and high quality yields* under conditions of a given farming and irrigation system. Several meetings were organized in the past few years in the region to exchange ideas and information and results of research on fertigation (FAO, 1991, Hamdy, 1991a; Technion, 1995; FAO, 1998).

CALCULATING NUTRIENT REQUIREMENTS AND FERTILIZER NEEDS

Total nutrient requirements are the amounts of each nutrient needed during the whole growth period to produce an estimated yield goal and defined quality. Fertilizer needs are the amounts of each nutrient (fertilizer) which should be provided to the crop to supplement the amounts taken from the soil and other inputs to cover the total requirements. Thus, fertilizer needs are: total requirements (nutrient provided from the soil and other inputs) multiplied by the use efficiency of the fertilizers used.

To calculate fertilizer needs under pressurized irrigation systems, the following pre-requisite information and data should be available:

- Accurate figures for total requirement of each nutrient (crop, cultivar) during the growth cycle.
- Requirements of each nutrient and the optimum ratio between nutrients at different growth stages.
- Content and distribution of nutrients in the soil (wetted area – root growth area) and soil characteristics.
- Quantitative information about possible nutrient inputs other than from the soil (organic manure, water ...etc.).
- Good control of the irrigation system (even distribution throughout the field).
- Information on the distribution of the applied nutrients in the soil.
- Water analysis.
- Availability of special quality of fertilizers suitable for fertigation and their nutrient contents and forms.
- The efficiency of fertilizer use under the system of irrigation used and the prevailing farming system.
- Economics of fertilizer use (prices of fertilizers, cost of application ... etc.).

Total Nutrient Requirements and Fertilizer Needs

Total nutrient requirements differ according to several factors:

Crop

It is well known that crops differ in their quantitative.

Cultivar

Recently, it was found that cultivars of the same crop differ in their efficiency of using nutrients, which might affect the total nutrient requirement. Nutrients affect not only the quantity of the yield of the crop but also the quality. For example, K is known to affect quality of some fruit crops, especially citrus. This should be taken into consideration when calculating requirements for a high quality yield.

Nutrient requirements can be estimated by different methods, some of which are just indicative or qualitative, while others are quantitative, e.g., visual symptoms, soil testing, plant analysis, field trials and balance method.

Visual Symptoms

When a crop is grown in a media poor in one or more nutrients, visual symptoms of the deficiency of such nutrient appear. Visual symptoms of nutrient deficiency are very specific for the particular nutrient and crop. However, this method is a *qualitative* one. Moreover, in some cases visual symptoms of one nutrient might hide symptoms for another one or overlap with each other and make diagnosis difficult. Thus, this method gives information on nutrients deficiency. However, it is not easy to recognize and is *not quantitative*. Symptoms normally appear too late to use accurate remedy measures, and do not give indicators for quantitative figures for fertilizer needs.

Soil Testing

Soil testing methods give information on the availability of nutrients to plants, the different soil factors affecting nutrients uptake, as well as nutrient leaching/ fixation and movement, ... etc. Each method should be calibrated by field trials under different farming systems and crops to give quantitative recommendations (Ryan and Matar 1992).

Soil testing assists in classifying (semi-quantitative classification) soils according to their nutrient content in different classes (Table 1), and indicate fertilizers needs. Critical levels should be given for each soil type / crop. It is a good tool to determine limiting nutrients in a given soil. However, adequate or excess amounts of a nutrient in the soil do not mean that all the amounts will be taken up by the plants in adequate quantities. This method was used very successfully in different countries and is one of the classic methods for determination of fertilizers needs especially for macronutrients. It is also an essential element in the determination of fertilizer needs, using the *balance method*. There are many chemical extractants used in the determination of nutrients in soil

samples; also water is used as soil extractant and gave good results in particular cases.

Table 1. Soil nutrient contents and fertilizers recommendations.

Class	Soil Nutrient Level	Fertilizer Needs	Micronutrient
A	Very low	Very high	High
B	Low	High	–
C	Medium	Removal	Removal risk avoiding by some crops only
D	High	50% Removal	–
E	Very high	No need	No need

Source : VDLUFA (1984)

Plant Analysis

Plant analysis is carried out using different plant parts for different purposes:

Total Plant, including Root: Plant analysis is the best method for the determination of the total plant nutrient requirements. Analysis of the total plant during the different growth periods and partitioning of nutrients is a very useful tool regarding the requirements for each nutrient during the different growth stages.

Leaf /Petiole: Analysis of leaves or a leaf part (petiole/ blade) is widely used to check the nutritional status of a crop. Based on leaf /petiole analysis and accumulated information and according to the critical values for each nutrient /crop, supplementary fertilizer needs can be quantitatively calculated and added during the vegetation period. Leaf analysis is a very useful tool used with great successes in fruit trees and vegetables and some field crops. It can be used for fertigated crops.

Plant Sap: Analysis of the sap of leaves, parts of them or total plant at early growth stages is used to determine fertilizer needs at these growth stages. It is mostly used in vegetable crops under protected environments (greenhouses), mainly to correct and adjust nutrient supply according to the physiological crop needs.

Flowers: This kind of analysis is newly introduced and is mainly used in deciduous fruit trees as an easy method to determine the nutritional status and fertilizer needs, of the trees early in the season. It can be of help to adjust the fertilizer needs of the trees.

A summary of the suitability of soil testing and plant analysis for different purposes is given in Table 2. Critical levels used for plant analysis differ according to crop / cultivar, analyzed part of the crop, and growth stage at which the samples are taken. Good interpretation of the results depends on availability of sufficient ranges for each crop /cultivar, and availability of optimum ratios between each two nutrients. This can lead to calculate the deviation from the optimum for a given nutrient and the gradient of deficiency. Besides being the only tool to determine total nutrient requirement, plant analysis provides information on:

- What the plant could absorb from the nutrients available in the soil or/and added as fertilizers.
- The nutritional status of the crop in a given time.
- The efficiency of the applied fertilizer program.

Table 2. Suitability of different methods for estimation of fertilizer needs

	Method /Parameter				
	Limiting Nutrient	Vegetables	Field Crops	Fruits Growth Stage	Fertilizer Recommendations
<i>Visual Symptoms</i>	++			+	
<i>Soil Testing</i>					
Soil properties					++
Extractable nutrients	++			++	++
Water Soluble nutrients (vegetables)	+			++	++
<i>Plant Analysis</i>					
Total plant		+++	+++	+++	
Leaf	+++			+++	++
Sap	++			++	++
Flower (fruit trees)	+			+	+
Petiole (some nutrients and crops)				+++	+++
<i>Balance Method</i>					+++
+ Can be used	++ Used	+++ Good method			

Through the determination of the uptake curves, peaks for high requirements of the nutrients during growth period can be fixed (Fig. 1), and fertilizer application rates/concentrations can be adjusted accordingly.

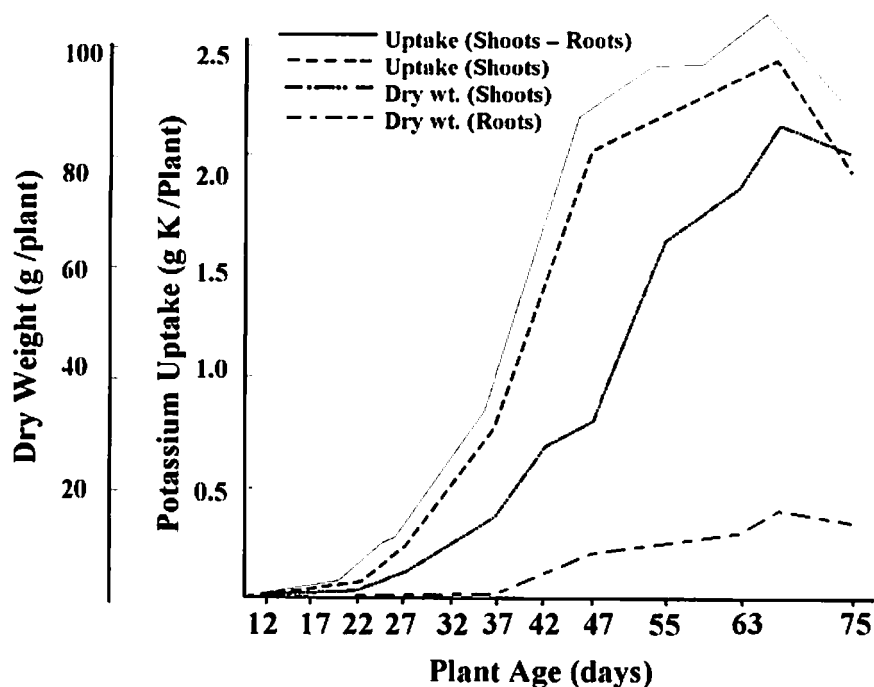


Fig. 1. Uptake curves of NPK by maize, indicating uptake peaks and decrease of nutrient contents at late growth stages. Source: El-Fouly et al. (1991).

Field Trials

Until recent, field trials by using increasing quantities of nutrients fertilizers were the main method used to determine fertilizer needs, based on response curves. The method is good, but cannot be the only method to be used. It is relevant only to one site or different sites with very similar conditions and is good and practical in case of one limiting nutrient (Fig. 2). When combinations of different limiting and deficient nutrients have to be tested, it becomes very difficult (Colwell, 1994) or even impossible to design a good simple experiment and make calculations for fertilizer needs. It is impossible to use it accurately in case of using compound fertilizers of different nutrient ratios or different nutrient forms (case of fertigation). In this case, it delivers only comparative results on the effect of the different compounds, and not on the fertilizer nutrient needs.

Balance Method

This method is based on calculating total nutrient requirement, then estimating the

fertilizer needs. This is based on nutrient output and input *Output* in the Total nutrient requirements based on crop uptake and removal. *Initial inputs* are from soil, air, water, and other sources, rather than fertilizers. Thus,

$$\text{Nutrient Needs} = \text{Total Nutrient Requirements} - \text{Initial Inputs}$$

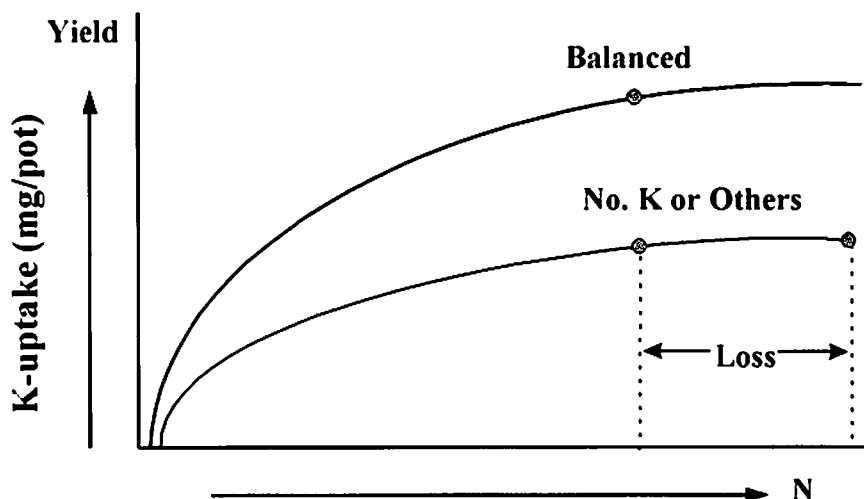


Fig. 2. Balanced nutrient management for yield and efficiency of fertilizers.

Estimation of Total Crop Nutrient Requirements

This estimation is based on the analysis of the total plant, including roots. In this connection, we should distinguish between two values, *removal* and *total uptake*.

- Removal /area /crop is the amount of each nutrient removed from the field by a crop at a definite yield level at harvest. It includes amounts of the nutrient in the economic parts as well as all other parts of the crop not remaining in the field after harvest.
- Total uptake /area /crop is the maximum amount of a nutrient taken by a crop during the vegetation period including the roots.

Normally, uptake is higher than the removal, not only because it includes the nutrients in the roots, but because the maximum nutrient taken up by the plant is normally at a growth stage before harvesting time and after that it declines (Fig. 3). Soil water content influences the nutrient uptake. In general, it was found that

increasing soil water content increases the nutrient uptake under different levels of the nutrient in the soil (Fig. 3), which indicates that the uptake amounts and curves under the pressurized irrigation systems will be different than those determined under other irrigation methods (or rain fed crops), and thus have to be established.

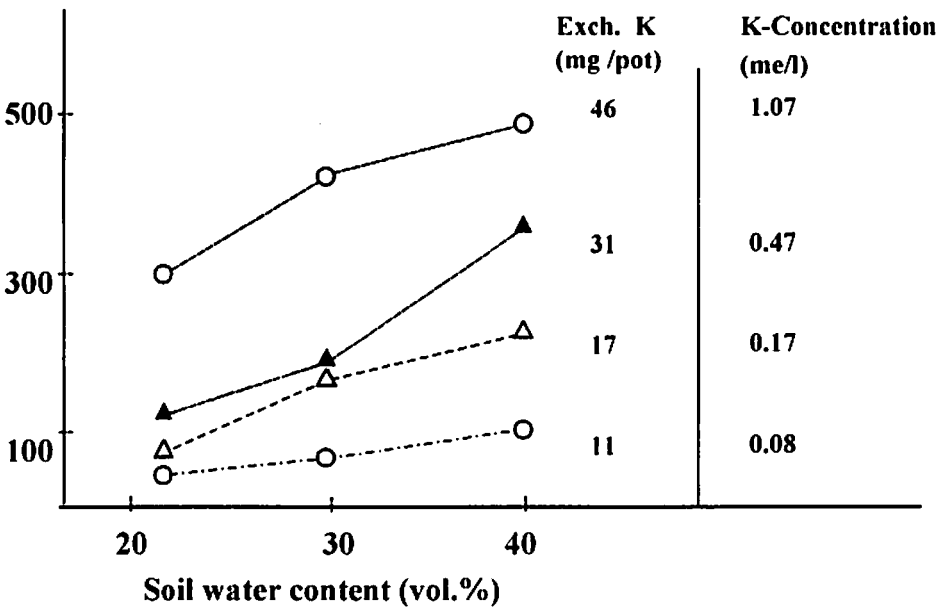


Fig. 3. Soil water content effect on K-uptake at four levels of potassium in the soil. Source: Grimme (1979).

Determining of Total Fertilizer Needs

Total fertilizer needs are calculated based on plant nutrient needs multiplied by the nutrient content in the fertilizer, multiplied by the fertilizer-use efficiency (under given conditions)

Frequency of Fertilizer Application

The distribution of fertilizer application should be coincident with crop growth needs at the different physiological stages based on absorption curves (Jourdan et al., 1998). The pressurized irrigation systems are providing through fertigation a very good tool to provide the crop with nutrients according to its physiological needs. Tables 3 – 6 give examples from Lebanon, South Africa, and Cyprus on how fertilization programs for different fertigated crops are recommended.

Fertilizer Use and Nutrient Availability are affected by:

- Needs according to plant growth stages
- Kind of fertilizer used
- Form of nutrients in fertilizer (Haynes and Swift, 1987)
- Ratio between nutrients for compound fertilizers
- Quality of irrigation water
- Soil characteristics
- Distribution of the nutrient in the wetted area (Bacon and Davey 1985 ; Kafkafi 1994)

Table 3. Fertilization program greenhouse tomatoes (Lebanon).

Week No.	Fertilizer Name	Compound	Quantity -kg /donum-
3	Kristalone	13+40+13	3
4	//	13+40+13	4
5	//	13+40+13	5
6	//	13+40+13	3
		13+5+26+3	2
7	//	13+40+13	2
		13+5+26+3	3
8	//	13+40+13	2
		13+5+26+3	4
9	//	13+5+26+3	6
		19+6+6+1	2
10	//	13+5+26+3	7
		19+6+6+1	2
11	//	13+5+26+3	8
		19+6+6+1	2
12 – 17	//	13+5+26+3	9
	Hydro calcium nitrate	15.5% Ammonia	2
18	Kristalone	13+5+26+3	8
19	//	13+5+26+3	7
20	//	13+5+26+3	6
21	//	13+5+26+3	5
22	//	13+5+26+3	4

General Conditions: Soil analysis before starting fertilization. **Pre-planting** 750 kg/ ha Compound fertilizer “Hydro Complex” (12+ 11+ 18+ 3). This programme is based on fertilizer needs from macronutrients (unit/ha) 200 (N), 135 Phosphate (P_2O_5), 320 Potassium (K_2O).

Table 4. The amount of fertilizer applied at different growth stages (days after emergence) of the potato plant as a percentage of the total amount of fertilizer applied.

Planting	Days After Emergence					
	0-21	22-42	43-63	64-84	85-106	107-128
<i>Early – Medium maturing cultivars (±100 days)</i>						
N	20	26	30	14	10	
P	70	10	15	5	0	
K	20	10	15	30	25	
Ca	0	12	32	30	26	
Mg	0	10	34	33	23	
<i>Medium – Late maturing cultivars (±120 days)</i>						
N	12	15	25	16	16	10
P	70	8	12	5	5	0
K	12	6	17	17	23	15
Ca	0	5	30	24	20	16
Mg	0	4	15	20	24	22

Source: Bester (1995), South Africa

Table 5. Recommended daily rates of N, P, K, for various fertigated vegetable crops, according to their growth stage.

Crop	Growth Stage	Potassium	Ammonium Nitrate	Phosphoric Acid, 85% ¹
	-----days-----	-kg/ha-	---kg/ha---	-----L/ha-----
Lettuce	Transplanting – 15	0.4	1.0	0.2
	16 – 30	2.5	4.0	0.6
	31 – 45	6.0	9.0	1.0
	46 – end	5.0	6.0	1.0
Melons	Seeding-flowering	1.4	2.2	0.7
	Flowering fruit set	2.0	2.7	0.7
Water-melons	Fruit set – ripening	3.0	8.7	1.0
	Ripening – harvest	0.8	2.3	-
Onion	Planting – 3 leaves	2.0	5.8	1.0
	Leaf development	2.7	7.1	1.0
	End leaf development			
	Bulb initiation	3.8	12.3	1.0
		1.3	4.2	0.6

¹Can be replaced by triple superphosphate (TSP) applied before planting. Source: Papadopoulos (1991), Cyprus

Table 6. Recommended daily rates of N, P, K, for various fertigated vegetable crops according to growth stage.

Crop	Growth Stage	Potassium	Ammonium Nitrate	Phosphoric Acid 85%
	-----days-----	---kg/ha---	---kg/ha---	-----L/ha-----
Tomato	Transplanting – 21	2.3	3.6	0.7
Eggplant	22 – 45	3.0	6.1	0.7
	46 – 70	3.0	6.4	0.7
	71 – 110	6.0	12.0	0.8
	110 – end	2.0	8.0	0.5
Pepper	Transplanting – 10	1.0	3.0	1.0
	11 – 30	1.5	4.6	1.4
	31 – 50	2.3	6.4	1.0
	51 – 75	2.5	7.4	1.0
	76 – end	3.8	10.4	0.5
Cucumber squash	Seeding – 30	3.0	4.5	0.7
	31 – 60	4.5	9.6	0.7
	61 – 90	6.0	10.8	1.0
	91 – end	6.0	10.8	-

Source: Papadopoulos (1991).

Factors Affecting Choice of Fertilizer

Fertilizer Characteristics: Total amount of nutrient(s) and form, nutrient concentration, ratio between nutrients, solubility, and pH

Plant: Length of the vegetation period, and physiological needs of the plant

Soil: Texture, and chemical and physical properties

Water: Availability, quality, and method of irrigation

Micronutrients and Fertigation in Middle East

The soil of the this region are mainly characterized by high pH and to some extent

high CaCO_3 content, which negatively affect the availability of micronutrients (El-Fouly, 1983). At the same time, using high-yielding varieties with short growth periods, besides the limited available area for absorption (wetted area) in drip irrigation, increases the demand for micronutrients (El-Fouly et al., 1995). Most of crops under the prevailing conditions in the region suffer from deficiency in more than one of the following nutrients, Fe, Mn, Zn, Cu (El-Fouly et al., 1993) and, in some cases, B and Mo. There is still very contradictory information about the efficiency of using micronutrient fertilizers to the soil through the irrigation water. While some compounds seemed to be effective, others are still debatable (Cadahia et al., 1988 ; Lucena et al., 1991 ; Zekri and Koo, 1992). It is still recommended to use micronutrients, in general, as foliar sprays.

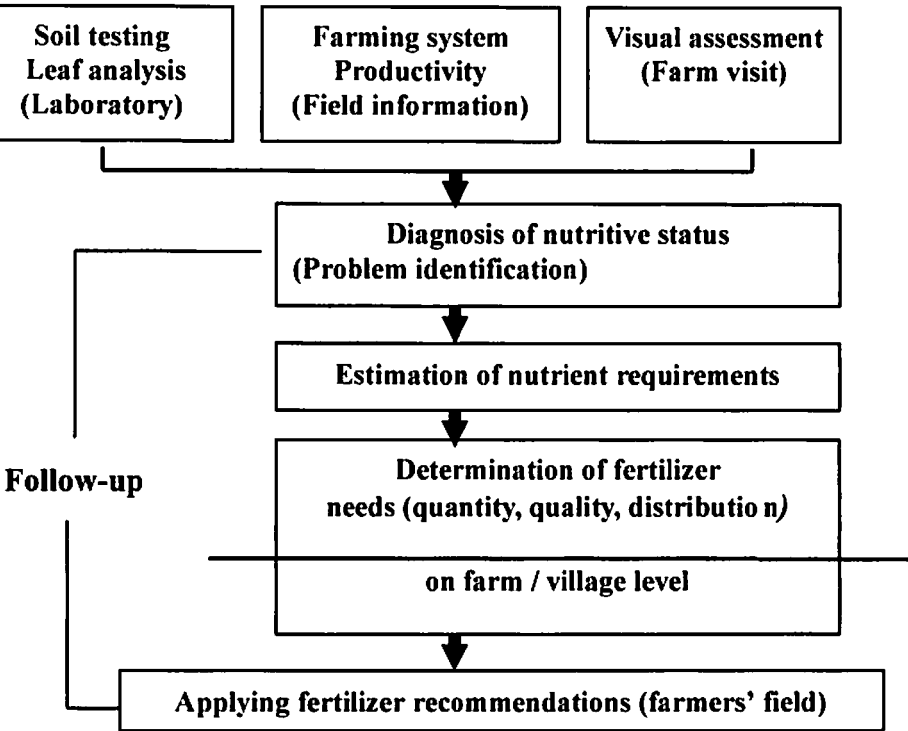


Fig. 4. Systematic and continuous determination of nutrient requirement and fertilizer needs.

Economics

Fertilizer application at farm level is the outcome of many factors (Fig. 4).

Fertigation needs special kind of fertilizers, which are normally more costly than traditional fertilizers, and it needs also special equipment. Thus, the economics of the use are of great importance. The response curves of good managed fertilization system is different than that of the traditional way of using fertilizers. Yield responses are much higher for the same amount of the nutrient. However, it is more difficult to economically evaluate the effect of fertigation rather than the traditional methods of using fertilizers (Battikhi et al., 1991).

CONCLUSIONS

Based on research and practice in the area of applying nutrients in irrigation systems, it is possible to make a few generalizations on what we know and what we need to do to enhance our knowledge of this critically important new technology.

1. Determination of crop total nutrient requirements and fertilizer needs should be mainly based on the *balance methods*, taking other methods into consideration.
2. Quantitative fertilizer recommendation is very specific and varies according to many factors, which should also be taken into consideration.
3. Agricultural extensionists/technicians should be trained on how to calculate recommendations using available local information as much as possible.
4. There are still great need for research on nutrient supply through fertigation to crops regarding the amounts needed at different growth stages for high yield and high quality. Nutrient uptake curves under pressurized systems should be established for major fertigated crops.
5. Movement of different forms of nutrients in different soil types and their availability to plant and thus efficiency of use, should be studied.
6. Exact trials on the use of micronutrients in fertigation versus foliar application should be conducted.

REFERENCES

- Bacon, P.E., and B.G. Davey, 1989. Nutrient availability under trickle irrigation phosphate fertilization. *Fert. Res.*, 19: 159 – 167.
- Battikhi, A., S. Khattar, T. Oweiss, and N. Abou Rub. 1991. Jordan's experience in fertigation. p. 231 – 240. *In Proc. Expert Consultation on Fertigation /Chemigation 8 – 11 Sept.1991, Cairo, Egypt. FAO, Rome, Italy.*

- Bester, G.G., 1995. Fertigation in South Africa. p. 275 – 286. *In Proc. Dahlia Greidinger Symposium on Fertigation*. Mar. 26 – Apr. 1, 1995. *Technicon*, Haifa, Israel.
- Cadahia, C., P. Garcia, J.J. Lucena, M.J. Sarro, and A. Garate. 1988. Solubility of Fe, Mn, Cu and Zn fertilizers as a function of the substrate type in a drip irrigation system. *Acta Hort.*, 222: 179 – 186.
- Colwell, J.D. 1994. Estimating fertilizer requirements. A quantitative approach. p. 262. CAB International, Wallingford, U. K.
- El-Fouly, M. M. 1983. Micronutrients in arid and semi-arid areas: levels in soils and plants and the need for fertilizers with reference to Egypt. p. 163–173. *In Proc. 17th Colloquium Inter. Potash Inst. IPI*, Bern, Switzerland.
- El-Fouly, M.M., A.F.A. Fawzi, and A.A. El-Sayed. 1993. Micronutrients and fertigation. Mimeographed FAO Regional Office for the Near East, Cairo, Egypt.
- El-Fouly, M.M., A.F.A. Fawzi, and A.A. El-Sayed. 1995. Optimizing fertilizer use in oranges through fertigation: A case study. p. 303 – 312. *In Proc. Dahlia Greidinger Intern. Symposium on Fertigation*. Mar. 26 – Apr. 1, 1995. *Technicon*, Haifa, Israel.
- El-Fouly, M.M., A.F.A. Fawzi, A.H. Firgany, and F.K. El-Baz. 1991. Uptake and removal of potassium by maize and effect of potassium sulphate on yield. *Der Tropenlandwirt*, 92: 73 – 79.
- FAO. 1991. Fertigation/Chemigation. p. 207 – 214. *Proc. Expert Consultation Fertigation /Chemigation*, 8 – 11 Sept., 1991. Cairo, Egypt. FAO, Rome, Italy.
- FAO. 1998. *Proc. Regional Workshop on “ Guidelines for Efficient Fertilizer Use Through Modern Irrigation*. 14.–16 Dec., 1998. Cairo, Egypt.
- Hamdy, A. 1991a. Advanced short course on fertigation, p. 248. Beirut, Lebanon 26 Oct.. – 3 Dec. 1995. CIHEAM / IAM – B, Bari , Italy.
- Hamdy, A. 1991b. Fertigation prospects and problems in Italy. p. 296. *In Proc of Expert Consultation “Fertigation /chemigation”*, 8 – 11 Sept. 1991. Cairo, Egypt, FAO, Rome, Italy.
- Haynes, R.J., and R.S. Swift. 1987. Effect of trickle fertigation with three forms of nitrogen on soil pH, levels of extractable nutrients below the emitter and plant growth. *Plant Soil*, 102: 211–221.
- Jourdan, O., B. Bourrie, and F. Etourneau. 1991. Elaboration of curves of absorption of mineral nutrients. Advantages and methodological approach. p. 101 – 106. *In: Proc. Expert Consultation on Fertigation/Chemigation* 8 – 11 Sept., 1991, Cairo, Egypt. FAO, Rome, Italy.
- Kafkafi, U. 1994. Combined irrigation and fertilization in arid zones. *Israel J. Plant Sci.*, 42: 301 – 320.
- Lelkes, J. 1996. Application of chemicals through irrigation systems. *ICID J.*, 45: 125 – 146.

- Lucena, J.J., M.A. Jimenez de Aberasturi, and A. Arate. 1991. Stability of chelates in nutrient solutions for drip irrigation. p. 63 – 67. *In* Y. Chen and Y. Hadar (ed). Iron nutrition and interactions in plants, Kluwer Acad. Publ.
- Papadopoulos, I. 1991. Fertigation in Cyprus and some other countries of the Near East region. p. 67–82. *In*: Proc. of the Expert Consultation on Fertigation /Chemigation. 8 – 11 Sept., 1991, Cairo, Egypt. FAO, Rome, Italy.
- Ryan, J., and A. Matar. 1992. Fertilizer use efficiency under rain-fed agriculture in West Asia and North Africa. p. 288. ICARDA, Aleppo, Syria.
- Rolston, D.E., R.S. Rauschkolb, C.J. Phene, R.J. Miller, K. Uriu, R.M. Carlson, and D.W. Henderson. 1981. Applying nutrients and other chemicals to trickle-irrigated crops. Cooperative Extension. p. 13. Univ. Calif. Davis, CA, USA.
- Technion. 1995. Fertigation. p. 377. *In* Proc. of “Dahlia Greidinger International Symposium on Fertilization”. Mar. 26 – Apr. 1, 1995 *Technicon*, Haifa, Israel.
- VLDUFA. 1984. Ermittlungen des Duengerbedarfs durch Bodenuntersuchungen und Pflanzenanalyse. p. 65. DLG Verlags-GmbH, Frankfurt, Germany.
- Zekri, M., and R.C.J. Koo. 1992. Application of micronutrients to citrus trees through micro-irrigation systems. *J. Plant Nutr.* 15: 2517 – 2529.

Soil Nutrient-Supplying Capacity under Pressurized Irrigation Systems in Morocco

Mohamad Badraoui

*Institute of Agronomy and Veterinary Sciences– Hassan
II, Rabat, Morocco*

ABSTRACT

In arid and semi-arid areas of the Mediterranean region, irrigation is necessary to obtain high and sustainable agricultural production. Among the 1 million hectares of irrigated in Morocco, about 20% is equipped with pressurized irrigation systems. Although considerable efforts have been made in developing irrigation, water-use efficiency, in terms of productivity per m³ of water, needs to be improved through appropriate fertilizer use and soil nutrient management.

In the process of making fertilizer recommendations for farmers, *soil nutrient-supplying capacity* during the growing season is necessary. The objectives of this paper are i) to present different methods of measuring soil nutrient-supplying capacity to crops and ii) to demonstrate the importance of soil properties in understanding the dynamics of nutrients nitrogen (N), phosphorus (P), and potassium (K) and their availability for crops under intensive cropping with pressurized irrigation systems.

Uptake of N, P, and K by crops from non-fertilized soils can be used as minimal values to estimate the *soil nutrient-supplying capacity*. These values are soil- and crop-specific. The rates of nutrients release from the soil under intensive cropping in a limited soil volume (pot experiments) could be used as potential values for the soil nutrient supplying capacity. The *potential buffering capacity* may also be used to determine the ability of the soil to replenish the soil solution by P and K after crop removal. In fertilized soils, the real relative contribution of the soil and applied fertilizer to plant nutrient uptake requires the use of isotopes (¹⁵N and ³²P).

Mini-sprinkler and drip fertigation systems are becoming common techniques used to produce very high vegetable crop yields. Soil reserves of nutrients contribute to a large extent to plant nutrition. More field research is needed to quantify the soil nutrient-supplying capacity of Mediterranean soils under pressurized irrigation systems with intensive cropping.

INTRODUCTION

In Morocco, like in any arid and semi-arid areas of the Mediterranean region, irrigation is necessary to obtain high and stable agricultural production. Up to now, 1 million ha is being irrigated in Morocco using different systems. Because of lower energy costs, large-scale surface irrigation is the most predominant one. In the last 15 years, an important effort has been made to develop localized irrigation systems. The total area equipped with pressurized irrigation systems in Morocco is estimated to about 180,000 ha (Table 1). More than a third of the area irrigated by localized systems is located in the southern region (Agadir and Taroudant). Large-scale sprinkler irrigation is concentrated in the Gharb and Loukkos regions. While sprinkler and center-pivot systems are used mostly for irrigating cereals, corn, sugar beet, and sugar cane, mini-sprinkler and drip irrigation systems are devoted to orchards and vegetable cash crops.

Table 1. Distribution of pressurized irrigation systems in Morocco.

Region	Localized ¹	Center-Pivot	Sprinkler
	-----ha-----		
North-West	5626	1693	130000
Central-North	1285	1916	-
Central	2348	8901	-
Central-South	4266	346	-
Tensift	3466	5680	-
South	11353	1298	-
Total	28344	20812	130000

¹ mini-sprinkler and drip irrigation systems. Source: MADRPM, (1997); Badraoui and Farhat (1997).

Although considerable effort has been made in developing irrigation, water-use efficiency, in terms of productivity per m³ of water, needs to be improved through appropriate fertilizer use and soil nutrient management. In the process of making fertilizer recommendations for farmers, which are based on soil analysis, it is necessary to have at least three important parameters: *a set of soil fertility levels for the major crops* in order to assess soil fertility status, *crop nutrient requirements for the potential yield*, and *soil nutrient supplying capacity* during the growing season.

The availability of a nutrient to plant uptake is related to the soil solution concentration of the nutrient, the soil buffer power, and the effective diffusion coefficient. The best situation is when the soil can provide, at any time during the growing season, enough water and nutrients to meet crop requirement for the optimum yield. Irrigation and mineral fertilizers should be added, only when the

rate of soil nutrient-supplying capacity (SNSC) is lower than the rate of plant nutrient uptake. In this situation, the amount of fertilizer to be added (Q) is based on the following equation:

$$Q = (\text{Crop Requirement} - \text{Soil Supply}) / \text{FUE} \dots\dots\dots(1)$$

The fertilizer-use efficiency is FUE. Accordingly, SNSC is then a key determinant of fertilizer-input requirement.

The objectives of this paper are to i) present the different methods used for measuring soil nutrient-supplying capacity to crops and ii) present some examples from experiments done in Morocco to demonstrate the importance of soil properties in understanding the dynamics of nutrients (N, P, K) and their availability for crops under pressurized irrigation systems.

HOW TO ESTIMATE SOIL NUTRIENT-SUPPLYING CAPACITY?

The most simple and direct way to measure the effective soil supplying capacity of a given nutrient is to determine the plant uptake in plots that did not receive this nutrient. When measured at the maturity stage, it represents the crop requirement. The difference between nutrient uptake in fertilized and unfertilized plots is generally used to calculate the nutrient fertilizer use efficiency (nutrient recovery from fertilizers) by a crop in a given soil.

Numerous soil nutrient availability indices such as *soil fertility tests*, *potential buffer capacity*, *N-mineralization potential* are used to assess the capacity of the soil to supply nutrients to the plants. The *sorption-desorption*, *fixation-release*, and *solubilization-precipitation* reactions permit an understanding of the dynamics of nutrients in the soil and thus their availability to plants (Badraoui et al., 1992a; 1997a; 1997; El Gharous, 1997; Matar et al., 1992; Soudi et al., 1992; Torrent, 1992).

Direct measurements of SNSC are performed by using isotope methods. Introducing ^{15}N and ^{32}P -labelled fertilizers permits discrimination between the source of N and P taken up by the crop. Using these techniques, the relative fractions of N and P derived from the soil and from the fertilizer are given by the following equations:

Fractions of N and P derived from fertilizers:

- $\text{Ndff}(\%) = (\% \text{ } ^{15}\text{N} \text{ atom excess in plant} / \% \text{ } ^{15}\text{N} \text{ atom excess in fertilizer}) \times 100$
- $\text{Pdff}(\%) = (\% \text{ } ^{32}\text{P} \text{ atom excess in plant} / \% \text{ } ^{32}\text{P} \text{ atom excess in fertilizer}) \times 100$

Fractions of N and P derived from soil:

- $N_{dfs} (\%) = 100 - N_{dff}$
- $P_{dfs} (\%) = 100 - P_{dff}$

The amount of soil inorganic N or P is termed “A value”. It is defined by:

- $N-(A \text{ value}) = (N_{dfs} / N_{dff}) \times N \text{ added to the soil (kg/ha)}$
- $P-(A \text{ value}) = (P_{dfs} / P_{dff}) \times P \text{ added to the soil (kg/ha)}$

The results of recent research in the West Asia and North Africa (WANA) Mediterranean region were reported by Abdel Monem and Ryan (1997), Asfary and Charanek (1997), and Moussadak et al. (1997).

SOIL NUTRIENT-SUPPLYING CAPACITY UNDER PRESSURIZED IRRIGATION

Although SNSC determination was not the main objective, data can be derived from many soil fertility and plant nutrition experiments using sprinkler, pivot, or localized irrigation systems in Morocco. However, only few studies used isotope-labeled fertilizers.

Wheat under Central Pivot

A survey of the soil fertility status in relation to wheat productivity was performed in the Bahira region in central Morocco (Farhat, 1995). The 0 to 40-cm surface horizon of 49 plots was sampled and analyzed for available Olsen P, exchangeable K and organic matter contents. Uptake of N, P, and K by wheat was determined at maturity stage and grain yield was measured.

Among the 49 plots, 30 did not receive K fertilizer, 20 did not receive P fertilizer, and only 12 were not fertilized with N. The amounts of N, P, and K used by farmers for the fertilized plots ranged from 14 to 200 kg N, 28 to 102 kg P_2O_5 , and 14 to 110 kg K_2O . Grain yields varied between 2.2 and 7.6 ha. With no addition of N, yield varied between 2.2 and 3.1 t/ha.

Soil N, P_2O_5 , and K_2O supplying capacities were estimated from the crop uptake of the non-fertilized plots. Soil N-supplying capacity ranged from 54 to 135 kg N/ha. This quantity is highly correlated to the amount of organic matter in the soil. It also explains to a large extent the grain yields obtained (Fig. 1A, 1B). The following regression permits us to estimate the soil N supply for wheat crops from the organic matter content in the soils of Bahira region under central pivot irrigation:

$$NSC \text{ (kg/ha)} = 5.96 + 79.05 \text{ OM (\%)}; r^2 = 0.87 (P < 0.001) \dots\dots (2)$$

Similar results were found by Benihya et al. (1994) for wheat under irrigation in the Doukkala region of Morocco. Although, the amount of organic matter is low, mineralization of organic N during the growing season is very high under irrigation conditions (Soudi et al., 1992; El Gharous, 1997). This is one reason why organic matter content of irrigated soils in the Mediterranean region is low.

Soil P-supplying capacity (SPSC) varied from 28 to 98 kg/ha. The yields obtained in non-P fertilized plots ranged 2.2 to 7.6 t/ha. Available P (Olsen P_2O_5) in the soil ranged from 9 to 58 mg/kg. The SPSC for irrigated wheat in the Bahira region could be estimated using the relationship presented in Fig. 1C. The variation of wheat grain yield is partly explained by the SPSC (Fig. 1D).

The amount of K taken up by wheat under center-pivot irrigation, when no K fertilizer was added, corresponds to the soil K-supplying capacity. It varied between 58 and 186 kg/ha. Exchangeable K in the soil was highly variable (120 – 452 mg/kg). A logarithmic relationship exists between exchangeable K and soil K supplying capacity (Fig. 1E). Although significant, the correlation between soil K-supplying capacity and grain yield is very low (Fig. 1F).

Sugar Beet under Sprinkler Irrigation

Sugar beet is a high N and K-demanding crop for high yields. Nutrient requirements are in the order of 320 kg N, 560 kg K_2O , and 60 kg P_2O_5 /ha for a yield of 80 t/ha of beets. This crop is cultivated under sprinkler irrigation in Doukkala region of western Morocco. Many crop-response-to-fertilizer-application experiments were conducted on soils with different fertility status (Badraoui et al., 1993). Because of high N and K requirements of sugar beet, special attention was given to the effects of these two nutrients and their interaction on both root and sugar yields. Tables 2 and 3 present the uptake of N and K at physiological maturity.

Table 2. Nitrogen uptake of sugar beet as a function of nitrogen and potassium treatments under sprinkler irrigation in Doukkala region.

Nitrogen/Potassium	K0	K150	K300	K450	K600	N Effect
	-----kg/ha-----					
N150	245	231	218	204	194	218
N300	315	303	276	250	245	278
N450	384	371	357	344	323	356
K Effect	315	302	284	266	254	284

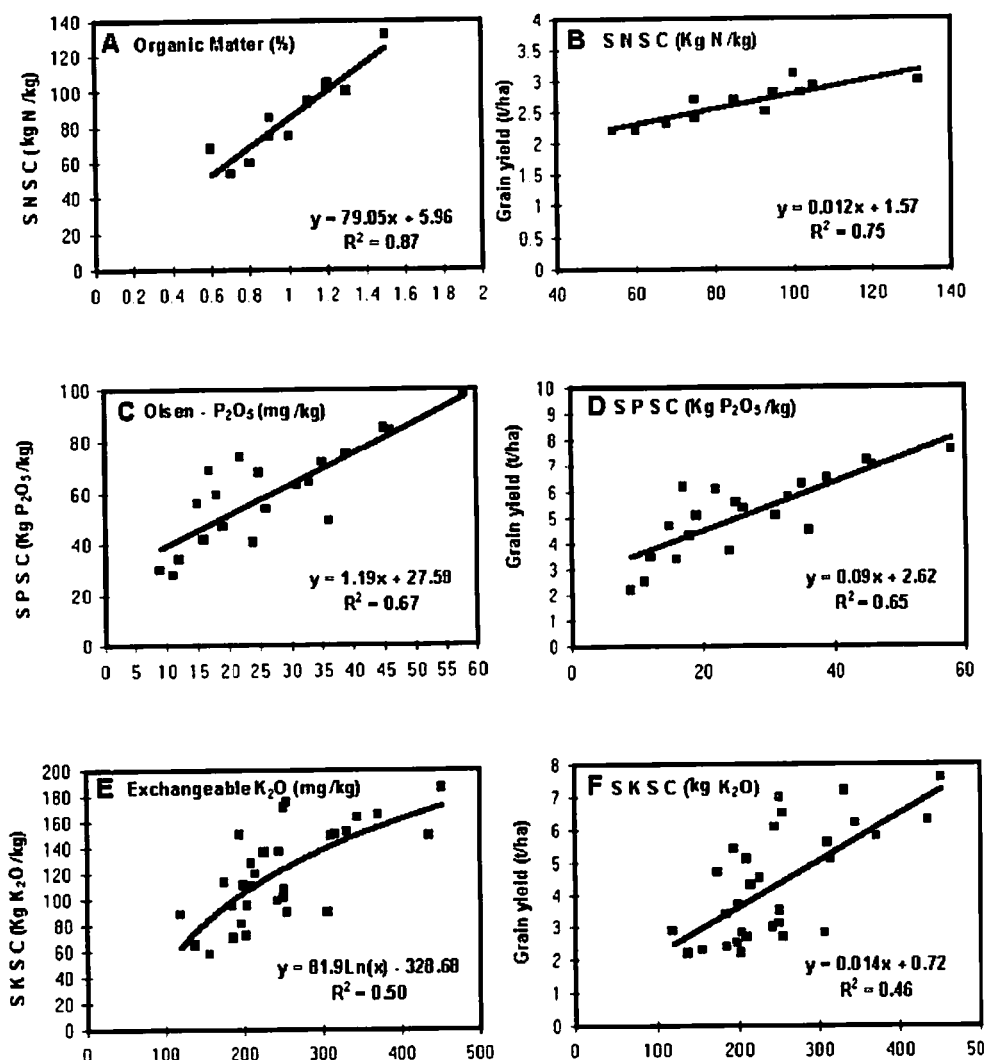


Fig. 1. Relationships between soil nutrient supplying capacity for nitrogen (SNSC), potassium (SKSC), and phosphorus (SPSC) and other parameters in relation to wheat grain yield under central pivot irrigation in the Bahira region of central Morocco.

Table 3. Potassium uptake of sugar beet as a function of nitrogen and potassium treatments under sprinkler irrigation in Doukkala region.

Nitrogen/Potassium	K0	K150	K300	K450	K600	N Effect
	-----kg/ha-----					
N150	440	495	565	624	638	552
N300	518	587	657	689	768	644
N450	599	652	722	771	828	714
K Effect	519	578	648	695	745	637

Using ^{15}N experiments, El Mesghalmi (1994) and Qaini (1995) found that the N fertilizer-use efficiency (NFUE) by sugar beet in Doukkala region was in the order of 20 to 35% depending on the amount of N fertilizer used. If a mean value of 30 % is applied to the results of Table 2, the soil N-supplying capacity can be calculated as follows:

$$SNSC = N \text{ Uptake} - N \text{ Added} \times NFUE \dots\dots\dots (3)$$

Table 4. SNSC for sugar beet as a function of nitrogen and potassium treatments under sprinkler irrigation in Doukkala region.

Nitrogen/Potassium	K0	K150	K300	K450	K600	N Effect
	-----kg/ha-----					
N150	200	186	173	159	149	173
N300	225	213	186	160	155	188
N450	249	236	222	209	188	221
K Effect	225	212	194	176	164	194

Table 4 shows that soil nutrient-supplying capacity range from 249 kg/ha for N450 $\times$ K0 treatment to 149 kg/ha for N150 $\times$ K600. The overall average was 194 kg/ha. It is interesting to see that soil capacity increases with the increase of N application at any given K treatment. For the same N treatment, K application has a negative effect on the soil nutrient-supplying capacity. Using ^{15}N , Qaini (1995) and El Mesghalmi (1994) found that the Ndfs is in the range of 162 to 251kg/ha. Our estimate, using the value of 30 % for NFUE, is correct.

Soil K supply for sugar beet can be estimated by K taken up at K0 treatment. It varies from 440 to 599 kg K_2O /ha. In practice, farmers use, at the most, 225 kg

K_2O /ha. Soil K release to supply the soil solution is very important in Doukkala soils. The rate of K release for highly K-demanding crops is a key determinant of the SKSC. Figure 2 shows an example of K release kinetics as related to the rate of K uptake by ryegrass under intensive cropping in limited soil volume such as in pot experiment (Badraoui et al., 1992b).

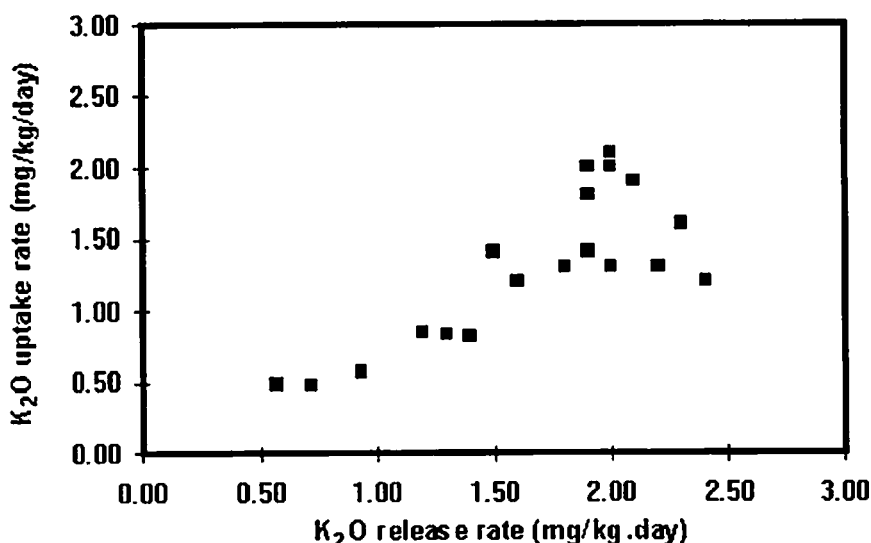


Fig. 2. Relationship between the rates of potassium uptake and release by ryegrass in different Moroccan soil types.

Soil Nutrient-Supplying Capacity for Cucumber under Drip Fertigation

Localized irrigation is being developed in Morocco for the fertigation of vegetable crops and fruit trees, especially in the Souss region in the south of Morocco. Many experiments were performed to understand the functioning of the system in order to improve its efficiency. The specificity of this system in comparison to the other pressurized systems is that only a part of the soil volume is irrigated.

Knowing the requirements of the crop for a given potential yield, one can add the exact amounts of water and nutrients when needed during the growing season. However, to my knowledge, the fertigation programs used in Morocco do not take into account the soil nutrient-supplying capacity.

An experiment was set by Abahmane (1992) to determine the effect of K on the productivity and fruit quality of cucumber cultivated under greenhouse on a

sandy loam soil. Four different K_2O levels were used: 150, 500, 1000, and 1500 kg/ha. Constant rates of N (450 kg/ha) and P (300 kg P_2O_5 /ha) were used. Abahmane (1992) showed that K had positive effects on fruit weight, fruit volume, and both total and export yields. The total yield varied from 140 to 181 t/ha. Plant uptake of N, P_2O_5 , and K_2O significantly increased with K application rates (Table 5).

Table 5. Total nutrient uptake by cucumber crop as affected by potassium treatments.

K Treatment	Nitrogen	Phosphorus (P_2O_5)	Potassium (K_2O)
	-----kg/ha-----		
K 150	200	118	382
K 500	273	154	539
K 1000	250	149	590
K 1500	230	133	530

N added = 450 kg N/ha; P added = 300 kg P_2O_5 /ha

Phosphorus fertilizer-use efficiency (PFUE) in Mediterranean soils is rarely greater than 15 % (Moussadak et al., 1997). Would this value be applicable to cucumber under drip irrigation system? Research is needed using ^{32}P in order to determine appropriate PFUE under drip fertigation. Using the above-mentioned figure, we can estimate the soil P-supplying capacity for cucumber. Soil N-supplying capacity can also be estimated using a NFUE of 35 %. With these assumptions, SPSC and SNSC in this experiment are presented in Table 6. These data should be verified by more research on soil fertility and nutrient management under intensive cropping with drip irrigation.

Table 6. Soil nutrient-supplying capacity for cucumber as affected by potassium applications.

Potassium Treatment	Nitrogen	Phosphorus (P_2O_5)
	-----kg/ha-----	
K 150	42	73
K 500	115	109
K 1000	92	104
K 1500	72	88

CONCLUSIONS

Soil nutrient-supplying capacity is a key determinant for fertilizer-use efficiency. It should be taken into consideration in the process of making fertilizer recommendations. Direct measurements using isotopes or plant uptake of control plots with no addition of fertilizer should be available for major crops, major soil types, and irrigation systems. Some results are available for wheat and sugar beet under sprinkler and central pivot irrigation systems. However, more research is needed to understand the dynamics of soil nutrients, especially P, and determine soil nutrient supplying capacity under localized fertigation systems.

The sustainability of intensive cropping agricultural systems under irrigation should be assured by the monitoring of both soil and water qualities. Soil nutrient supplying capacity would be a good indicator of soil quality changes.

REFERENCES

- Abahmane, L. 1992. Effets de doses croissantes en potassium sur la croissance, le développement, le rendement et la qualité du fruit chez le concombre cultivé sous serre. MSc. Thesis, IAV Hassan II, CHA, Agadir, Morocco.
- Abdel Monem, M., and J. Ryan. 1997. Nitrogen fertilizer use efficiency in WANA as determined by ^{15}N technique. p. 57 – 63. *In* J. Ryan (ed.) Accomplishments and future challenges in dryland soil fertility research in the Mediterranean area. ICARDA-IMPHOS Workshop. 19 – 23 Nov. 1995. ICARDA, Aleppo, Syria.
- Asfary, F., and A. Charanek. 1997. Nitrogen fertilizer-use efficiency studies by Syrian atomic energy commission using ^{15}N -labelled fertilizers. p. 64 – 70. *In* J. Ryan (ed.) Accomplishments and future challenges in dry-land soil fertility research in the Mediterranean area. ICARDA-IMPHOS Workshop, 19 – 23 Nov., 1995. ICARDA, Aleppo, Syria.
- Badraoui, M., M. Agbani, A. Merzouk, P.R. Bloom, R. Bouabid, B. Soudi, A. Mimouni, and S. Bouchaara. 1992a. Chemistry and mineralogy of potassium in Moroccan soils: implications for fixation and release. p. 16 – 27. *In* J. Ryan and A. Matar (ed.), Fertilizer-use efficiency under rain-fed agriculture in WANA region. Proc. Fourth Regional Workshop, 5 – 10 May 1991, Agadir, Morocco. ICARDA, Aleppo, Syria.
- Badraoui, M., P.R. Bloom, and A. Delmaki. 1992b. Mobilization of non-exchangeable K by ryegrass in five Moroccan soils with and without mica. Potash Rev., Int. Potash Inst., Basel, Switzerland.
- Badraoui, M., M. Agbani, B. Soudi, and K. El Mehdi. 1993. Effect of potassium on nitrogen use efficiency by sugar beet in Doukkala region of Western Morocco. *In* M. El Fouly (ed.) Environmentally sound, location- and crop-specific application of fertilizers in arid areas of North Africa and the Near East. Proc.

- German-Egyptian-Arab Workshop. 6 – 17 June, 1993. Cairo, Egypt.
- Badraoui, M., M. Agbani, and B. Soudi. 1997a. Status of potassium in soils and crops in Morocco: present K use and need for improved recommendations. p. 115-124. *In* A.E. Johnston (ed.) Regional Workshop on Food Security in the WANA Region; The Essential Need for Balanced Fertilization. 26 - 30 May 1997. Bornova, Turkey.
- Badraoui, M., B. Soudi, Y. Moujahid, F. Bennani, S. Bouhlassa, and M. Mikou. 1997b. Mineralogical considerations in soil fertility management in Morocco. p. 267 – 278. *In* J. Ryan (ed.) Accomplishments and future challenges in dryland soil fertility research in the Mediterranean area. ICARDA-IMPHOS Workshop. 19 – 23 Nov., 1995. ICARDA, Aleppo, Syria.
- Badraoui, M., and A. Farhat. 1997. Developpement de l'irrigation par pivot au Maroc. Transfert de technologie Bull. N° 38. MADRPM/DERD, Rabat, Morocco.
- Benihya, B., B. Soudi, and A. Bouaziz. 1994. Fertilisation azotée du blé dans les Doukkala. Projet de développement et d'amélioration de la production céréalière en irrigué dans les Doukkala. Vol. III. DPA/IAV Hassan II, Rabat, Morocco.
- El Gharous, M. 1997. Nitrogen challenges in dryland agriculture. p.47 – 56. *In* J. Ryan (ed.), Accomplishments and future challenges in dryland soil fertility research in the Mediterranean area. ICARDA-IMPHOS Workshop. 19 – 23 Nov. 1995. ICARDA, Aleppo, Syria.
- El Mesghalmi, I. 1994. Evaluation de l'efficience d'utilisation de l'azote par la betterave à sucre: utilisation de la technique de marquage au ^{15}N . M.Sc. Thesis, Soil Science Dept., IAV Hassan II, Rabat, Morocco.
- Matar, A., J. Torrent, and J. Ryan. 1992. Soil and fertilizer phosphorus and crop response in the dryland Mediterranean zone. *Adv. Soil Sci.* 18:81-146
- Moussadak, J., J. Stroehlein, and J. Ryan. 1997. Use of radioactive phosphorus in soil fertility research: mobility in an acidified soil. p. 181 – 190. *In* J. Ryan (ed.) Accomplishments and future challenges in dryland soil fertility research in the Mediterranean area. ICARDA-IMPHOS Workshop. 19 – 23 Nov., 1995. ICARDA, Aleppo, Syria.
- Soudi, B., C.N. Chiang, M. Badraoui, M. Agbani, and M. Ben Haslima. 1992. Characterization and distribution of nitrogen forms in selected soils of Morocco. *In* J. Ryan and A. Matar (ed.) Fertilizer-use efficiency under rain-fed agriculture in WANA region. Proc. Fourth Regional Workshop, 5 – 10 May 1991, Agadir, Morocco. ICARDA, Aleppo, Syria.
- Torrent, J. 1992. Mineralogy of Mediterranean soils and its implication in phosphorus behavior. p. 3 – 15. *In* J. Ryan and A. Matar (ed.), Fertilizer-use efficiency under rain-fed agriculture in WANA region. Proc. Fourth Regional Workshop. 5 – 10 May 1991. Agadir, Morocco. ICARDA, Aleppo, Syria.

Phosphorus Levels in Soils of Different Vegetable Crops in Jordan Valley

Sayed Khattari

*Department of Agricultural Resources and Environment,
Faculty of Agriculture, University of Jordan*

ABSTRACT

Fertilizer use ideally should be based on the amounts of the nutrient already available in the soil for the crop. Where levels of such nutrients are high, little or no fertilizer may be needed. Thus, it was important to establish a rational basis for phosphorus fertilizer use in Jordan. Accordingly, soil samples were collected from 377 vegetable farms located in the central region of the Jordan Valley. All farms were under drip irrigation. Fertility management varied between farms with similar crops, which have included *tomato*, *cucumber*, *squash*, *potato*, *carrot*, *eggplant*, and *melukhia*. Extractable P was determined in the soil sample taken at different depths. Results indicated that P has accumulated in the soils up to 60 cm, with substantial amounts in the topsoil. Although fertigation is available, the farmers are still practicing the traditional method of applying P fertilizers, where they incorporate it with the soil before planting, besides the addition of soluble compound fertilizers by fertigation. It is obvious that farmers are lacking the skills of fertilization management utilizing the advanced technique of fertigation through the drip irrigation system.

INTRODUCTION

Phosphorus is an essential macronutrient that plays a major role in plant growth and development. It forms the main constituent of the nucleic acids, DNA and RNA, that carry and translate the plants genetic information. Phosphate esters and energy-rich phosphate are considered the deriving mechanisms of the metabolic processes in the plant cells, where it forms an intermediate metabolites in biosynthesis and degradation, especially the energy metabolism of the cell and energy-rich phosphate. Inorganic P in the cell has also a regulatory role in many enzyme reactions, where inorganic P is either a substrate or an end product. In addition, it has a controlling function in photosynthesis and carbohydrate metabolism.

Phosphorus requirement for the optimal growth of plants ranges from 0.3 to 0.5% of the plant dry weight. Its deficiency decreases the root hydraulic

conductance, and therefore retards the plant growth by retarding the cells and leaf expansion more than the chlorophyll formation. Subsequently, in deficient plants, the chlorophyll content per leaf area becomes higher and the leaves become darker than normal in color, with substantial reduction in the photosynthetic efficiency per unit of chlorophyll.

The major problem in providing the plant with its P requirement is the considerably low availability of indigenous and added P fertilizers. Very little of this element is lost by leaching, therefore P from added fertilizers is mainly accumulated in the topsoil, particularly in those intensively cropped with vegetables, where P fertilizers are heavily used.

In calcareous soils, the availability of soluble P that is applied as fertilizers is reduced through several reactions of precipitation and fixation by Ca ions, free carbonates, and Ca-saturated clays. Fixation reactions start immediately after the addition of soluble P fertilizers, with a magnitude depending mainly on soil pH and carbonate content. Addition of organic matter to the soil modifies the pH, where P availability increases.

However, P availability increases through fertilization management which may include the use of appropriate fertilizers, time of application, and method of application. Fertigation is one of the most efficient techniques used at present for delivering soluble fertilizers in adequate quantities to meet the changing requirements of the different stages of plant growth.

Fertigation in Jordan was introduced in early 1970s along with the intensive cultivation of the protected vegetable crops. At that time, suitable P fertilizers for drip irrigation were not available, and the traditional solid P fertilizers of varying solubility, including single superphosphate (SSP), triple superphosphate (TSP), and diammonium phosphate (DAP) were heavily used during land preparation before planting. Such practices are still going on, where many farmers add P fertilizers as one application and incorporate it with the soil, in addition to the P added with the soluble compound fertilizers throughout the season. The continuous fertilizing of the intensive vegetable cropping in Jordan Valley may have created substantial buildup of P in the soil, although it may not be uniform because of the small farm size and management differences.

Therefore, the objective of this study was to establish the extent of P buildup in the Jordan Valley by assessing the extractable P levels in the soils of vegetable farms under fertigation.

METHODS AND MATERIALS

An area located in the central Jordan Valley, between Kurimeh and Arda, was selected for this study. This area is intensively cultivated with vegetable crops under drip irrigation where fertigation is commonly used. In the first phase (1995 – 96 season), representative soil samples were taken at three depths (0 – 15, 15 – 30, and

30 – 60 cm) from 46 open fields of tomato, 48 plastic houses of tomato, 50 plastic houses of cucumber, and 8 open fields of squash.

In the second phase (1996–97 season), topsoil was sampled from 25 farms of each of the following crops: tomato, cucumber (each was sampled twice in the beginning and the end of the season), squash, potato, carrot, and *melukhia* (Jewish melon). All crops were grown in plastic houses under drip irrigation.

All soil samples were air-dried, ground and passed through a 2-mm sieve. Available soil P was determined by extracting with a 0.5 M NaHCO₃ solution buffered at 8.5 (Olsen procedure). The soil of this area is generally characterized as calcareous clay loam, with high CaCO₃ content and high pH (7.4 – 8.2).

RESULTS AND DISCUSSION

Results of the first phase indicated that P accumulation in the soils of tomato-producing plastic houses was substantially higher than that in the open fields at all depths, although both were under drip irrigation. In soils of plastic houses (48 sites), P had accumulated in the topsoil (0 – 15cm), ranging from about 25 to 112 ppm (Table 1). Highest P concentration (428 ppm) was observed in one farm, while the lowest value (22 ppm) was also observed in one farm only. In the subsoil (30 – 60 cm), P concentration was much lower, being in a range of 1.0 to 6.2 ppm, while the lowest value observed was 0.5 ppm.

In open fields of tomato (48 sites), P concentration in the topsoil ranged from 13.9 to 41.8 ppm. Concentrations as high as 79.7 – 129.5 ppm P were observed in a few sites, while lowest values, 5.3 and 7.1 ppm, were observed in two sites only.

In the subsoil (30 – 60 cm) of the open fields, the trend of P concentration was similar to that observed in the plastic houses. The concentration had decreased to a range of 0.5 to 5.0 ppm, while in two sites P concentration was about 10 ppm.

The high accumulation of P in the plastic houses is mainly associated with the high plant density and cultivation practices, where farmers tend to add higher quantities of soluble fertilizers of different types and grades, in addition to the traditionally added DAP or TSP and manure during the land preparation before planting or transplanting. In contrast, lesser amounts of P fertilizers are usually added to the open fields.

In cucumber-producing plastic houses (59 sites), P concentration in topsoils ranged from about 20 to 70 ppm (Table 3). Higher concentrations were observed in two sites (80.9 and 103.6), while in one site P was extremely low (2 ppm) in the topsoil. Such results indicate an extreme variation in fertilization management in the area. It is obvious that lesser quantities of fertilizers were generally added to cucumber which has a shorter season compared with the longer season of tomato in the Jordan Valley. In the subsoil (30 – 60 cm), P was much lower; concentrations ranged from 0.7 to 8.6 ppm, while in two sites the subsoil P was 27.2 and 62.2 ppm. It is obvious that less fertilizer is generally added to cucumber, which has a shorter season, than to tomato.

Table 1. Available phosphorus concentration at different soil depths in tomato-growing plastic houses (1995).

Farm No.	Soil Depth (cm)			Farm No.	Soil Depth (cm)			Farm No.	Soil Depth (cm)		
	0-15	15-30	30-60		0-15	15-30	30-60		0-15	15-30	30-60
	-----ppm-----				-----ppm-----				-----ppm-----		
-											
6	39	1.7	1.0	46	89	-	-	73	-	23.7	1.8
9	84	33.8	1.0	48	-	3.0	-	73	-	-	5.2
10	36	7.4	0.7	49	-	24.8	1.2	74	38	-	-
11	57	30.1	3.1	50	66	6.8	-	75	428	7.1	6.2
13	30	7.1	-	51	31	-	4.2	80	50	-	3.0
14	36	9.0	0.5	52	92	-	0.9	81	25	6.6	4.8
21	75	67.2	-	53	36	-	19.3	82	-	4.9	-
22	22	6.1	-	54	47	24.4	1.8	83	42	5.1	2.5
25	72	-	-	55	34	-	-	85	-	3.8	3.0
26	-	23.5	-	56	-	18.7	1.2	86	-	4.9	-
27	-	-	1.0	57	84	10.9	-	89	-	23.9	3.5
28	-	-	2.1	58	69	26.6	2.4	91	-	33.5	5.5
39	64	20.5	6.2	61	49	17.5	0.2	92	-	11.3	2.4
43	35	-	5.0	64	112	-	1.4	95	-	19.0	3.1
43	42	34.8	2.5	64	-	-	1.8	95	-	28.6	5.7
45	42	-	1.2	68	-	-	2.7	96	-	7.7	-

Table 2. Available phosphorus concentration at different soil depths of tomato open fields (1995).

Farm No.	Soil Depth (cm)			Farm No.	Soil Depth (cm)			Farm No.	Soil Depth (cm)		
	0-15	15-30	30-60		0-15	15-30	30-60		0-15	15-30	30-60
	-----ppm-----				-----ppm-----				-----ppm-----		
1	30.7	99.0	0.5	35	-	14.7	2.5	63	-	3.0	0.5
2	-	9.4	1.4	36	-	11.1	-	64	23.5	-	1.8
4	22.3	19.3	1.4	38	-	7.4	0.6	64	21.1	10.3	9.4
5	20.5	16.9	4.2	39	-	-	5.0	65	13.9	10.9	-
9	-	11.2	5.3	40	5.3	1.4	-	66	-	12.7	-
12	79.7	45.8	10.6	41	-	3.5	0.9	67	-	4.8	-
15	7.1	1.4	-	42	15.5	-	-	68	11.0	-	1.2
17	20.6	-	0.7	46	39.8	11.2	-	70	41.8	-	1.0
19	36.2	28.4	0.7	47	14.8	8.3	-	71	19.0	5.9	-
23	-	-	1.8	48	-	41.5	0.8	76	22.1	7.7	2.4
27	129.5	3.6	3.1	51	-	-	2.7	80	20.8	-	-
30	-	2.0	-	54	-	19.5	4.3	82	25.0	-	3.8
31	-	3.8	-	55	-	17.5	-	93	-	10.4	1.2
32	-	-	1.5	59	-	9.7	0.7	94	39.0	-	3.5
33	-	-	129.5	60	16.9	10.3	1.5				
34	21.0	-	2.0	62	-	6.6	1.5				

¹ Values rounded off to nearest decimal.

Table 3. Available phosphorus concentration at different soil depths of cucumber plastic houses (1995).

Farm No.	Soil Depth (cm)			Farm No.	Soil Depth (cm)			Farm No.	Soil Depth (cm)		
	0-15	15-30	30-60		0-15	15-30	30-60		0-15	15-30	30-60
	-----ppm-----				-----ppm-----				-----ppm-----		
-											
5	2.2	18.7	62.2	32	-	-	1.2	69	20.2	-	1.5
6	48.2	33.7	5.3	43	-	19.5	2.0	70	33.4	12.9	-
7	48.2	34.9	27.2	43	42.2	21.1	4.3	73	22.6	-	-
10	53.0	9.4	1.7	43	-	-	2.9	74	53.4	-	3.7
11	38.5	33.7	-	43	-	8.1	1.9	75	-	18.8	1.8
12	79.5	4.2	1.4	44	69.5	7.4	-	76	23.1	-	2.4
14	-	34.9	3.0	45	54.6	12.4	3.5	80	41.5	19.6	2.1
15	-	-	1.2	45	47.2	6.8	34.6	82	28.5	-	3.8
16	103.6	22.4	6.6	48	-	5.3	1.7	82	-	24.2	1.8
18	27.2	15.7	-	49	38.3	2.5	3.3	86	-	14.5	-
19	51.8	34.6	6.6	49	47.6	12.8	-	87	-	11.0	-
21	64.9	-	-	51	72.2	12.7	1.9	88	43.2	-	2.2
22	-	-	1.7	53	19.9	3.0	-	89	-	8.0	-
23	-	52.3	8.6	55	49.8	-	0.7	90	83.7	-	-
24	-	-	1.7	56	72.2	6.2	-	91	80.5	-	-
25	-	-	1.8	57	-	14.5	1.0	92	36.2	-	1.8
27	-	-	1.0	58	-	9.0	2.4	92	-	-	4.3
28	80.9	-	-	65	-	11.5	2.2	95	-	-	5.9
29	-	-	2.4	68	-	19.0	3.1	96	-	6.1	-
30	-	4.0	-	69	22.5	-	-				

Table 4. Available phosphorus¹ concentration (ppm) at different soil depths of squash fields (1995).

Farm No.	Soil-Depth (cm)		
	0 - 15	15 - 30	30 - 60
	-----ppm-----		
5	-	-	3.4
9	20.1	-	5.4
17	9.7	-	1.5
31	22.0	-	-
55	-	-	2.7
58	-	5.0	-
66	21.1	13.3	-
72	19.0	8.9	2.3

¹ Values rounded off to nearest decimal.

Table 5. Available phosphate¹ concentration in tomato farms under fertigation.

Farm No.	Season		Farm No.	Season	
	Beginning	End		Beginning	End
	-----ppm-----			-----ppm-----	
95	25	44	115	79	133
99	36	55	116	65	133
101	139	169	117	145	109
102	163	56	118	67	48
105	109	139	122	79	103
106	127	91	123	13	79
107	85	133	124	56	13
109	58	246	125	139	85
110	198	258	127	97	175
111	198	311	128	91	66
112	115	186	130	31	121
113	48	85	131	10	139
114	151	169			

¹ Values rounded off to nearest decimal.

Table 6. Available phosphorus¹ concentration in cucumber-producing plastic houses under fertigation.

Farm No.	Season		Farm No.	Season	
	Beginning	End		Beginning	End
	-----ppm-----			-----ppm-----	
2	48	204	28	85	169
7	121	109	32	25	204
8	67	119	38	62	94
9	40	33	39	7	163
15	109	151	40	127	109
17	109	73	42	33	133
18	121	48	48	79	103
19	73	48	49	36	91
20	50	76	51	139	186
22	48	66	54	151	66
25	151	258	57	151	169
26	234	138	62	264	276
27	61	300			

¹ Values rounded off to nearest decimal.

Table 7. Available phosphorous¹ concentration in potato fields.

Farm No.	Phosphorus	Farm No.	Phosphorus	Farm No.	Phosphorus
	-----ppm-----		-----ppm-----		-----ppm-----
104	25				
108	12	139	50	148	31
129	67	140	23	149	48
132	186	141	186	150	139
133	133	143	25	151	151
134	56	144	97	152	61
135	18	145	31	153	145
137	15	146	83	154	73
138	48	147	7	157	169

¹ Values rounded off to nearest decimal.

Table 8. Available phosphorous¹ concentration squash and eggplant farms.

Farm No.	Squash	Farm No.	Squash	Farm No.	Eggplant	Farm No.	Eggplant
	---ppm---		---ppm---		---ppm---		---ppm---
1	13	61	79	12	115	126	31
3	61	64	97	13	103	136	91
5	97	68	79	21	41	142	103
6	48	72	15	30	36	155	7
10	115	73	29	34	139	156	85
14	7	77	48	35	90	162	73
23	18	83	85	46	101	164	25
24	58	84	13	50	48	165	31
29	133	87	80	56	133	166	48
44	36	92	18	70	36	167	85
52	44	94	29	76	103	168	25
58	32	97	23	100	103	169	25
60	109			103	48		

¹ Values rounded off to nearest decimal.

Table 9. Available P¹ concentration in carrot and melukhia farms (1996).

Farm No.	Carrot	Farm No.	Carrot	Farm No.	Melukhia	Farm No.	Melukhia
	---ppm---		---ppm---		---ppm---		---ppm---
36	7	80	7	170	139	183	151
37	36	81	7	171	79	184	31
55	31	85	18	172	67	185	70
59	18	86	97	173	151	186	198
63	48	89	48	174	109	187	85
65	13	91	31	175	94	188	216
66	44	93	115	176	417	189	97
67	31	158	97	177	228	190	139
71	48	159	38	178	133	191	103
74	73	160	48	179	69	192	50
75	73	161	67	180	145	193	97
78	103	163	67	181	109	194	133
79	7			182	79		

¹ Values rounded off to nearest decimal.

Squash fields in the surveyed region were few (9 fields). This crop receives less care from farmers because of its lower cash value. Therefore, lesser amounts of fertilizers are usually added. Consequently, low P concentration (about 20 ppm) in the topsoil, and even extremely lower concentration (1.5 – 5.4 ppm) were observed in the subsoil (Table 4).

In the second phase of the study (1996-97 season), extractable P from topsoil of 25 tomato sites were measured at the beginning and the end of the season. Although the topsoil P was high in the beginning of the season, P has increased substantially in 18 sites out of the 25 sites as measured at the end of the season. Some values reached as high as 311.9 ppm (Table 5). The magnitude of P accumulation varied from one farm to another, reflecting poor fertility management as indicated by the extremely high amounts of extractable P nutrient left in the soil after the crop removal.

Soils of the cucumber sites (25) were also analyzed at the beginning and the end of the season. Extractable P ranged from 25.7 to 264.3 ppm, (except one site had 7.9 ppm) at the beginning of the season (Table 6). At the end of the season, P that had increased in the soils of 17 out of the 25 sites. Extractable P concentration ranged from 33.6 to 276.2 ppm.

Such P values indicate similar trend to that observed in tomato fields. In potato fields (25), lowest P concentration, ranging from 7.9 to 23.9 ppm, was observed in five sites, while a concentration ranged from 25.7 to 186.9 ppm was in the other 20 sites (Table 7).

In squash fields, extractable soil P ranged from 7.9 to 23.9 ppm in 7 sites, while the range in the other sites (18) was 32.9 to 133.6 ppm (Table 8). However, extractable soil P in the eggplant fields ranged from 25.7 to 133.6 ppm in all sites, except one site where the concentration was as low as 7.9 ppm.

Soils of carrot farms contained lower P concentration than the other vegetable fields. Extractable P in seven sites has ranged from 7.9 to 18.6 ppm, while in the other sites it ranged from 31.1 to 97.7 ppm (Table 9). Unexpectedly, soils of melukhia farms had accumulated extremely high quantities of extractable P. Concentration ranged from 50 to 216.7 ppm in over all sites, except in one site where the concentration was 31.1 ppm.

Results indicated that excess amounts of P fertilizers have been added to the vegetable crops grown under fertigation practices. Available P values were very high at west sites, in spite of the fact that the soil properties (high pH, high CaCO_3 ...) enhance the P fixation and precipitation. The farmers are still practicing the traditional method of P fertilizers application (addition to the soil before planting) side by side with fertigation by using soluble compound fertilizers which contain P as well as other nutrients.

CONCLUSIONS

It was observed that excess P in soil has induced micronutrient deficiency. Therefore, the majority of the farmers used to add one micronutrient or more as foliar application, or through fertigation. The data obtained from this survey of the Jordan Valley could support the following conclusions:

- The present fertilization practices have caused accumulation of high amounts of P in soils of most vegetable growing fields.
- Farmers are still lacking the technical “know-how” regarding fertigation, although it is the most flexible and efficient method that meets the changing demand of plant at different growth stages.
- Addition of high P caused nutrient imbalance, including macro and micronutrients in soil and plant. Such irrational additions have promoted the addition of other nutrients (fertilizers) causing serious environmental impacts.
- There is an urgent need for research regarding crop P requirements, together with standardization and calibration tests.

Root Systems and Fertigation

Munir J. Mohamad Rusan

*Department of Natural Resources and the Environment,
Jordan University for Science and Technology, Irbid, Jordan*

ABSTRACT

Roots are the primary plant parts that absorb water and nutrients, anchor the plant, synthesize growth regulators, and metabolize photosynthates for the growth. To enhance crop production and to develop an economically efficient and environmentally responsible farming systems, one must have a better understanding of root growth, development and performance under various cropping and farming systems.

Root distribution in the cultivated soil layer is greatly determined by methods of irrigation. Roots tend to proliferate mainly in the wetted zone where, both water and fertilizers supply are positionally more available. Therefore, topsoil is exhausted of available water first, the crops then have to extract water from the lower layers. This may illustrate the favorable effect of fertilizers on stimulating root growth and branching in the lower layers of the soil, which can be achieved by fertigation. This is reflected on increasing both water and fertilizer-use efficiency.

On the other hand, unfavorable conditions can restrict root growth and affect fertilizer-use efficiency. The unfavorable stress soil conditions can be of a chemical or physical nature. Under fertigation, application of irrigation waters in amounts greater than the water requirement can create anaerobic conditions and reduce root growth. Several factors affect the extend to which the fertilizer-soil interaction would have on the nutrient and indirectly root distribution in the soil. These factors include: discharge rate and application rate of irrigation water, the uniformity of water application by the system, rate and type of fertilizers used, soil texture, and the soil chemical parameters. Since the wetted soil volume under fertigation is relatively more concentrated with fertilizers, care should be taken to avoid any possible negative impact on root system. Roots are significantly influenced by high concentration of chloride and nitrate/ammonium ratio, where high nitrate supply reduces any possible harmful effect of chloride.

Phosphorus is of particular importance to the growth and development of root system. By fertigation, P can be supplied in soluble readily available form during the establishment of seedlings, where P is needed the most for root initiation and development. Since nutrient distribution influences root pattern, one should

consider the following to ensure more uniform distribution of fertilizer under fertigation system: a) Inject fertilizers only after the irrigation system is full of water and stop injection before the irrigation period ends; b) Avoid clogging of the irrigation system and mainly the emitters; and c) Avoid overirrigation or underirrigation.

On the other hand, one should be aware that continuous and prolonged fertigation of fertilizers to the reduced wetted soil volume means that only a small fraction of the cultivated soil is actually fertilized. This may increase the potential of creating a problem of salt and toxic ion accumulation in the root zone. The mechanism of nutrient movement in the soil and the methods used for studying root system are discussed.

INTRODUCTION

Roots are the primary plant parts that absorb water and nutrients, and crop growth and yield are directly related to availability of both water and plant nutrients in the soil (Barber, 1984). They also anchor the plant, synthesize growth regulators, and metabolize photosynthates for growth (Russell, 1982). To help increasing crop production and to develop an *agronomically sound, economically efficient and environmentally responsible management*, one must have a *better understanding of root growth, development and performance under various cropping and farming systems*. Understanding the pattern of root distribution and consequent water and nutrient uptake under various cropping system and the seasonal distribution of root systems in response to different management and agricultural practices is essential for developing a sustainable and more efficient farming systems.

In the past, soil and plant scientists have paid less attention to the study of root system. They have mainly focused on looking at the soil-plant interaction through monitoring the yield and biomass parameters. There are several reasons behind the minor interest of plant and soil scientist in investigating growth and function of root systems. These reasons include the variable forms and proliferations among the same plant species which complicate their investigations, and complexities, difficulties and time consummation of most methods employed to extract and representatively sample and quantify root system parameters. However, researchers have recently become more interested in root research, especially after more convenient methods of root study has become available.

ROOT GROWTH AND MORPHOLOGY

Root morphology mainly determines the capacity of roots to explore the soil for water and nutrients (Richards, 1992). Root morphology parameters include *root type, root branching and geometry, distribution pattern, root depth, root length,*

diameter and *surface area* and the number of root hairs and root tips. Most of these parameters are genetically controlled, but also can be considerably influenced and modified by environmental factors associated with various cropping systems (Russell, 1982; Derera et al., 1969; Troughton and Whittington, 1969).

Most herbaceous non-woody dicots have a dominant taproot which is usually formed during early stages and extend deeply into the soil. Later, lateral roots are developed (e.g., alfalfa). In other species (e.g., carrot), the dominant taproot is shorter. Other common herbaceous dicots (e.g., soybean and tomato) have a taproot difficult to which is distinguish from branch roots. In monocots, especially in grasses, lateral roots develop from the seminal roots and form a dense highly branched root system. Tree root morphology can be complex and much larger compared to annual plants. In fact, tree roots can extend outwardly from tree trunks much further than do aboveground branches. Root depth also differ considerably among species where perennial crops generally have deeper roots than annuals (Rogers and Head, 1966; Hurd, 1968). Even though root growth, depth, and morphology are genetically controlled, external environmental factors (soil moisture, aeration, mechanical impedance, and plant nutrient status) have a big influence on them (Russell, 1982).

Root-Shoot Relationships

To understand root growth pattern and consequently to consider it for developing a more efficient management of irrigation water and fertilization, one should consider the co-ordination and interrelationship between roots and shoots. While roots anchor the plant in the soil and absorb water and nutrients, shoots entrap solar radiation and synthesize metabolites on which growth and development depend (Russell, 1982). These are the most obvious functions illustrating the interdependence and interrelationship between roots and shoot which, at the microlevels, are much more complex. Under constant environmental conditions, a relationship between the weights of shoots and roots has been noted many decades ago (Pearsall, 1927).

It is generally observed that the roots and shoots grow in parallel during the early stage; thereafter, shoots continue to grow while root growth drastically decline or even ceases at all, and the death of the older roots are not fully compensated for by new growth. Absorption of nutrients is mainly restricted to young newly developed fine roots, which have larger surface area. Older roots lose their root hairs and become suberized and, thus, their absorbing power is significantly reduced.

Moreover, the size and length of the roots are considerably variable at different growth stages and with soil depth. During the early growth stages, the root system is relatively smaller and concentrated in the surface soil. The growth rate of roots

would markedly increase during vigorous vegetative growth period; thereafter, the growth rate declines again (Brouwer, 1965). The co-ordination between this root growth pattern and that of the shoot will varies according to both genetic and mostly environmental factors. Therefore, root growth pattern and root morphology parameters should be investigated under various cropping system to enable us more precisely and efficiently schedule fertilization programs of various crops.

Practical Considerations of Root-Shoot Relationships

The variations in the growth patterns between roots and shoots should be considered in managing and formulating and scheduling of fertilization recommendation. Since with fertigation we have the advantage of controlling the levels of fertilizers applied at each growth stage, differences in growth cycles between roots and shoots should be taken into account. One should be easily able to manage and control the rate and frequency of fertigation according to root and shoot growth patterns.

Addition of higher rates of fertilizers during periods of slow growth rate for roots would increase chances for nutrient losses and decrease fertilizer-use efficiency. Otherwise, the efficiency of fertigation is expected to be lower during the late growth stage due to the inability or reduced capacity of roots to absorb nutrients applied. This may explain the relatively low fertilizer-use efficiency in some cases under continuous fertigation.

Root Pattern and Water and Nutrient Distribution under Fertigation

The distribution of root systems at different growth stages within the soil profile or within the cultivated soil layers is of great importance for scheduling fertigation programs. It was widely shown that root distribution in the cultivated soil layer is greatly determined by methods of irrigation. Roots tend to proliferate mainly in the wetted zone where both water and fertilizers supply are positionally more available (Goss et al., 1992; Mullins, 1993; Maria do Rozario, 1996; Zhang et al., 1996). Essentially, roots grow where they can. In moist and fertile soil, regions, roots proliferate extensively until water or nutrient are depleted, and then grow into new regions searching for more favorable conditions. Therefore, agricultural practices have a big influence on root morphology parameters, which should be carefully studied and understood to optimize the efficiency of our farming systems.

Distribution of Irrigation Water

In general, crops extract more water from the topsoil, mainly from the top layers of

the effective root zone. Therefore, the topsoil is first exhausted of available water, and the crops then have to extract water from the lower layers. Besides the topsoil dries first due to evaporation and therefore is subjected more to frequent wetting and drying cycles. Having this in mind, one can realize the favorable effect of fertilizers on stimulating root growth and branching in the lower layers of the soil, which can be achieved by fertigation.

This will certainly be reflected on increasing both water and fertilizer-use efficiency. In this regards, it should be noted that adequate fertilization enhances water-use efficiency through increasing root growth and branching, which will be able to explore more soil volume for both water and nutrients. In addition, adequate fertilization also decreases the water requirement, for example, potassium ability to close the stomata, thus reducing losses due to transpiration.

Moreover, adequate fertilization increases plant growth and the soil will be covered by the more efficiently and quickly. This reduces the losses by evaporation and increase water-use efficiency. Finally, adequate fertilization increases the crop yield, which directly affect the utilization efficiency of both water and fertilizers. Water and fertilizer-use efficiency is the yield of crop per unit of water and fertilizers, respectively.

Root distribution in the soil profile greatly depends on water supply. Under adequate supply, roots tend to concentrate in surface layers. During the drying cycle, where water can be considerably lost from the surface layers and roots density in these dry layers decreases due to death by desiccation; a compensatory growth will be observed in deeper more moist soil layers. This phenomenon was widely recognized that roots tend to proliferate in the zones of more favorable nutrients and water supply, thus, compensating for poor root growth in zones of unfavorable or stress conditions (Maria do Rosario et al., 1996; Egball and Maranville, 1991).

If the soil is well aerated and constantly and adequately supplied with water and nutrients, roots will usually grow normally and will support considerable shoot growth. In contrast, unfavorable soil conditions can restrict the growth and performance of the roots and the yield would be lower than the genetic potential maximum.

The unfavorable stress soil conditions can be of a chemical nature, which is caused by the *inadequate nutrients* or their *unbalanced supply* or by the presence of *toxic substances*, or of physical nature, which caused by shortage of soil moisture, by *water-logging* and *anaerobic conditions*, by unusually low or high soil *temperature*, or by the mechanical impedance to root penetration. Anaerobic soil conditions can occur under total waterlogging. Both aerobic and anaerobic zones, and therefore aerobic and anaerobic processes occur simultaneously in adjacent zones in the soil.

Under fertigation, application of irrigation water in amounts greater than the

water requirement of a specific growth stage can create anaerobic conditions in some regions in the soil. This is especially important during the early growth stage where roots are still smaller and less active due to low soil temperature. The anaerobic conditions in certain zones can even affect root growth in the aerobic zones through diffusion of products of anaerobic processes which are toxic to roots and through shortage of oxygen quantity in the root zone, and due to losses of soluble forms of nutrients. It is important to note that even very short waterlogging conditions (24 hours), as a result of heavy rains or excessive irrigation, can sometimes cause permanent injury to plants. It was reported that maize was seriously damaged by 24 hours water-logging during early growth stage.

Fertilizer Distribution

The distribution of roots in the soil usually affected by the placement of fertilizers. Roots density was found to be severalfold in zones of P fertilizer placement and even more in zones where both N and P were concentrated. Bands of concentrated fertilizers attract plant roots and significantly enhances nutrient uptake (Drew, 1975; Anghioni and Barber, 1988).

In today's modern irrigation farming system, conventional direct soil fertilization is neither effective nor convenient. Instead, fertigation, which is the application of fertilizers through the irrigation water, is considered the most appropriate and effective method of fertilization. With fertigation, one can control precisely the rate of nutrients applied and the time of application. This will enhance water- and fertilizer-use efficiencies and, consequently, root growth and distribution within the soil layers (Papadopoulos, 1985).

Fertilizer distribution under rainfed agriculture is mainly influenced by tillage operations, and under irrigation agriculture by method of irrigation. Unlike under rainfed farming systems, where roots grow compensatory and branch more near the sites of fertilizer application, as is clearly demonstrated with band application of P fertilizers, roots as well as water and fertilizers are distributed relatively more uniform within the wetted soil volume under irrigation agriculture (Papadopoulos, 1988). In addition, since fertilizers are applied and are distributed mainly within the small wetted soil volume, root growth, branching, and proliferation will be concentrated in this same small volume. Moreover, soil volume explored by roots under fertigation would be less, and, since surface soil layers dry more frequently, crops become more sensitive to drought and saline conditions.

In addition, increasing root length increases root density and the distance between the root axes is reduced; thus greater competition between roots for nutrients is expected due to the overlap of the depletion zones of adjacent roots. That is why nutrient uptake levels off above a certain high root density value. Therefore, enhancing nutrient uptake by increasing root density is practically

limited unless higher levels of nutrients are provided by fertigation.

Although, the distribution of the nutrients would be expected to follow that of irrigation water, the interaction between these nutrients and the soil system would influence their distribution within the soil layers. The ion charge greatly influences the distribution pattern of nutrients. Negatively charged and water-soluble nutrients tend to follow the distribution of irrigation water, while positively charged nutrients tend to be attracted and adsorbed onto the soil colloids, thus restricting their further movement in the soil (Mohammad et al., 1999).

Several factors affect the extend to which the fertilizer-soil interaction would have on the nutrient and indirectly root distribution in the soil. These factors include *discharge rate* and *application rate of irrigation water*, the *uniformity of water application* by the system, *rate and type of fertilizers* used, *soil texture* and the *soil chemical parameters*. Since the wetted soil volume under fertigation is relatively more concentrated with fertilizers, care should be taken to avoid any possible negative impact on root system. Roots are significantly influenced by high concentration of chloride and nitrate/ammonium ratio, where high nitrate supply reduces any possible harmful effect of chloride.

Phosphorus is of particular importance to the growth and development of root system. By fertigation, P can be supplied in soluble readily available form during the establishment of seedlings, where P is needed the most for root initiation and development. Therefore, one should be aware of the necessity of providing P during early growth stages. This is of importance also because during this stage soil temperature is usually lower and roots which are sensitive to soil temperature, are much less active. In some cases, therefore, a pre-plant application of P might be necessary. Since nutrient distribution influences root pattern, one should consider the following to ensure more uniform distribution of fertilizer under fertigation systems:

- Inject the fertilizers only after the irrigation system is full of water, and stop injection before the irrigation period ends. When the system is not full with water, the discharge rates of various emitters are significantly different. Consequently, water and fertilizers are not distributed uniformly. A similar scenario is expected when injection of fertilizers is continued the last moment of irrigation
- Avoid clogging of the irrigation system, mainly the emitters, which tend to change the discharge rate of these emitters causing non-uniform distribution of both water and fertilizers.
- Apply only the water requirement of the crop. Over-irrigation will necessarily lead to over fertilization and consequently to water and fertilizer leaching beyond the root zone. This will decrease water and fertilizer-use efficiencies and cause non-uniform distribution of both water and fertilizers.

- One should be aware that continuous and prolonged fertigation of fertilizers to the reduced wetted soil volume means that only a small fraction of the cultivated soil is actually fertilized. This may increase the potential of creating a problem of salt and toxic ion accumulation in the root zone. This is of more importance during the more sensitive stages of early growth and root initiation. Therefore, nutrient requirements must be applied according to needs of the physiological stages.

Nutrients and Root Growth and Development

Generally, fertilization favors root growth. Roots tend to proliferate in zones containing fertilizers, particularly if the zone contains both N and P (Drew and Saker, 1978). Increasing N favors top growth in relation to root growth. Therefore, excessive N stimulates vegetative growth, which uses up the available water, carbohydrate, and nutrients. In addition, excessive N tends to increase the auxin levels, which may inhibit root growth. Adequate N fertilization tends to promote deeper and more profuse rooting early in the season, probably due to increased photosynthesis and caused a direct increase in root hair proliferation. Potassium seems to have no direct effect on root elongation or branching. However, it indirectly influences root growth through role of K in enhancing plant growth in general.

Mass flow and diffusion are the two major mechanisms by which nutrients move in the soil system toward the roots. Most N is moved and supplied by *mass flow*, while most of the P and K are by *diffusion*. It should be mentioned that soil moisture level is a key factor affecting both mechanisms of nutrient movement. Mass flow refers to movement of nutrients through the soil to the roots in the convective flow of water caused by plant water absorption, where the amount of nutrient supplied by this mechanism would equal to the amount of water absorbed by the plant multiplied by the concentration level of the nutrient in question.

Diffusion, on the other hand, occurs as a result of concentration gradient where nutrients are diffusing along the gradient toward the root surface area, i.e., from zone of higher to that of lower concentration until equilibrium. However, this equilibrium is not established, because roots continuously absorb nutrients and thus create depletion zones near the root surface and, therefore, maintain the concentration gradient toward the root surface.

The effective diffusion coefficient of nutrients is directly related to soil moisture, which emphasizes the importance of keeping the soil moisture high enough to facilitate and enhance nutrient diffusion. This is particularly important for immobile nutrients, such as P, and during the early growth stages where P is needed the most for root initiation and development and where soil moisture is relatively low, which restrict growth and activity of roots and consequently uptake

rate of nutrients is reduced. Lower uptake rate under these conditions may fail to create the depletion zone necessary for establishing the concentration gradient toward the roots. Under these conditions, fertigation is of great importance to maintain the nutrient concentration in the soil solution high enough to support their uptake by the plant roots.

Under fertigation, the concentration of these nutrients should be maintained constantly high to ensure higher rates of nutrient uptake. Irregular fertigation frequency may expose the plants to a rather low nutrient concentration toward the next fertigation cycle, thus the rate of nutrient uptake will be considerably reduced. In fact, the parameters in the Michaelis-Menten equation can be used to characterize the nutrient uptake pattern of roots of various plant species and under different cropping systems. Thus, a desirable uptake rate can be identified and be used to properly manage the fertigation rate and frequency accordingly.

Barber (1984) developed a mechanistic models which successfully predicted the uptake of nutrients based on quantifying the three major processes which determine nutrient uptake. They are; *root growth rate*, *nutrient uptake rate per unit of root surface area*, and *movement rate of nutrients by mass flow and diffusion to the root surface*. The strong relationship between the observed and predicted uptake found by this model indicate the practical importance of addressing root morphology parameters such as root length, surface area as strongly related to nutrient uptake.

For actively absorbed nutrients (e.g., P), more frequent application of adequate rate will ensure higher uptake rate. On the other hand, some nutrient could be required at higher concentration during the early stages for root initiation and development; in this case, a pre-plant application might be necessary. Potassium is readily redistributed within plants as well as being able to enter virtually the entire root system. In contrast, calcium can enter solely into younger tissues and its translocation toward root apices is negligible (Marschner and Richer, 1973). Therefore, Ca, but not K, must be continuously supplied to the newly growing root apices.

Potassium and phosphate move across the cortex by symplastic, but calcium moves by apoplastic pathway. Therefore, symplastic movement of K and P through plasmodesmata is not restricted or interrupted by suberization of the endodermis. Nitrate and ammonium ions move mostly by symplastic pathways. Therefore, high rate of ammonium uptake, especially during early growth stages, may lead to accumulation of ammonium ions in the cytoplasm at a rate higher than the rate of its assimilation which consequently cause a toxic effect.

When N is applied as ammonium, which is a positively charged cation, it tends to be adsorbed onto negatively charged clay colloids, moving only a small distance from the point of application. This will happen more clearly with low rate of fertilizers and low discharge rate of emitters. When the concentration of the

ammonium ions in the irrigation water is high (high fertilizer application rate), they can saturate the exchange sites on the soil colloids and afterward move into deeper soil layers. Accumulation of ammonium ions near the soil surface, are usually present most of the time in the saturated zone below the emitters (Mohammad et al., 1999). Therefore, nitrification, in these saturated zones, is expected to be relatively much lower. Besides, under high soil pH and alkaline conditions, serious losses of N as ammonia volatilization is expected.

Urea is water soluble and can move in the soil deeper below the emitters and is not strongly adsorbed onto the soil colloids. Therefore, urea concentration near the soil surface will be lower, thus minimizing losses by volatilization. Nitrate is negatively charged and move freely in the soil with irrigation water and be distributed nearly as water distribution. Moreover, over-irrigation will lead to nitrate leaching, and roots will not have access to the leached nitrogen. On the other hand, higher frequency of fertigation therefore minimizes leaching and enhances fertilizer-use efficiency.

Phosphorus is an immobile in the soil and applied P tends to be precipitated and adsorbed in most soils, and subsequent movement from its point of application is limited (Mengel and Kirkby, 1982). Phosphorus applied with the irrigation water will not move more than 20 to 30 mm, thus most P will remain near the soil surface. However, application of high rates of soluble P fertilizers through drip irrigation system greatly enhances P movement in the soil. Application of P into a small soil volume below the drippers will provide P in amount adequate for saturation of soil reaction sites by P near the point of application and subsequent movement downward below emitters, thus increasing the distance of P movement which can reach 300 mm.

Methods of Studying Root Systems

Root system can be studied through *direct measurements* or *indirect observations*. The following parameters can be targeted in any research on root system:

Distribution

Several methods have been reported for studying the distribution of root systems in the soil. These methods vary in the complexity and accuracy of obtaining representative samples and in the type of information they provide. The following approaches have been used for studying root distribution:

- **Visual Inspection.** This can be achieved simply by examining the sides of the soil profile made within a crop row. This can provide qualitative information on root distribution in the soil. This inspection can provide information about the possible presence of mechanical impedance of root growth and they indicate the

needs for sub-sampling for further detailed examination and where to sample.

- **Separation of Intact Roots** can be obtained by using a board with pins vertically attached to it at a desirable distance (10 cm). This “pin board” can be driven through into the soil to a depth sufficient to pass through the root system. Then by excavating the soil from the surrounding and the soil volume removed by the pin board can be taken intact. The soil is subsequently washed away carefully by water, thus the root system will stay supported by the pins nearly as its original position in the soil. This method is time-consuming and larger errors can be made if not carefully performed in taking the representative sample.
- **Core-Sampling Method.** An auger can be used to get a soil sample at a desired soil depth. The volume of the auger must be known or the soil core can be divided into several sections of known volumes. Auger with 5 cm or more in diameter are usually used. The roots from each soil core section are removed and the length and dry weight are recorded.
- **Nuclear Techniques** can be used through injection of radioactive tracer into plant shoots which is uniformly distributed through the root system.

Root Function and Performance (nutrient and water uptake)

- **Radioactive Tracers** can be applied to a different depths to compare the quantity of nutrients absorbed from these soil depths. This will indicate relative growth of roots with soil depth and suggest an appropriate placement for fertilizers.
- **Another Nuclear Technique** can be used to measure the soil moisture depletion from the different soil depths. Since root growth tend to follow water distribution, soil and plant scientists used to monitor water depletion zones and use it as an indication of the root distribution pattern within the soil profile. The use of neutron moisture probe was successfully employed for this purpose.

Morphology

Root morphology parameters such as length, diameter, and surface area. are very important to nutrient and water uptake. There are several procedures to quantify these parameters. Some of them are:

- **Newman’s Line-Intersect Method:** This method is well known and widely spread and is suggested to estimate root length based on the following empirical relationship:

$$R = \pi \times N \times A / 2H$$

Where:

R = total root length

N = number of intersections between the roots and a set of randomly placed straight lines

A = the area of the place in which the roots are arranged

H = the length of the straight lines

This method of visual quantification of root system was widely used, but is, however, a relatively more time-consuming and much less accurate than the automated enumeration achieved by photoelectric detection or by video-camera imaging or by edge discrimination using a desktop scanner. The later technique provides better accuracy and precision, and creates high resolution images of root systems. In addition, this technique give the opportunity to measure not only root length but also root diameter and surface area (Pan and Bolton, 1991).

- **Rhizotrons:** This is a device where the plants are grown adjacent to subterranean passages with transparent sides through which roots can be observed.
- **Lysimeters:** These are enclosed volume of soil from which water lost by drainage can be collected, or changes in soil moisture can be measured by weighing. This gives opportunity to deal with more convenient system for studying root system then any method mentioned above.

FUTURE ROOT RESEARCH

Although research on roots is relatively limited than that on aerial plant parts due to difficulties involved in their study, there is more opportunity of improving plant growth by altering the root environment. Men have more control on the root environment than on the shoot environment. Therefore, one can improve plant growth by altering root environment through controlling for example, soil moisture by irrigation, soil temperature by tillage and mulching, and fertility level by fertilization. On the other hand, changing the shoot environment by agronomical practices is practically impossible. Therefore, root study should be given more emphasis than at present

REFERENCES

- Anghioni, I., and S. A. Barber. 1988. Corn root growth and nitrogen as affected by ammonium placement. *Agron.J.* 80: 799 – 802.
- Barber, S. A. 1984. Soil nutrient bioavailability: a mechanistic approach. John

Wiley & Sons. New York, NY.

- Brouwer, R. 1965. Root growth of cereals and grasses. In F. L. Milthorpe and J. D. Ivins (ed.) *The growth of cereals and grasses*. Butterworths. London p. 153 – 166.
- Caldwell, M. M., L. M. Dudley, and B. Lilieholm. 1992. Soil solution phosphate, root uptake kinetics and nutrient acquisition: Implications for a patchy soil environment. *Oecologia*. 89: 305 – 309.
- Derera, N. F. D.R. Marshall, and L.N. Balaam. 1969. Genetic variability in root development in relation to drought tolerance in spring wheat. *Expl. Agric.* 5: 327 – 337.
- Drew, M.C. 1975. Comparison of the effect of a localized supply of phosphate, nitrate, ammonium and potassium on the growth of seminal root system and the shoots in barley. *New Phytol.* 75: 479 – 490.
- Drew, M.C., and L.R. Saker. 1978. Nutrient supply and the growth of seminal root systems in barley: III. Compensatory increases in growth of lateral roots and in rates of phosphate uptake, in response to a localized supply of phosphate. *J. Exp. Bot.* 29: 435-451.
- Eghball, B., and J. W. Maranville. 1993. Root development and N influx of corn genotypes grown under combined drought and N stresses. *Agron. J.* 85:147-152.
- Goss, M. J. M. H. Miller, L. D. Bailey, and C. A. Grant. 1992. Root growth and distribution in relation to nutrient availability and uptake. In H. F. Reetz (ed) "Roots of Plant Nutrition". Meeting proceedings, July 8 – 10, Champaign, Illinois.
- Hurd, E.A. 1968. Growth of roots of seven varieties of spring wheat at high and low moisture levels. *Agron. J.* 60: 201 – 205.
- Marschner, H. 1986. Mineral nutrition of higher plants. Academic Press, London .
- Mohammad, M. J. S. Zuraiqi, W. Quasmeh, and I. Papadopoulos. 1999. Yield response and nitrogen utilization efficiency by drip-irrigated potato. *Nutrient Cycling in Agroecosystems*. 54: 243–249.
- Mullins, G. L. 1993. Cotton root growth as affected by P fertilizer placement. *Fert. Res.* 34: 23 – 26.
- Pan, W.L., and R.P. Bolton. 1991. Root quantification by edge discrimination using a desktop scanner. *Agron. J.* 83: 1047 – 1052.
- Papadopoulos, I. 1985. Constant feeding of field-grown tomatoes irrigated with sulphate water. *Plant Soil* 88:231-236.
- Papadopoulos, I. 1988. Nitrogen fertigation of trickle-irrigated potato. *Fert. Res.* 16: 157 –167.
- Pearsall, W. H. 1927. Growth studies. VI. On the relative size of plant organs. *Ann. Bot.* 41: 449 – 556.
- Troughton, A., and W. J. Whittington. 1969. The significance of genetic variation

- in root systems. p. 296 – 313. *In*: W. J. Whittington (ed.). *Root growth*, Butterworths, London.
- Richards, W. J. 1992. Plant root research. Its importance to soil and water conservation in the 1990's. *In* H. F. Reetz (ed) "Roots of Plant Nutrition". Meeting proceedings, July 8 – 10, Champaign, Illinois.
- Rogers, W. S., and G. C. Head. 1966. The roots of fruit trees. *J. hort. Soc.* 91: 198 – 205
- Russell, R. S. 1982. Plant root systems. Their function and interaction with the soil. *McGraw-Hill Book Co.* UK.
- Rosario, M. do, G. Oliveira, and A. M. Calado. 1996. Tomato root distribution under drip irrigation. *J. Amer Soc. Hort. Sci.* 121(4): 644 – 648.
- Zhang, M. A. K. Alva, Y. C. Li, and D. V. Calvert. 1996. Root distribution of grapefruit trees under dry granular broadcast vs fertigation method. *Plant Soil* 183: 79 – 84.

SECTION III:

FERTIGATION WITH PHOSPHORUS FERTILIZERS

F04
F06

Use of Phosphorous Fertilizers in Pressurized Irrigation Systems: Problems and Possible Solutions

John Ryan¹ and Maher Saleh²

¹Natural Resource Management Program, ICARDA, P.O. Box 5466, Aleppo, Syria. ²College of Agriculture, El-Shatby, Alexandria University, Alexandria, Egypt.

ABSTRACT

In a world where water is so essential for agricultural and industrial purposes, as well as human consumption, this vital resource has to be managed with care. In the acutely water-short countries of the Mediterranean, the issue of *efficient water use* is of concern at the social and political levels. Food has to be produced to support the burgeoning populations in the region - and it *depends on water*, whether from rainfall, which is low, or from rivers and groundwater, which are limited. With an emphasis on water-use efficiency, there has been a shift from open irrigation systems, such as flooding, to closed systems which involve water being pumped through sprinkler and drip irrigation pipes or conduits. Although such pressurized systems of irrigation are initially expensive, they are if properly managed efficient in terms of water use and are cost-effective in the long-term.

An essential input in modern crop production is commercial fertilizers, which provide the necessary nutrients for adequate crop growth. However, *while it is desirable that nutrients are applied through pressurized irrigation systems, such application is not without its problems.*

Nitrogen (N), the nutrient needed in largest amounts by crops, can easily be dissolved and applied in sprinkler and drip irrigation systems; it readily enters and moves through the soil, but it may be subjected to volatile loss, especially with sprinklers, to an extent depending on environmental conditions, i.e., air temperature, relative humidity and wind conditions. Using acid-based fertilizers helps mitigate this loss. Another element, potassium (K) that could be applied in irrigation systems is easily dissolved, does not precipitate readily, and has greater movement within the soil. However, its requirement in fertilizer form in the Middle East is comparatively low since most soils are well supplied with plant-available K; indeed some irrigation water is also rich in K.

The use of conventional phosphorus (P) fertilizers has other and more intractable difficulties. These include problems with (1) dissolution of the fertilizer

to facilitate distribution with the water, which depends on the quality and solubility of the fertilizer, (2) precipitation of P as insoluble compounds within the drip lines and blockage of drip emitters by such precipitates, which is favored by water of high pH and high concentrations of calcium and magnesium, and (3) limited mobility within the root zone due to retention /precipitation by solid - phase soil compounds and adverse reactions with soluble constituents. Poor “positional” availability due to P “filtering” by soil clays is more of a problem in fine-textured soils compared to sandy soils.

These problems with P application have led farmers to adopt initial soil application of P fertilizers at planting time only. However, the development of acid-based fertilizers offers some solution to the problem of chemical precipitation, emitter blockage and limited soil mobility. This would be attractive in intensive greenhouse and field production systems. This presentation highlights the problems of P use within pressurized irrigated agriculture in the context of the Middle East area and endeavors to identify possibilities for compatible use of P fertilizers within such systems.

INTRODUCTION

The major constraint to agricultural production, and consequently to society as a whole, in many areas of the world is *lack of water from rainfall*, but its *distribution is also erratic*. Arid and semi-arid areas, mainly in Africa and many parts of Asia and Latin America, are where the developing countries are invariably with high population growth rates, where food demand is greatest, and with unrelenting pressure to produce more and more from meager natural resources.

While irrigation, a practice that is with us from ancient times, may at first glance seem a panacea, it is not a realistic option for many arid regions, where available surface water source are already exploited to the limit and where “fossil” groundwater or sources with limited recharge are being rapidly depleted.

However, recent technical developments in irrigation science offer some solution to the problem of using scarce water in agriculture. Traditional systems of irrigation were, and are, insufficient and result in considerable water loss through *leaching, evaporation* and *poor utilization* by the crop. Thus, modern pressurized systems, e.g., sprinklers and especially drippers, are far more efficient in terms of producing greater crop yields from any given amount of available water (Papadopoulos, 2000). With competition for water use from non-agricultural sources, e.g., urban and recreational, today’s agriculture has to use water efficiently; in many developed countries, this is also fueled by environmental considerations.

Notwithstanding their advantages, modern irrigation systems are not without their problems and drawbacks. They are *expensive* in the short term, but *cost-effective* in the long-term, given the increased output and reduce water use. Such

economic considerations can be a major constraint in lesser-developed countries. Indeed broad economic policies and market availability for the increased crop output can be major determining factors for the success or failure of modern irrigation systems in any given situation. As with any developed technology, a corresponding increased level of management skills is required – and there are inherent problems associated with any new technology.

Crops cannot be successfully grown unless the supply of nutrients is adequate – these come from the soil and are added in the form of fertilizer. Under modern high-demand cropping systems, fertilization is indispensable since few soils are rich enough to meet crop nutrient needs. Nitrogen (N) is invariably needed in high amounts in all non-legume cropping systems in the Middle East (Ryan, 1997). Similarly, as available soil phosphorus (P) levels are generally low in the region's mainly calcareous soils (Matar et al., 1992), P fertilization is also needed, but the problems of P use are different from these with N. Fortunately, potassium (K) is well supplied in such soils (Ryan et al., 1997), but may be needed in intensive production systems, sandy soils, and with high K-demanding crops.

An advantage of pressurized irrigation systems is being able to apply needed crop nutrients along with the irrigation water in a manner that increases efficient (and safe) use of nutrients as well as water. Water-run application of fertilizers saves time and labor, fuel and equipment costs, as well as allowing flexibility in fertilizer-application timing, but needs careful metering and may not always be as accurate as soil-application.

The main nutrient added with irrigation water is N, since it is soluble, does not react with the soil, and can move with the water to the root zone where it can be readily take up by the crop (Soil Improvement Committee, 1980). However, it may lead to losses depending on the application method. Surface or flood systems can allow for volatile loss of N as ammonia (NH_3) under certain conditions (high water pH, urea and ammonium sources); sprinklers may promote even more NH_3 loss depending on environmental conditions, especially wind and high temperature. Leaf burn may also occur where fertilizer concentrations are too high.

Drip irrigation systems eliminate all the problems associated with surface or sprinkler systems. While K can also be applied with water in any irrigation system without any loss or significant reduction in efficiency, the practice is not as common as with N. Micronutrients can also be applied with irrigation water as can any other chemical to control weeds, diseases, etc. From the fertilizer and plant nutrient standpoint, the major problem is with P, a nutrient that is invariably limited in the soil and one that is needed in fertilizer form. There are potential advantages of applying P through pressurized irrigation systems if the problems unique to P fertilizers could be overcome.

Thus, in keeping with the theme of fertigation – the application of fertilizer with irrigation water – the focus of this paper is on specific obstacles associated

with the use of P fertilizers in drip irrigation systems and possible solutions to mitigate or eliminate them, some examples from the laboratory and field work of the authors to illustrate some of the issues associated with P use. It draws heavily on the extensive review of fertigation in pressurized irrigation systems by Papadopoulos (2000) and the FAO paper of Matar (1992), which refers to several original papers of the senior author.

THE PROBLEM WITH PHOSPHORUS FOR FERTIGATION

Prior to examining specific problems with P in irrigation systems, let us consider the criteria for effective fertilizer application in such systems. Beginning with the fertilizer itself, it should be *amenable to dissolution* in water and have little or no insoluble residues. Subsequently, it should move within the irrigation pipes *without reaction with constituents of the water causing precipitate to form* within the tubing or blocking the minute pores or emitters. Finally, at the emitter site, *the nutrient should move with the water throughout the wetted soil root volume* so that it can be taken up effectively by the crop. In the case of P, obstacles to efficiency of application occur at each front.

Form of the Fertilizer

Traditional P fertilizer sources, i.e., ordinary superphosphate (8% water-soluble P) and triple superphosphate (12% water-soluble P) are considered unsuited for use in irrigation systems because of the difficulty of dissolving them, and the fact that they contain some insoluble P and considerable solid residues. With pelleting or granulation, they are more suitable for broadcast or band-application in the soil. While the latter approach is more efficient in terms of uptake, the amount of P taken up by the crop in any one season rarely exceeds 20% due to limited P mobility in the soil. *Fertigation offers some potential to improve P uptake efficiency* and thus increase the economic return on fertilizer use. The limited P movement in the soil is due to reaction of soluble P with soil constituents. That same reaction makes it unfeasible to apply P in surface or sprinkler systems, as it would remain on the top 1 – 2 cm of soil and not reach the roots (Lauer, 1988).

However, while conventional P sources are not suitable for drip systems (Haynes, 1985), new developments in fertilizer technology have led to more soluble and concentrated P sources that are suitable for application with water. For example, liquid phosphoric acid (H_3PO_4) meets such criteria (Rauschkolb et al., 1976). Indeed, any acid material, such as sulfuric acid (H_2SO_4), which can dissolve insoluble P from the soil itself (Ryan and Stroehlein, 1979), can be applied with irrigation water. The only problems with agricultural use of such acids are the need for specialized handling in storage, transport and application, and possible

corrosion of metal parts.

There are several liquid P fertilizers that, being fully soluble, can be applied with the irrigation water, but their reactions with constituents in the water preclude their use. Liquid ammonium orthophosphate and ammonium polyphosphate react with calcium (Ca^{++}) in the water – and water of drier regions tend to have relatively high Ca^{++} levels – causing insoluble Ca-phosphates to precipitate, thus increasing the relative sodium (Na) concentration, i.e., sodium absorption ratio (SAR) which, in turn, impedes water penetration in the soil.

A relatively new and experimental material which is soluble and suitable for water application is urea phosphate (UP), an adduct of urea and phosphoric acid. Being high in soluble N (17%) and P (19%), this solid fertilizer has less corrosivity (Achorn, 1984) and lower losses of volatile NH_3 (Stumpe et al., 1984). On-going studies in Egypt (Saleh and Aboushal, 1998) have shown that acid-based fertilizers such as UP have increased agronomic effectiveness compared to N and P alone.

Other solid sources of P, which are widely used, are mainly soluble with high nutrient concentration i.e., monoammonium phosphate (MAP) and diammonium phosphate (DAP), but those have some solid residues that would need to be filtered before entering the closed pipe system. Another novel material that meets the solubility criteria is glycerophosphate (Rolston et al., 1974), but it is not attractive due to high costs of production.

In-Line Precipitation

The chemical factors which cause the soluble applied P to react with Ca^{++} in the water at the mixing – tank level also operate to cause precipitation within the plastic piping of the drip irrigation system – colder temperatures can aggravate the problem. The precipitates thus formed inevitably clog the emitter pores or orifices, thus reducing or completely cutting off the water supply to the soil around the root zone. Such blocking is reflected in increased pressure within the lines.

The traditional method for controlling Ca^{++} or Mg^{++} precipitates or depends within the drip lines is to inject acid into the system on a continuous or an intermittent basis in order to reduce the pH of the water. The amount of acid required depends on the buffering capacity of the water, in essence, carbonates of these cations. The acid most commonly used is sulfuric – not only to prevent precipitation, but also to dissolve precipitates already formed and to clear blocked orifices (Rauschkolb et al., 1976). Metering H_2SO_4 into irrigation canals and Ca-P rich water can effectively eliminate Ca-P precipitation if done properly (Miyamoto and Ryan, 1976). Other acids such as hydrochloric acid are equally effective, but are more expensive and pose additional handling problems. Phosphoric acid can similarly modify the water pH, but is more problematic in relation to the Ca^{++} and Mg^{++} concentrations.

A novel development in controlling precipitation in-line has been the use of liquid polymers (Meyer et al., 1991); using waters of high bicarbonate (mainly Ca) of 4 to 4.5 meq/l, the use of maleic anhydride polymer was injected at 2 mg/l (2 ppm) into water to irrigate strawberries. Over the 6-month growing period, the flow rate in the treated system was only slightly decreased (and thus with little or no precipitation in the lines) while that in the untreated water was reduced by 50%. Thus, the amount of time needed to irrigate the crop was correspondingly increased. The amendment is therefore effective in increasing the irrigation efficiency.

Poor Mobility Within the Root Zone

Even if the P solutions reach the soil at the emitter point without any loss at the mixing point or in the drip lines due to precipitation, the soil itself poses an even more intractable obstacle to uniform P distribution within the root zone where it is needed. The reactivity of soluble P with soil constituents and its implications for crop fertilization and, more recently for environmental considerations is one of the most researched topics in soil science.

Reactions with soil constituents (Ca^{++} , CaCO_3 , Fe^{+++} , Al^{+++} , clays, organo-metallic complexes, etc.) range from precipitation with constituents in solution to surface reactions – adsorption and absorption (Matar et al., 1992). The immediate and net effect is a rapid reduction in solubility because of sorption (Torrent, 1987) and subsequent plant availability of the added soluble P (Ryan et al., 1985a); the reduction in availability proceeds with time, i.e., longer-term reactions (Ryan et al., 1985b).

When soluble P emerges from drip orifices into the soil, the reactions involve progressive adsorption by soil layers (Logan and McLean, 1973); as reaction sites are saturated, P moves with the water to the next layer of unsaturated sites (Raushkolb et al., 1976). The extent to which added P moves from the dripper site reflects the soil properties that react with P; texture is a major variable, with greater movement in sandy soils because of the reduced level of P-reactive soil constituents (i.e., clay). Given this innate behavior in soil, it is pertinent to examine the actual movement of P from drip irrigation systems and how this mobility is affected by the type of fertilizer.

Using conventional P sources in sprinkler systems, P did not penetrate more than 4 to 6 cm from the surface of a sandy loam soil (Lauer, 1988). With drip systems and such P sources, movement was limited to a few cm vertically – and even less laterally – from the emitter point (Ryan et al., 1988a; O'Neill et al., 1979; Bar Yosef and Sheikloslami, 1976). Again, mobility increased with lighter texture and the amount of P applied. However, substantial increases in mobility were recorded with less conventional P fertilizers. Thus, it is of interest to consider

properties of various fertilizers in relation to precipitation /mobility.

Phosphoric Acid

In addition to controlling precipitation to the point of entry to the soil, H_3PO_4 has also a considerable effect on P mobility in the soil. With similar P application rates, movement of P from H_3PO_4 was 5 to 10 times greater than with triple superphosphate (Raushkolb et al., 1976). This led to twice the efficiency in terms of fertilizer P uptake by sandy soil; movement of P from H_3PO_4 occurred into twice the volume of soil compared to that from spot-placed TSP at the same rate (O'Neill et al., 1979). The apparent beneficial effects of H_3PO_4 are related to the reduction in pH and thus to reduce precipitation of Ca-P compounds and perhaps the simultaneous dissolution of insoluble soil P.

Urea Phosphate

The study of Ryan et al. (1988a) showed higher water-soluble and NaHCO_3 – soluble P after addition of acid fertilizers such as urea-phosphate (UP) compared to TSP, but noted the greater lateral and depth-wise movement of P within a heavy clay soil than with H_3PO_4 or conventional materials. Other studies with up showed much greater mobility in the soil than TSP and, as a consequence, greater fertilizing efficiency for tomato (Mikkelsen and Jarrell, 1987) and lettuce (Chase, 1985). In the latter case, P movement downwards was 12 cm and 10 cm laterally – all encompassing the crop root zone.

Glycerophosphate

As organic P sources do not react readily with soluble inorganic constituents, they were tested for suitability in drip irrigation systems. Thus, glycerophosphate, applied at 39 kg P /ha to a clay loam soil, moved as much as 25 cm horizontally and permeated a volume of soil four times greater than an equivalent amount of H_3PO_4 , with corresponding increases in P-fertilizing efficiency (Rolston et al., 1974). The only restriction on mobility of movement of P in this form would be enzymatic hydrolysis (Costro and Rolston, 1977), after which reactions with inorganic constituents would occur.

Other Fertilizers

The review of Matar (1992) listed several fertilizers other than TSP that could be used in drip or sprinkler systems because of comparatively better mobility in

calcareous soil: monoammonium phosphate (Papadopoulos, 1985), diammonium polyphosphate (Hergert and Reuss, 1976), and potassium dihydrogen phosphate (Al-Rawi et al., 1986).

Indirect Effects of Acidic Fertilizers

While acids such as H_2SO_4 , applied directly to the soil or in water, can dissolve much of the native soil P and considerably influence the soil's chemistry (Ryan et al., 1974; Ryan and Stroehlein, 1979), especially in terms of water movement, acidic P fertilizers can have similar effects on the soil. Incubation studies showed that UP had an influence in increasing Mn and Zn availability in calcareous soil (Ryan et al., 1986). However, there was no effect on extractable Fe, and indeed in another study (Ryan et al., 1988b), UP at high application rates tended to increase chlorosis in soybean. This may have been related to a negative effect on soluble Fe caused by the increase in pH following urea hydrolysis. However, this acid material was shown to be effective in increasing infiltration in Na-affected soils (Ryan et al., 1988a; Ryan and Tabbara, 1989), an effect which was attributed to the dissolving effect of the H_3PO_4 component of UP on soil $CaCO_3$ and the subsequent decrease in the solution SAR. The latter parameter is a key criterion in soil water relations, especially infiltration and permeability.

CONCLUSIONS

In this brief overview of the use of P fertigation systems, it is abundantly clear that it is not appropriate to use P in either furrow or sprinkler systems. While problems with its use in drip systems seem intractable, they can in fact be overcome.

While P is manually applied on an annual basis to the soil as band or broadcast application for broad-acre field crops, depending on the soil P levels, intensive irrigated cropping, as in greenhouses, requires continuous nutrition of the crop. While N can be readily applied with the water and be distributed within the root zone with the water, it is equally desirable that P be applied in the same manner.

Clearly, fertigation with P in drip system can be effective – but not with conventional fertilizers used for soil application. Of the potential material amenable to such application, H_3PO_4 is the most attractive. It not only eliminates precipitation in the mixing tank and within the drip lines, but it can also dissolve precipitates already formed and which have been clogging the emitters. Sulfuric acid, an even cheaper and acid source, can effectively do the same thing. However, as a carrier of P, phosphoric acid can effectively penetrate the wetted soil volume more effectively than other materials, and thus lead to more effectively agronomic use. While urea phosphate has also many advantages with respect to fertigation, they, in fact, stem from the phosphoric acid component and thus behave similarly

to the acid used alone. It does, however, have the advantage of combining a high N concentration with the P source.

Innovations in one technology frequently require adaptation in other associated technologies. The provision of a liquid acid fertilizer to combine with water-efficient drip irrigation systems is a good illustration.

REFERENCES

- Achorn, F.P. 1984. Acid fertilizers solutions (May-June): 33-39.
- Al-Rawi, M.N., A. Alsenbol, R. Salih, and A. Salih. 1986. Effect of nitrogen and phosphorus application with trickle irrigation on yield of potatoes. *J. Agric. Water Resources Rev.* 5(1): 139 – 150.
- Bar-Yosef, B., and M.R. Sheikholeslami. 1976. Distribution of water and ions in soils irrigated and fertilized from a trickle source. *Soil Sci. Soc. Am. J.* 40: 575 – 582.
- Castro, C.L., and D.E. Rolston. 1977. Organic phosphate transport and hydrolysis in soil: Theoretical and experimental evaluation. *Soil Sci. Soc. Am. J.* 41: 1085 – 1092.
- Chase, R.G. 1985. Phosphorus application through a subsurface trickle system, p. 393-400. *In Proc. "Drip/Trickle Irrigation Congress"*. Fresno, CA. 18 – 21 Nov. 1985. ASAE, St. Joseph, MI.
- Haynes, R.J. 1985. Principles of fertilizer-use for trickle irrigated crops. *Fert. Res.* 6: 235 – 255.
- Hergert, G.W., and J. O. Reuss. 1976. Sprinkler application of P and Zn fertilizers. *Agron. J.* 68: 5 – 8.
- Lauer, D.A. 1988. Vertical distribution in soil of unincorporated surface-applied phosphorus under sprinkler irrigation. *Soil Sci. Soc. Am. J.* 52: 1685 – 1692.
- Logan, T.J., and E.O. McLean 1973. Effects of phosphorus application rate, soil properties and leaching mode on P₃₂ movement in soil columns. *Soil Sci. Soc. Am. Proc.* 37: 371 – 374.
- Matar, A. 1992. Phosphorus in relation to fertigation. Food and Agriculture Organization FAO, Special Publ. Regional Near Office, Cairo, Egypt.
- Matar, A., J. Torrent, and J. Ryan. 1992. Soil and fertilizer phosphorus and crop responses in the dryland Mediterranean zone. *Adv. Soil Sci.* 18: 82 – 146.
- Meyer, J.L., M.J. Snyder, L.H. Lalenzuela, A. Harris, and R. Strohmman. 1991. Liquid polymers keep drip irrigation lines from clogging. *Calif. Agric.* 45(1): 24 – 25.
- Mikkelsen, R.L. 1989. Phosphorus fertilization through drip irrigation. *J. Prod. Agric.* 2:279 – 286.
- Mikkelsen, R.L., and W.M. Jarrell. 1987. Application of urea phosphate and urea sulfate to drip-irrigated tomatoes grown in calcareous soils. *Soil Sci. Soc. Am. J.* 51: 464 – 468.

- Miyamoto, S., and J. Ryan. 1976. Sulfuric acid for the treatment of ammoniated irrigation water. II. Reducing calcium precipitation and sodium hazard. *Soil Sci. Soc. Am. J.* 40: 305 – 309.
- O'Neill, M.K., B.R. Gardner, and R.L. Roth. 1979. Orthophosphoric acid as a phosphorus fertilizer in trickle irrigation. *Soil Sci. Soc. Am. J.* 42: 283 – 286.
- Papadopoulos, I. 1985. Constant feeding of field grown tomatoes irrigated with sulfate water. *Plant Soil* 88: 231 – 236.
- Papadopoulos, I. 2000. Fertigation: Present situation and future management under pressurized irrigation systems in the Mediterranean area. Workshop Proc. April 25 – 27. 1999. Amman, Jordan. ICARDA, Aleppo, Syria and IMPHOS, Casablanca, Morocco. (this volume)
- Rauschkolb, R.S., D.E. Rolston, R.J. Miller, A.B. Carlton, and R.G. Burau. 1976. Phosphorus fertilization with drip irrigation. *Soil Sci. Soc. Am. J.* 51: 1055 – 1062.
- Rolston, D.E., R.S. Rauschkolb, and D.L. Hoffman. 1974. Glycerophosphate as phosphate fertilizer. *Calif. Agric.* 28(8): 8 – 10.
- Ryan, J. 1997. Accomplishments and future challenges in dryland soil fertility research in the Mediterranean area. In Proc. Int. Soil Fertility Workshop, Nov. 19–23, 1995, ICARDA, Aleppo, Syria.
- Ryan, J., and J. L. Stroehlein. 1979. Sulfuric acid treatment of calcareous soils: effects on phosphorus solubility, inorganic phosphorus forms, and plant growth. *Soil Sci. Soc. Am. J.* 43: 4: 731–735.
- Ryan, J., and H. Tabbara. 1989. Influence of urea phosphate on infiltration and sodium parameters of a calcareous sodic soil. *Soil Sci. Soc. Am. J.* 53: 1531–1536.
- Ryan, J., S. Miyamoto, and J. L. Stroehlein. 1974. Solubility of manganese, iron, and zinc as affected by application of sulfuric acid to calcareous soils. *Plant Soil.* 40: 421–425.
- Ryan, J., D. Curtin, and M. A. Cheema. 1985a. Significance of iron oxides and calcium carbonate particle size in phosphorus sorption and desorption in calcareous soils. *Soil Sci. Soc. Am. J.* 49 (1): 74 – 76.
- Ryan, J., H. Hasan, M. Baasiri, and H. S. Tabbara. 1985b. Availability and transformation of applied phosphorus with time in calcareous Lebanese soils. *Soil Sci. Soc. Am. J.* 49(5): 1215 – 1220.
- Ryan, J., M. Hamze', S. Darub, and S. N. Harik. 1986. Nutrient availability in incubated urea phosphate-treated calcareous soil. *J. Fert. Issues* 3(4): 146 – 150.
- Ryan, J., S. Masri, and Z. Masri. 1997. Potassium status in soils and crops, recommendations and present use in Syria. p. 134 –145. In A.E. Johnston (ed) Food Security in WANA Region, the Essential Need for Balanced Fertilization. Proc. Regional Workshop, May 26–30, 1997. Ege University, Bornova, Turkey

- Ryan, J., M. A. Eisa, H. Tabbara, and M. Baasiri. 1988a. Phosphorus movement following water-applied urea phosphate and phosphoric acid in a calcareous clay soil. *J. Fert. Issues* 5(3): 89–96.
- Ryan, J., M. Hamze', S. N. Harik, and S. Darub. 1988b. Influence of urea phosphate on iron-inefficient soybeans. *J. Fert. Issues* 5(2): 56–60.
- Saleh, M.E., and A.A. Aboushal. 1988. Response of wheat to NP-acid-type fertilizer application in calcareous soils. p. 481 – 488. *In Proc. Int. Symposium on "Arid-Region Soils"*. 21 – 24 Sept. Menemen, Izmir, Turkey.
- Stumpe, J.M., P.L.G. Vlek, and W.L. Lindsay. 1984. Ammonia volatilization from urea and urea phosphates in calcareous soils. *Soil Sci. Soc. Am. J.* 48: 921 – 927.
- Soil Improvement Committee, California Fertilizer Association. 1980. *Western Fertilizer Handbook*. The Interstate Printers and Publishers, Inc. Danville, Illinois 61832, USA.
- Torrent, J. 1987. Rapid and slow phosphate sorption by Mediterranean soils: effect of iron oxides. *Soil Sci. Soc. Am. J.* 51: 78 – 82.

A Comparison of the Efficiency of Conventional Soil Phosphorus Application and Phosphorus Fertigation

Leena Ristimäki¹, and Ioannis Papadopoulos²

¹Kemira Agro oy, P.O.Box 330, 00101 Helsinki, Finland ,

²Agricultural Research Institute, Nicosia, Cyprus

ABSTRACT

Fertigation, the application of nutrients dissolved in the irrigation water, is probably the most efficient method of using fertilizers, particularly on calcareous soils. In this study, fertigation was compared with soil phosphorus (P) application in field trials on calcareous soil. Triple superphosphate, as a single soil application while planting, was compared to the continuous application of either diammonium phosphate, monoammonium phosphate, or urea phosphate as P sources with the irrigation water. Irrespective of the source, P applied with the irrigation water was more effective than direct soil application. The results also indicate that the more acidic the fertilizer P source, the higher the yields that are obtained. It can be concluded that the amount of P fertilizer could be reduced if acidic fertilizers are used.

INTRODUCTION

In fertigation, fertilizers are applied dissolved in the irrigation water, and consequently only fully water-soluble fertilizers can be used. The practical application of nitrogen (N) and potassium (K) fertilizer sources in this way has been successful, even though the quality of the irrigation water may be low. But in the case of phosphate (P) there can be serious management problems as a result of the incompatibility of certain fertilizing materials with the irrigation systems. If the irrigation water is hard, i.e., it contains high amounts of calcium and magnesium, these may precipitate as phosphate salts and cause clogging of irrigation pipes and nozzles.

This problem can, however, be overcome by acidifying the irrigation water (Gascho and Mashali, 1991; Mikkelsen, 1989). In practice, farmers use either acids, such as phosphoric or nitric acid, or acidic fertilizers. While the handling of liquid acids is hazardous and requires special care, the use of acidic fertilizers does not require any special precautions.

There are several acidic P fertilizers currently available on the market, such as monoammonium phosphate (MAP), monopotassium phosphate (MKP) and urea phosphate (UP). Of these three, UP is most acidic, due to the fact that one of the raw materials used in its manufacture is phosphoric acid. A process for producing UP was developed as early as 1922 (Mikkelsen and Bock, 1988), but there are still only a few manufacturers in the world. It has been proven that UP reduces ammonia volatilization losses (Ali and Stroehlein, 1991; Bremner and Douglas, 1971; Moavad et al. 1984; Mikkelsen and Bock, 1988; Stumpe et al., 1984), enhances micronutrient availability (Mikkelsen and Jarrell, 1987) and improves the plant's uptake of P (Mikkelsen and Jarrell, 1987; Raun et al., 1987).

In these experiments, the aim was to compare the conventional method of applying N, P and K fertilizer to the soil with the application of water-soluble fertilizers through fertigation, and also to evaluate the effects of P when it is applied in the form of UP, MAP, or diammonium phosphate (DAP).

All the field trials were conducted in Cyprus on a Pellic Vertisol (26% sand, 32% silt, 42% clay). The CaCO_3 content of the soil was 50 to 60% throughout the soil profile to a depth of 90 cm. The soil had a pH of 8.2 – 8.4 to a depth of 90 cm, and the irrigation water had a pH of 8.2.

PHOSPHOROUS SOURCES AND FERTIGATION: TOMATO

Materials and Methods

This trial consisted of four randomised blocks, each divided into eight plots. Each plot was 3.6-m wide and 10-m long and contained three rows with the centre row being used for data collection. The rows on each side of the centre row served as "guard" rows. All irrigation treatments were applied using drippers (figures in parentheses indicate concentrations of N, P and K, mg/l, in the irrigation water). The numbered treatments were:

1. Soil application of N, P, K (equivalent to 150-47-235 kg /ha applied with fertigation to 230 m³, corresponding to 2000 mm of irrigation water for the whole trial period)
2. Fertigation $\text{NH}_4\text{NO}_3 + \text{K}_2\text{SO}_4 + \text{H}_3\text{PO}_4$ (75-47-235)
3. Fertigation -/- -/- -/- (150-47-235)
4. Fertigation -/- -/- -/- (225-47-235)
5. UP+ KNO_3 +Urea (150-47-235)
6. UP+ KNO_3 +Urea (150-35-235)

pp 4 p 34
tomatoes
calcareous soils
acid soils,
yield increase
an experiment

7. $\text{MAP} + \text{KNO}_3 + \text{NH}_4\text{NO}_3$ (150-47-235)

8. $\text{DAP} + \text{KNO}_3 + \text{NH}_4\text{NO}_3$ (150-47-235)

The soil application of N, P, and K at 300, 94 and 470 kg/ha, respectively, was carried out while planting with 100 kg/ha ammonium nitrate, 448 kg/ha triple superphosphate, and 1084 kg/ha of potassium sulphate.

The irrigation and fertigation system comprised six injectors, eight main lines of plastic tubing into which each of the eight fertilizer combinations were injected, and three lateral lines for each plot. The drippers (one per plant) were spaced at 60-cm intervals. One fertilizer injector was used to supply Treatments 2, 3, and 4 with NH_4NO_3 . A second injector was used to supply uniform quantities of P and K to Treatments 2, 3, and 4. Four separate injectors were used for Treatments 5, 6, 7, and 8. The N, P, K contents of the irrigation water was negligible. All the plots were irrigated simultaneously.

Four sets of tensiometers were installed at depths of 15 and 30 cm in the soil beneath the dripper in Treatment 3. Irrigation was performed using all treatments when the soil water potential in Treatment 3 at 15-cm depth was between 0.03 and 0.04 MPa (0.1 MPa = 1 bar). The amount of water applied was based on Epan evaporation (US Weather Bureau, Class A screened pan) using a starting value of 0.3, which was gradually increased to full Epan evaporation at full growth. A total of 200 mm of water (2000 m³/ha) was applied over a period of 118 days.

One-month-old tomato seedlings (*Lycopersicon esculentum* Mill) of the hybrid "Luxor", raised in peat compost cubes, were planted on 27 March at 60-cm intervals. The different fertilizing treatments commenced with the first irrigation.

Results and Discussion

The experiment was terminated when 200 mm of irrigation water had been applied. Using this amount of water, the cumulative amount of N, P, K applied in all treatments was equivalent to the amounts of nutrients anticipated for Treatment 1 while planting.

The results indicate that, irrespective of the combination of fertilizers, fertigation was superior to the soil application of fertilizer (Table 1). Even with 50% less N (Treatment 2), higher yield was obtained by fertigation, suggesting that N is more efficient when applied dissolved in the irrigation water. Application of N to the soil is more susceptible to leaching and a single application may not supply the plant with sufficient nutrients for the whole season.

Treatment 6, with UP as a source of P, gave the highest yield, even though the P supplied was actually 25% less than in all other treatments. The most probable explanation for this could lie in the additional decrease in soil pH following urea hydrolysis. The ammonium ion produced by hydrolysis is acid in its final reaction

with the soil. It seems that the initial increase of pH due to the hydrolysis of the urea is offset by the overall acidity of the fertilizer. This may create conditions which improve the availability of P to crops.

Table 1. Tomato plant yield as a factor of fertigation using different fertilizers.

Treatment	Yield ¹
	--kg/ha--
Soil N, P, K application (equivalent to the 150-47-235 applied with fertigation with 200 mm for the whole period)	85.4 d
Fertigation NH ₄ NO ₃ +K ₂ SO ₄ +H ₃ PO ₄ (75-47-235)	95.6 c
Fertigation -//- (150-47-235)	98.4 c
Fertigation -//- (225-47-235)	98.7 c
UP+KNO ₃ +Urea (150-47-235)	104.2 b
UP+KNO ₃ +Urea (150-35-235)	115.8 a
MAP+KNO ₃ +NH ₄ NO ₃ (150-47-235)	106.8 b
DAP+KNO ₃ +NH ₄ NO ₃ (150-47-235)	104.0 b

¹Means in the same column followed by different letters are significantly different at the 5% level.

PHOSPHOROUS SOURCES AND FERTIGATION: EGGPLANT

In this trial, the fertilizer P effects of UP, MAP and DAP at two levels of application were evaluated when applied using fertigation.

Materials and Methods

This trial consisted of four randomised blocks, each of which was divided into six plots. Each plot was 3.6-m wide and 10-m long, and contained three rows, the centre row being used for data collection. The two outside rows served as "guard" rows. The total experimental area was 864 m². All treatments were applied irrigated by drippers (figures in parentheses indicate concentrations of N, P and K mg/l, in irrigation water). The numbered treatments tested were:

All the fertilizer treatments were produced using a combination of DAP, MAP, UP with potassium nitrate and ammonium nitrate:

1. DAP-1, N=120, P=50, K=200
2. DAP-2, N=120, P=35, K=200
3. MAP-1, N=120, P=50, K=200
4. MAP-2, N=120, P=35, K=200
5. UP-1, N=120, P=50, K=200
6. UP-2, N=120, P=35, K=200

The irrigation and fertigation system comprised six injectors, six main lines of plastic tubing into which the six fertilizer combinations were injected, and three lateral lines for each plot. The drippers (one per plant) were spaced at 60-cm intervals. The N, P, K content of the irrigation water was negligible. All plots were irrigated simultaneously.

Irrigation-Fertigation Scheduling: The total amount of water used and the monthly frequency of irrigation were as follows:

	Month						
	April ¹	May	June	July	Aug	Sept	Oct
Amount of water, m ³	6	45	116	156	184	156	32
Number of irrigations	2	13	14	14	16	14	4
Water per irrigation, m ³	3	3.5	8.3	11.1	11.5	11.1	8

¹Planting was carried out on 18 April 1996, and final harvesting took place on 17 October, 1996.

The amount of water applied was based on Epan evaporation (United States Weather Bureau, Class A screened pan) starting with a value of 0.3 and increased gradually to full Epan evaporation at full growth. A total of 695 m³ of water (8043 m³/ha) was applied during the whole growth period. Fertilizer injection started with the third irrigation and was continued until the first week of October. One-month-old eggplant seedlings of the "Bonica" hybrid, raised in peat compost cubes, were planted on 18 April at 60-cm intervals. The experiment was terminated on 17 October 1996.

Results and Discussion

The number of fruits, their mean weight and the yield are given in Table 2.

Table 2. Fruits number, mean fruits weight and yield of eggplant as affected by fertilizers applied at two concentrations (Cyprus, 1996).

#	Fertilizer Treatment	Fruit Number	Fruit Weight	Yield
		---'000/ha---	---g/fruit---	---t/ha---
1.	DAP-1, N=120, P=50, K=200	681.4 d ¹	181.3 ns	123.5 c ¹
2.	DAP-2, N=120, P=35, K=200	665.9 d	184.4 ns	122.8 c
3.	MAP-1, N=120, P=50, K=200	708.1 cd	182.7 ns	129.4 cb
4.	MAP-2, N=120, P=35, K=200	723.4 c	189.4 ns	137.0 b
5.	UP-1, N=120, P=50, K=200	773.1 b	177.0 ns	136.8 b
6.	UP-2, N=120, P=35, K=200	814.2 a	182.2 ns	148.4 a

¹Means in the same column followed by different letters are significantly different at the 5% level.

The lowest yield was obtained with DAP at both levels of P due to reduced fruit setting. The mean weight of fruits was similar in all treatments. This indicates that fertigating with DAP is less effective than fertigating with UP and MAP in these conditions.

Urea phosphate resulted in improved fruit-setting compared to DAP and MAP, irrespective of the P concentration. The best setting, however, was obtained with the UP-2 treatment, i.e., the lower of the two P contents used. The improved setting of fruit had a significant effect on the overall yield per hectare, which was highest with the UP-2 treatment. These effects, as discussed earlier, could be attributed to the direct and indirect acidification pattern produced by UP, which after inducing an increased uptake of P, probably also increased the uptake of other nutrients.

UREA PHOSPHATE FERTIGATION: SWEET PEPPER AND EGGPLANT

Two field trials were designed to compare three levels of N (115, 150, 185 mg/l) at two levels of P, 35 or 50 mg/l applied to sweet pepper and eggplant in the form of UP in irrigation water. The main objective of these trials was to test whether higher levels of N are required in combination with UP due to its high P efficiency. All fertilizer treatments were prepared using UP, KNO_3 and urea.

The highest yield of sweet pepper was obtained by using Treatments 1 and 4 (see Table 3). This indicates that in the case of sweet pepper, the 115 mg N/L level was adequate and that the yields achieved using 50 mg P/L could be achieved at a lower level of P (35 mg/L). These results are in agreement with results obtained in the previous trials. The increase in yield was due to the higher number of fruits per plant.

Table 3. Weight and number of sweet pepper fruits as a function of six fertilizer treatments.

#	Treatments	Yield ¹	Fruit Number ¹
-----kg/plot=7.2 m ² -----			
1.	N=115, P=35, K=200	57.64 a	457.6 a
2.	N=150, P=35, K=200	46.42 b	393.8 b
3.	N=185, P=35, K=200	49.94 b	439.3 b
4.	N=115, P=50, K=200	59.14 a	467.5 a
5.	N=150, P=50, K=200	50.45 b	430.8 b
6.	N=185, P=50, K=200	46.56 b	399.8 b

¹Means in the same column followed by different letters is significantly different at the 5% level.

The results obtained with eggplant are given in Table 4. The N requirement of

eggplant appears to be higher than that of sweet pepper. The highest yield was obtained with 150 mg N/L. As in the case of the sweet pepper, Treatment 2 (35 mg P/L with 150 mg N/L) gave the same yield as Treatment 5 (50 mg P/L with 150 mg N/L).

Table 4. Weight and number of eggplant fruits of six fertilizer treatments.

#	Treatments	Yield ¹	Fruit Number ¹
-----kg/plot=12 m ² -----			
1.	N=115, P=35, K=200	120.0 b	606.5 b
2.	N=150, P=35, K=200	131.3 a	675.3 a
3.	N=185, P=35, K=200	121.2 b	617.0 b
4.	N=115, P=50, K=200	121.9 b	644.0 b
5.	N=150, P=50, K=200	128.7 a	680.0 a
6.	N=185, P=50, K=200	129.9 a	680.5 a

¹Means in the same column followed by different letters is significantly different at the 5% level.

The results indicate that with both eggplant and pepper the acidic properties of UP increases P availability. Therefore, with the 35 mg P/L, the yield could be similar with that of the 50 mg provided that N is adequate. The results obtained therefore do not necessarily support the hypothesis of higher N levels required with the use of UP. It should be stressed, however, that the role of K could be also important, and it may be that elevated K levels are also required with high efficiency P fertilizers. This aspect of the subject requires further study.

CONCLUSIONS

The results of these experiments indicate that fertigation is a far more efficient method of nutrient management than direct application of fertilizer to the soil. Yields of tomato increased by as much as 35% when fertigation was employed. This is in line with the generally accepted advantages of fertigation compared to conventional methods of fertilization, as mentioned in numerous contexts (Bar-Yosef, 1977; Bresler, 1977; Klein et al., 1989; Miller et al., 1981; Mohtar et al., 1990; Phene and Beale, 1976; Papadopoulos, 1995; Stark et al., 1983). In respect of UP, the results support the findings of Mikkelsen and Jarrell (1987) who observed that less P fertilizer is required to increase plant P concentrations with drip-applied UP than with soil-applied triple superphosphate.

These trials indicated that acidic fertilizers perform very efficiently in calcareous soils; DAP, being alkaline, performed worst in terms of yield in all the crops studied. Both MAP and UP performed better, and furthermore, in the trials with two P application rates, there was a trend indicating that lower rates provided

higher yields. Overall, the highest yields were obtained by using UP at the lower rate. This higher P efficiency provided by UP was also noted by Raun et al., (1987), who observed that UP (in granulated form) provided higher corn yield, grain P uptake and total P uptake than DAP in calcareous soil.

Urea phosphate, the powder-form adduct of urea and H_3PO_4 , dissolves very easily in water to become urea and H_3PO_4 again. One argument for higher yields obtained by UP is most probably the higher P efficiency of UP compared to that of MAP and DAP in calcareous soil. When UP is applied to soil, the H_3PO_4 part of the product retards the hydrolysis of the urea and reduces gaseous loss of urea N as ammonia (Bremner and Douglas, 1971). This is probably another explanation for the higher yields obtained by UP in these trials.

A phenomenon observed in the first two experiments and also in other experiments not described here is the fact that the lower P application rates of UP and MAP result in significantly greater yields than higher P rates. Although this is difficult to explain, one possible hypothesis could be the unbalanced nutrient status due to the "unexpectedly" higher amount of P which is available to the plant. It was to test this hypothesis that the third trial with three levels of N was set up. The results of this third trial did not, however, support the hypothesis, and further research is needed to clarify the phenomenon.

In summary, *use of fertigation offers several advantages over soil-applied fertilizers*. Higher yields with improved quality can be obtained and the efficiency of nutrients and irrigation water is clearly enhanced. Although the use of P fertilizers in drip systems may cause practical drawbacks due to clogging of pipes and emitters, these can be overcome by choosing proper fertilizer materials such as acidic MAP, and particularly UP, in calcareous soil. It appears that by using UP, similar or even higher yields could be obtained by reducing P application rate dosage by 25% from current recommendations. This is considerable of importance from the farmer's commercial viewpoint, and also from the environmental aspect.

REFERENCES

- Ali, A.S., and J.L. Stroehlein. 1991. Reactions of urea phosphate in calcareous and alkaline soils: I. Ammonia volatilization. *Commun. Soil Sci. Plant Anal.*, 22 (11&12): 1243 – 1256.
- Bar-Yosef, B. 1977. Trickle irrigation and fertilization of tomatoes on sand dunes; water, N and P distributions in soil and uptake by plants. *Agron. J.* 69:486 – 491.
- Bremner, J.M., and L.A. Douglas. 1971. Decomposition of urea phosphate in soils. *Soil Sci. Soc. Amer. Proc.*, 35: 575 – 578.
- Bresler, E. 1977. Trickle-drip irrigation; principles and application to soil-water management. *Adv. Agron.*, 29: 343 – 393.

- Gascho, G.J., and A.M. Mashali 1991. Soil-water-nutrient interactions under fertigation systems. p.83–100 *Fertigation/Chemigation. Proc. Expert Consultation*, 8–11 Sept. 1991, Cairo. FAO. Rome, Italy.
- Klein, I., I. Levin, B. Bar-Yosef, R. Assaf, and A. Berkovitz. 1989. Drip nitrogen fertigation of “ Starking Delicious” apple trees. *Plant Soil* 119: 305–314.
- Mikkelsen, R.L. 1988. Phosphorus fertilization through drip irrigation. *J. Prod. Agric.* 2: 279–286.
- Mikkelsen, R.L., and B.R. Bock. 1988. Ammonia volatilization from urea phosphate fertilizers p.75 – 189. *In* B.R. Bock and D.E. Kissel (ed.) *Ammonia volatilization from urea fertilizers*. Nat. Fert. Devel. Center, TVA. Bull. Y-202.
- Mikkelsen, R.L., and W.N. Jarrell. 1987. Application of urea phosphate and urea sulfate to drip irrigated tomatoes in calcareous soils. *Soil Sci. Soc. Am. J.* 51: 464 – 468.
- Miller, R.J., D.E. Rolston, R.S. Rauschkolb, and D.W. Wolfe. 1981. Labelled nitrogen uptake by drip-irrigated tomatoes. *Agron. J.* 73: 265–270.
- Moavad, H., S.A.Z. Mahmoud, S.M.S. Badr El-Din, F. Rawia, F. Gamal, and M.H. Enany. 1984. Transformation and effects of urea derivatives in soil. *Z. Pflanzenernaehr. Bodenk.* 147: 785–792.
- Mohtar, R., V.F. Bralts, C.D. Kesner, and W.M. Klein. 1990. Comparative nitrogen application methods for tart cherry trees in Michigan. *Proc. Third National Irrigation Symposium*, Oct. 28 – Nov. 1, Phoenix, Arizona: 444–452.
- Papadopoulos, I. 1995. Use of labelled fertilizers in fertigation research. p. 399–410. *In* *Nuclear techniques in soil-plant studies for sustainable agriculture and environmental preservation*. FAO /IAEA.
- Phene, C. J., and D.W. Beale. 1976. High-frequency irrigation for water nutrient management in humid regions. *Soil Sci. Soc. Am. J.* 40: 430–436.
- Raun, W.R., D.H. Sander, and R.A. Olson. 1987. Phosphorus fertilizer carriers and their placement for minimum till corn under sprinkler irrigation. *Soil Sci. Soc. Am. J.*, 51: 1055–1062.
- Stark, J.C., W.M. Jarrell, J. Letey, and N. Valoras. 1983. Nitrogen-use efficiency of trickle-irrigated tomatoes receiving continuous injection of nitrogen. *Agron. J.* 75: 672–676.
- Stumpe, J.M., P.L.G. Vlek, and W.L. Lindsay. 1984. Ammonia volatilization from urea and urea phosphates in calcareous soils. *Soil Sci. Soc. Am. J.* 48: 921 – 927.

Phosphorous Sources for Fertigation

Bruce A'Bear

Omnia Fertilizers, Bryanston, 2021 South Africa.

ABSTRACT

Phosphorous has been routinely applied as a pre-plant fertilizer in a granular form even in cases where fertigation as such is utilised. Often this is due to the perception that water-soluble forms of P are more expensive than granule forms or that P is not mobile in the soil. There are, however, a number of products available on the market today that provide a water-soluble form of P that does not create precipitates or reactions as experienced in the early days. Products commonly used are: monoammonium phosphate ($\text{NH}_4\text{P}_2\text{O}_4$), monopotassium phosphate (KH_2PO_4), urea phosphate [$(\text{NH}_4)_2\text{CO} \cdot \text{H}_3\text{PO}_4$], and phosphoric acid (H_3PO_4). Less common materials include: diammonium phosphate or DAP [$(\text{NH}_4)_2\text{HPO}_4$], while other materials are still being tested: long-chain polyphosphates, diammonium pyrophosphate [$(\text{NH}_4)_2\text{HP}_2\text{O}_7 \cdot \text{H}_2\text{O}$], and orthoammonium phosphate ($\text{NH}_4\text{H}_2\text{PO}_4$).

The products available have a range of applications. Water and soil acidification, drip system maintenance, and obviously the P supply, can all be carried out depending on the product used. In all cases, the products tend to be *acidic*. The important point is that water-soluble P products offer more than one benefit to the grower. In most cases, more than one element is supplied with the most of the available products. The use of water-soluble P sources such as MAP, MKP, and urea phosphate (UP) is increasing every year. This is partly due to the increasing utilization of drip irrigation plus the growing demand for high-quality, high-yielding crops where the 'cost' of P is not a major factor and where P movement in the soil is important.

PHOSPHORUS SOURCES: FERTIGATION

Introduction

From the Southern African point of view, we should be one of the largest users of fertigation products in the world. According to a report from the International Commission on Irrigation and Drainage (ICID) in 1995, we were then the fourth largest users of micro-irrigation, with only America, Spain, and Australia having

larger areas. The reality is that a very small percentage of growers makes use of a full range of fertilizers in a fertigation program. We are developing a system called *'Growth Curve Plant Nutrition'*, whereby all the nutrients are fed in ratio and in synchronization with the plants growing requirements.

One of the least utilised elements in fertigation tends to be phosphorous. There are a number of unfounded reasons for this which, once have been overcome, will lead to an increase in the use of fertigated P. There is a considerable advantage to using the correct P source, and this will give a leveraged result to the grower. The majority of farmers still tend to apply a pre-plant application of P and then make use of side-dressings of primarily N and some potassium through the irrigation. The market's requirement for better quality produce, and in particular the export market, tends to force the grower to make optimal use of available inputs. The grower's requirement for a higher yield requires them to seek the best production methods, one of which is making optimal use of available plant nutrients.

Past Experiences

In general crop production, all the P is applied prior to planting the crop due to the fact that granulated P is not very mobile in the soil. This has led to the mindset that once in the ground the P will remain available to the plant as the roots grow into the areas where the P granules have dissolved. The thinking is then that there is no need to apply P as a side-dressing through the season as enough P is in the soil. A grower who moves across to a micro-irrigation system is generally reluctant to move away from this mindset and has difficulty in seeing the advantages of P fertigation.

A second reason for holding back on the use of water-soluble P that is the perceived extra expense compared to a granular P source. Again, this is a mindset that needs to be worked on. The leveraging of input costs versus an increase in yield and quality should be the approach to take, not adhering to the idea of trying to reduce the input costs to increase the bottom line.

Thirdly, past experience with inferior products on the market and poor technical service, both in fertilizer products and micro-irrigation systems, resulted in chemical reactions between P and other elements. This often led to the grower moving back to the 'safer' granules, using water-soluble products only as a last resort. We certainly had a tremendous decrease in drip irrigation usage about 10 years ago, when farmers actually removed drip irrigation from their lands due to the perceived notion that it was a useless system. This was entirely due to poor technical backup from both fertilizer and irrigation companies. Coupled to this is that the earlier readily available source of soluble P was phosphoric acid, which is a hazardous material and requires careful handling at all times. For general farm labour, the above points were a good reason to stay away from what was seen as 'high tech' products.

Changes in Agriculture

The last few years have seen a dramatic increase in the use of micro-irrigation. From the ICID report, worldwide usage increased 63 % over the 5-year period prior to 1995 and 329 % over a 10-year period. The shift is toward more intensively grown crops, and this is growing by about 12 % per year in South Africa. For Southern Africa, this represents a substantial area. Reasons for this is the improvement in drip irrigation technology and a better understanding of the management of drip irrigation, particularly irrigation scheduling, which has shown what can be achieved in semi-arid and arid regions.

Perhaps the other major input that has also allowed for the expansion has been the availability of fertilizers, not only liquids but also powders for those far from a liquid fertilizer factory. Other products, such as crop protection chemicals, have been developed for drip irrigation that make it easier for the grower to apply chemicals effectively to the crop. The worldwide quest for better quality produce and higher yields has forced growers to seek the best production methods, and fertigation is certainly high on that list.

Products Available

There are a number of P products available on the market. The most commonly used are the following:

Monoammonium Phosphate (MAP)

The benefits of this material include being readily available in powder form. Use is widespread in the field, both in fertilizer blends and as a product on its own. Nitrogen in this product is in the ammonium form, immediately available to the plant. This also has an acidification effect on the soil due to the release of an hydrogen ion and absorption of an hydroxide ion by the root (Salisbury and Ross, 1991). It is reasonably priced relative to other products.

Its chemical characteristics are a formula of $\text{NH}_4\text{P}_2\text{O}_4$, with concentration of 8% N and 24% P_2O_5 . It is a white, free-flowing powder and is acidic with a pH of about 4.7 at one gram per litre of distilled water. The electrical conductivity value is approximately 1.16 mS/cm at one gram per litre of distilled water. Solubility is approximately 230 gram per liter water at 15 °C. Its limitations are chemical reactions that may occur under stock-tank conditions; commonly, these reactions are with calcium and magnesium to form insoluble P products.

Urea Phosphate (UP)

It is a dry form of phosphoric acid, and is safer to handle than phosphoric acid. It is acidic and thus suitable for acidifying water and soil. Frequent or continuous use will keep drip systems free from clogging. Its N is in the urea form. With a

chemical formula $\text{CO}(\text{NH}_2)_2 \cdot \text{H}_3\text{PO}_4$, it has 17% N and 44% P_2O_5 . It is a white free-flowing flake. The acid value is pH 2.7 at 0.5 grams per litre of distilled water. Solubility is 120 grams per litre of distilled water. Electrical conductivity is 1.3 mS/cm at one gram per litre water. Its use is limited to the horticultural industry, mainly greenhouses and tunnels, due to the higher cost compared to MAP. Where soil acidification is not desired, it should not be used.

Monopotassium Phosphate (MKP)

It is a source of both P and K, with no N. It is used where a high K level is required in a fertigation program without pushing up the N level, mainly used on tomato and pepper. It is also known as monobasic phosphate. The product has a low "salt index" and is a 'soft' chemical. It is commonly used in hydroponic nutrient solutions.

The chemical characteristics of MKP, with a formula KH_2PO_4 , are 34% K_2O and 52% P_2O_5 . Is a free-flowing white powder, and has pH value of a 1 % solution is at 4.5. Solubility is 330 grams per litre distilled water, and electrical conductivity is 0.7 mS/cm. The only limitation on its use is that as a P source it is generally seen as too expensive compared to MAP.

Phosphoric Acid

It is primarily used for pH control and as a P source, it has no nitrogen, its chemical formula is H_3PO_4 , and it has 54 % P_2O_5 . Is a liquid, with a pH value of 2.2 at one gram per litre. Its electrical conductivity value is approximately 2.0 mS/cm at one gram per litre. It is a hazardous chemical, and thus difficult to work with.

Other Products

South Africa is a primary producer of P, either as phosphoric acid or monoammonium phosphate. Both products are exported. For this reason, they are the two main products in use and to compete against them with imported products is difficult. Urea phosphate is the latest product in our market, but tends it to remain a specialised product.

The only 'new' product is the ammonium polyphosphates, which is, not to my knowledge, used in South Africa; these are polymeric forms of phosphates, such as diammonium pyrophosphate $[(\text{NH}_4)_2\text{H}_2\text{P}_2\text{O}_7]$, and orthoammonium phosphates $\text{NH}_4\text{H}_2\text{PO}_4$ (Burt, et al., 1995).

REFERENCES

- Burt, C., K. O'Connor, and T. Ruehr. 1995. *Fertigation*. Calif. Polytechnic State Univ. Central Coast Printing, Grover Beach, CA. USA.
- Salisbury, F., and C. Ross. 1992. *Plant Physiology*. 4th Ed., Wadsworth Inc., Belmont, Ca. USA.

Management of Phosphorous Fertigation at Farm Level in Tunisia

Kawther Latiri¹, Naïma Kolsi², Ali Mhiri², and Naceur Hamza¹

¹INRGREF, ARIANA, Tunis, ²Institut National Agronomique de Tunisie (INAT), Tunis, Tunisia.

ABSTRACT

Water and mineral nutrients are the main limiting factors to crop production. Fertigation facilitates giving both at the same time to the crop. In Tunisia, fertigation started being widely used by farmers in 1995 when drip irrigation equipment became highly subsidized, although attempts to introduce drip irrigation were older. At present, fertigation is developing very rapidly with drip irrigation. It is mainly used for vegetables (tomato, potato), high productive crops (strawberries) and fruit trees (grape, citrus, other fruit trees).

This technique is adopted in very different types of farms, from small and traditional farms (0.5 – 5 ha) to large and highly sophisticated farms (>50 ha). In this paper, fertigation for tomato production in Cap Bon (northeast Tunisia) is presented. Between 1995 and 1998, the area fertigated in tomato increased from 60 to 3100 ha. With fertigation, an important increase in tomato yield occurred, field production varying between 60 and 120 t/ha depending on the farm, while the average production with flood irrigation was less than 40 t/ha.

With drip irrigation, farmers irrigate every day or every other day with less cost in labor, while with surface irrigation water was applied less often (once a week or less), which did not prevent water deficit to the crop and lost of water in leaching. The amount of water given to the crop depended on farmers and either permitted an increase in the area irrigated or over estimated evapotranspiration (ET). However, even when the needs of the crop were overestimated, water-use efficiency was increased through increased production.

Nutrients were applied to the whole field both before planting and by fertigation during the growing season. Before planting, P was applied either as diammonium phosphate (DAP), or as superphosphate P_2O_5 (45 %); the amount varying between 70 and 90 kg/ha. During the growing season, P was given either as phosphoric acid in order to clear emitters or as composed soluble fertilizer mixed with N and K with variations both in amount and timing. In a large number of farms, the needs of the crop were overestimated and farmers did not take into account that nutrients can have negative effects on costs and cause pollution, but also on production or on soil salinization.

Fertigation is developing very rapidly and farmers are learning how to use it. The increase in yield is encouraging its development. However, production and

water and nutrient-use efficiencies can still be increased and farmers should now be more accurate in the process of estimating water and nutrients needs of the crop.

INTRODUCTION

Water and nutrients are the main limiting factors for crop production (Mazoyer and Roudart, 1997). Fertigation allows for both to be given at the same time to the crop, thus reducing costs and losses in water and nutrients. In a world where nutrients are expensive and where water is a scarce resource, fertigation is a technique to reduce the quantities of both nutrients and water applied to the crop and to increase their efficiencies (Phene and Beale, 1976).

However, fertigation is a highly specialized technique and is based on an accurate knowledge of the needs of the crop, both in the amount applied and the application timing. The theory behind fertigation has become a reality in vegetable nutrition, where water and nutrients can be applied to plants in the correct amounts and at the time appropriate for a specific stage of plant growth. Hence, for the farmer, management of fertigation involves applying, at field level, all this knowledge regarding crop water and nutrient requirements. Yet, this technique is now widely used in the world; when introduced anywhere, extension of the area in micro-irrigation using fertigation is usually very rapid.

Among nutrients used in fertigation are major the elements, N, P, and K. When provided with fertigation, they are given to the crop at the level of the rhizosphere, and their availability is higher than when given with other application techniques (Bar-Yosef, 1977; Papadopoulos, 1995). For use in fertigation systems, fertilizers should be water-soluble and should not precipitate as insoluble salts when reacting with each other, with constituents in irrigation water, or with active soils components.

Adding to that, management of each element has different considerations. For N and K, which are highly mobile, giving nutrients with small amounts of water allows for highly increased efficiencies. For P in calcareous soils, which are common in Mediterranean regions, part of it can be fixed on the soil components, which reduces its availability to the crop and its efficiency. This reduction in P availability increases with time, and timing of P application will then have consequences on its recovery; in other situations, the soil can be a source of P to the crop (Arvieu and Bouvier, 1974; Barrow, 1985; Kolsi, 1999).

At present in Tunisia, fertigation is developing very rapidly for vegetables (tomato, potato, and strawberry...), fruit trees, and citrus. Soils are mainly calcareous, and these crops are among those consuming largest amount of nutrients per hectare (Harris, 1998). *When using surface irrigation, water consumption is large and involves loss in drainage and low water-use efficiencies.* Fertigation will then allow increasing water and nutrient efficiencies for crops among the ones that

are using more nutrients and more water per hectare.

In this paper, a general description of fertigation in Tunisia is given with its place and prospects in Tunisian agriculture. Fertigation is described at farm level and consequences of its on-farm functioning are discussed.

Tunisia's Climatic Conditions and Agricultural Production

Tunisia is in the Mediterranean basin with a true Mediterranean environment, with hot summers, winter rainfall and mild winters and major year-to-year variations in rainfall. From the north to the south of the country, there is major variation in climatic characteristics. The average annual temperature rises from 15°C in the northwest to over 21°C in the south. Rainfall also varies between the extreme north (1000 mm) and the south (<100 mm), but 80 % of the rain falls between October and March (Bortoli et al., 1969). Total annual evapotranspiration varies between 1200 mm (Zaghouan) and 1900 mm (Kébili); daily average evapotranspiration in Tunis is 1.3 mm in December, while it reaches 6.3 mm in July (Riou, 1980).

Tunisia is almost entirely underlain by sedimentary rocks. Marls, calcareous and sandstone rocks or sediments were deposited until the middle of the Tertiary period and were affected by the Atlas orogeny. The soils are mainly from continental formations or from coastal formations and their characteristics as well as their nutrient status and their agricultural use are related to both the landscape and the climatic area (Belkhoja et al., 1973).

Tunisia has a total area of 163,610 km² of which cropland is 4.8 million ha, constituting about 31% of land area and located mainly in the northern half of the country. Cropland is composed of 2.8 m hectares of annual crops and 2.04 m ha of permanent crops (Min. Agric., 1996a). The total population is estimated at 9.3 million, of which 37 % is rural (FAO, 1999). Agriculture employed 28 % of the labour force in 1990 (World Bank, 1998).

There are about 471,000 farm holdings with an average area of 11.2 ha. However, 53% of holdings are less than 5 ha and represent 9% of the crop area, while only 3% of the holdings are of more of 50 ha and represent 37% of the cropped area (Min. Agric., 1996a).

Agricultural production includes cereals, olive trees, other fruit trees, and vegetables. Irrigated crops are mainly fruit trees and vegetables, but also part of the area is in cereals. Production in non-irrigated areas (cereals, olive oil) shows great year-to-year variability related to the rainfall, while production is less variable in irrigated areas.

Irrigation

Water is a limited resource and it is mainly used for agriculture, involving 89% of

annual freshwater withdrawals (World Bank, 1999). Irrigated land increased during the last 20 years and progressed from 4.9 to 7.4% of the cropland reaching 380000 ha in 1998 (FAO, 1999), which is almost the maximum area that can be irrigated with available water resources. Agricultural production in irrigated areas represents about one third of total agricultural production (Fig. 1), half of it being irrigated vegetables and the other half fruit trees (Min. Agric., 1996b).

Water comes either from irrigation network, from tubewells or from open wells developed individually by farmers; they represent 29, 21 and 50 % of the irrigated area, respectively (Min. Agric., 1996a). Irrigation is used all the year round for different agricultural production and can be either full or partial irrigation; it is also used on cereals and on fodder crops in case of severe drought. For vegetables, irrigation is the main source of water for the crop. Year-to-year variability in vegetable production is low, and the level of production reflects more a good knowledge of techniques than a weather effect. For fruit trees, irrigation is either used during the early years of their development or during all their growth.

Irrigation is present in 124,000 holdings (28%); however, this proportion depends on the region, e.g., in Cap Bon (northeast Tunisia) irrigation is present in 53% of the holdings. Irrigation is mainly surface application with low water-use efficiency. Sprinkler irrigation is used in 18 % of the irrigated area with high-pressure pipes. Micro-irrigation is developing very rapidly; while it was only 2 % of irrigated area in 1991 (FAO, 1997), it reached 7 % of the total irrigated area in 1998 (Direction du Génie Rural, 1999).

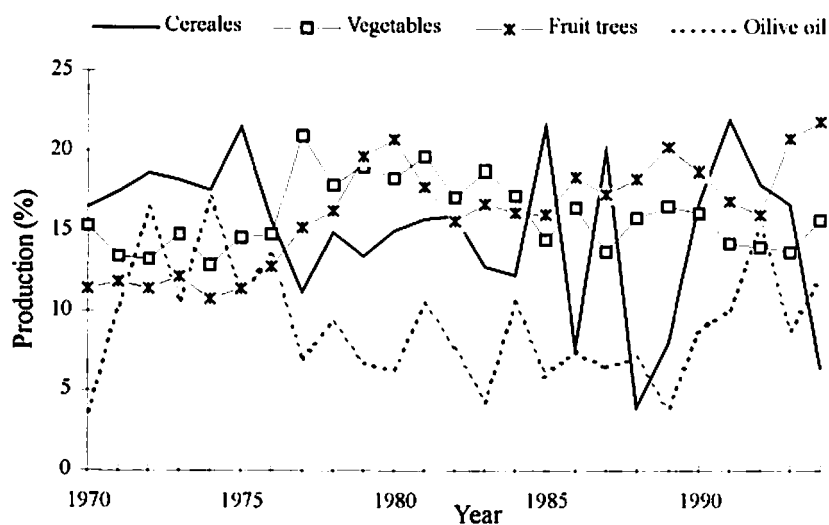


Fig. 1. Agricultural production value as a percentage of total agricultural production.

Micro-irrigation

Water resources being limited, the national objective is now to reduce water losses and to increase water-use efficiency. Micro-irrigation is one of the techniques that can help reaching that objective. Since 1995, its use by farmers is encouraged and equipment is highly subsidised (40 to 60% of the total cost of installation, depending on the size of the farm). From the period micro-irrigation started being highly subsidised in 1995, a more than threefold increase was observed in the area irrigated (Fig. 2). In 1994, the micro-irrigation area was 7978 ha, while it became 6540 ha in 1998 (Direction du Génie Rural, 1999).

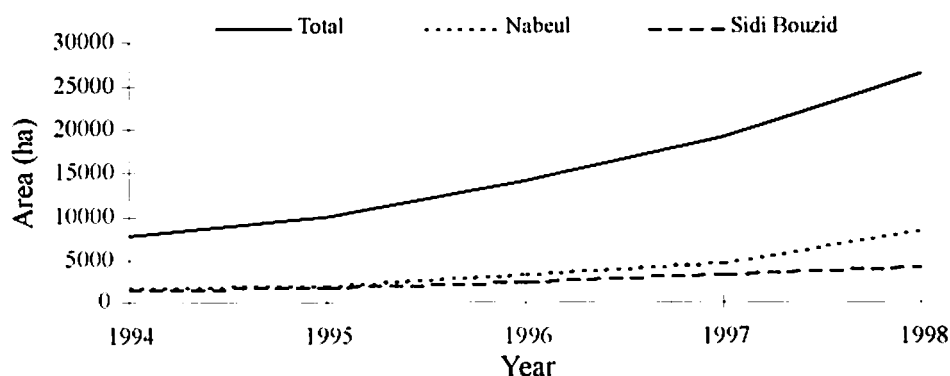


Fig. 2. Evolution of the area in micro-irrigation in Tunisia.

Micro-irrigation is present in different parts of the country, but its development is very important in Cap Bon, with 32 % of the total area in micro-irrigation) and in Sidi Bouzid (centre of the country, 18 % of the total area). The very rapid increase of the area in micro-irrigation attests to its adoption by farmers; in most cases, fertigation is involved. In this presentation, we are going to focus on the Cap Bon region, describing of the way micro-irrigation and fertigation are used by farmers.

FERTIGATION IN CAP BON

Area and Crops

Since 1995, micro-irrigation in Cap Bon increased from 2107 to 8400 ha (Commissariat Régional au Développement Agricole, Nabeul, 1998). In 1995,

micro-irrigation was used mainly for fruit trees (79 % of the area in 1995), development of micro-irrigation came through an important increase in its use with vegetables; in 1998, it represented 64 % of the area micro-irrigated in Cap Bon (Fig. 3).

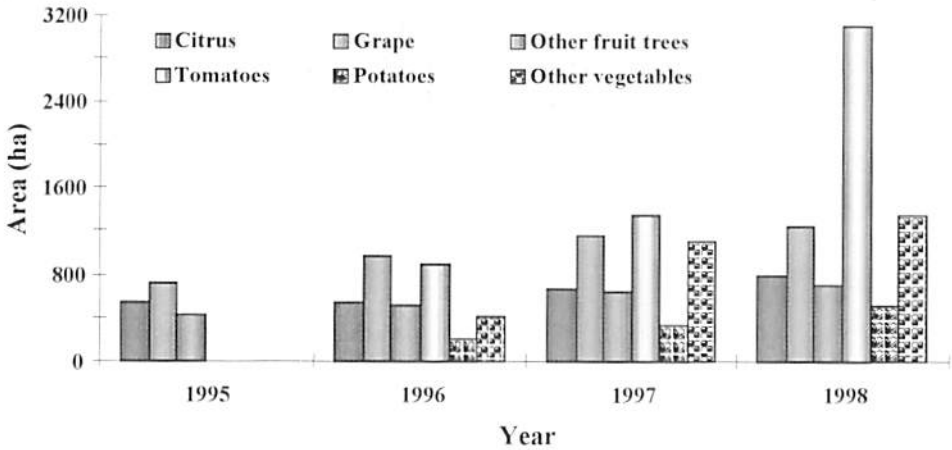


Fig. 3. Micro-irrigation in Cap Bon (Tunisia).

Increase in the area micro-irrigated in vegetables was mainly related to the increase in the area micro-irrigated in tomato; on the total 11000 ha of tomato in 1998, 3100 ha were micro-irrigated, which is 28 % of the area in tomato in that region. Other vegetables and fruits are also micro-irrigated, e.g., potato (500 ha while the area in potato in Cap Bon is: 7300 ha) or strawberries (about 400 ha in 1998, and all are fertigated).

For fruit trees, the area in micro-irrigation increased by 1.6, mainly through increased area in grapes (1250 ha, 45 % of the micro-irrigated area is in fruit trees). The area micro-irrigated in citrus is about 800 ha; while Cap Bon is the main area in citrus in Tunisia, with 10300 ha.

Farmers

Fertigation is used in very different types of farms with very different farming systems, either traditional with surface-irrigated vegetables and fruit trees, and cereals and fodder crops on larger farms or high-input farming systems. However, tomato production is mainly present in small traditional farms, and they represent the largest proportion when related to the area (Fig. 4).

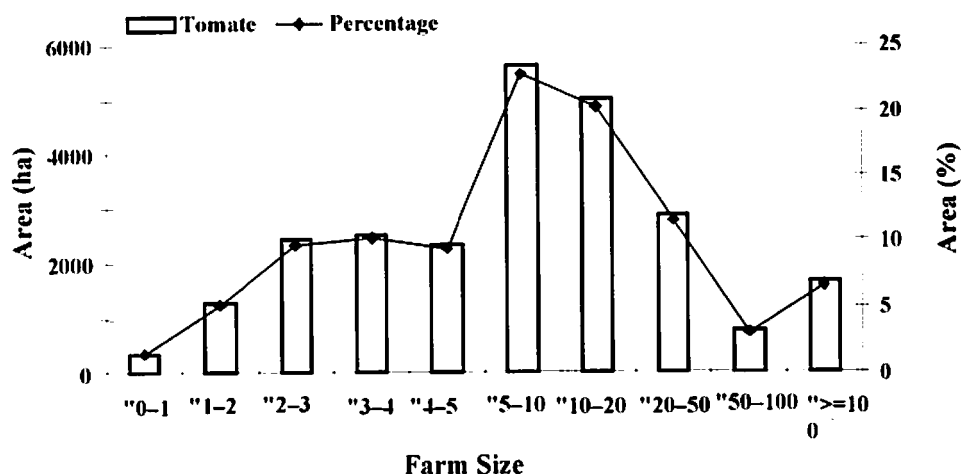


Fig. 4. Area in tomato, and farm size.

In the traditional farms, are present with tomatoes, other vegetables (potato, garlic) and other irrigated crops and fruit trees (citrus). In some farms, there are also present cereals and fodder crops, which allow the presence of cattle and production of manure. Drip irrigation is present on part of the area irrigated, while surface irrigation is still used on other vegetables. For some farmers, the same equipment that was acquired for tomato can be used later in the year with potato. Farmers are working full time, and they are used to irrigate either vegetables or fruit trees with water coming from the water-table and, in part of the Cap Bon, they can also use water from the irrigation network. The average farmer is between 50 and 60-years old, only went to primary school, has a small farm on which he is working full time, he has been working in agriculture for years, and is used to irrigation (Min. Agric., 1996a).

Fertigation is also present in high-input farms. These farms are specialized; they can be owned and run by technicians who have a technical background. In such farms, more equipment is present and investment can be important for irrigation equipment. Hence, fertigation is used by very different farmers with very different background and very different practical experience. They can have a long experience of traditional irrigation for fruit trees, citrus and vegetables or they can run specialised and modern farms.

Equipment

Private sellers provide equipment to farmers; they can also provide its design and

installation and even its funding with a loan. On farms, different kinds of equipment are observed; there is either sophisticated equipment run by technicians or “do-it-yourself” solutions adapted by others. The basic components include the *irrigation tubing*, a *fertilizer tank*, an *injector*, a *filter*, a *pressure gauge*, *check valves*, and a *pressure regulator*. Sometimes parts of the equipment can be missing or disfunctionning. Basic components for micro-irrigation are present and equipment for fertigation is adapted. Fertilizer tank can be a simple tank that is put higher 50 cm above the irrigation tubing, and the solution is delivered through it with a valve located at the bottom of the tank.

For most of the farmers, there is no real choice of the equipment and they take what is available in their area. Choice is more related to funding possibilities and to equipment availability than to technical characteristics.

Scheduling Techniques

At regional level, crop water requirements are adapted by extension from average monthly evapotranspiration (ET) and corrected by crop coefficients. Through that estimate, amount of water given to the crop is determined and converted as duration of irrigation by farmers. For tomato, irrigation is planned every day for half an hour to two hours. From that basic pattern, the amount of water can be modified by farmers; they will correct the duration of irrigation according to their own observation of crop behaviour. On most of the farms, there are no measurements of soil water content and on few farms, weather data can be used to adapt the duration of irrigation.

However, it seems that water needs are adjusted to highest value of ET, which results in a seasonal over-estimation (Pernin, 1998). Adding to that, farmers are used to surface irrigation and tend to have high levels of moisture in the root zone. From measurements made on farmers’ fields from May to August, total ET (Penman) was 648 mm, pan Evaporation was 925 mm, and the farmer-applied irrigation was 1000 mm (Pernin, 1998) (Fig. 5).

Considering observations on different farmers fields, water consumption of a tomato crop varied between 6000 m³ and 10000 m³/ha, which represents between 0.9 and 1.5 of time total estimated Penman evapotranspiration. In other situations, total water consumption can be reduced to 5000 m³/ha, but this is related to a reduction in water availability in July. When water is limited, water stress can be observed.

Fertilizers

Total nutrient requirements are evaluated using the balance-sheet method (GICA, 1997; Hamza, 1998), and extension gives advice for the amount of nutrients needed

by the tomato crop which takes into account the vegetative period of growth and target yield. For phosphorous in calcareous clay soil, a correction coefficient is used, considering that clay soils fix P and that in calcareous soils P could also be precipitated and even immobilized; P soil can also be released.

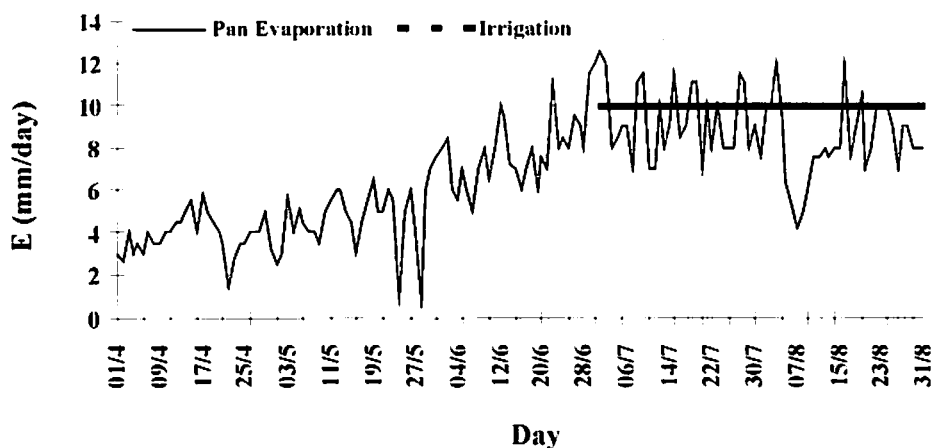


Fig. 5. Daily pan evaporation (Kamech, 1 April – 30 Aug. 1998).

However, P dynamics in the soil is complicated and estimates of the amount of P available to the crop are difficult. According to Hamza (1998), a correction coefficient could be 2 when considering P applied as pre-plant fertilizer, and 1.2 for P as phosphoric acid; according to Kolsi (1999), in fine-textured calcareous soils, the correction coefficient could be of 1.4 for phosphoric acid. The fertilizer amount should then be estimated by taking into account nutrients from the soil and the P dynamics in the soil.

Growers give nutrients (Table 1) as green manure, manure, pre-plant fertilizer (P and K) and fertigation (N, P and K). When manure is applied, it can be of different origin and it is applied before soil tillage in amounts varying between 30 and 50 t/ha. In that case, farmers do not take into account its contribution to the nutrition of the crop, but they believe in its role in maintaining soil fertility.

Required P and K fertilizer can be pre-plant incorporated into the bed or banded along side the row. Potassium is given as potassium chloride or as potassium sulfate, while P is given either as triple superphosphate (45%, P_2O_5) or as diammonium phosphate (DAP). In our survey, we observed that amount of P given as pre-plant fertilizer varied between 70 and 90 kg P/ha, which corresponds to more than the total amount recommended by extension services for a tomato

yield of 50 t/ha (GICA, 1997). This amount of P takes into account a correction coefficient of 2 (Hamza, 1998) and it covers more than the needs of the crop, even without what is provided by fertigation.

Table 1. Fertilizer used by farmers in Cap Bon (1999).

Pre-plant		Fertigation		Total	Recommended (per 100 t/ha)
Form	Range	Form	Range		
-----kg/ha-----					
N,P,K	–	Commercial Solution			
N	–	Ammonium Nitrate	100 – 300	100–300	260
P (DAP, TSP)	70–90	Phosphoric Acid	0 – 60	70–150	40–50
K ₂ SO ₄	75–100	Potassium Nitrate	100 – 150	100–250	300

Fertigation

Some farmers give to the crop soluble fertilizer containing N, P and K. Nutrient solution is adapted to the vegetative period of the crop. However, this fertilizer is very expensive. Others prepare their own solution by dilution of the fertilizer in tanks. Nitrogen is given as ammonium nitrate from every other day to every week; amount are variable between farmers and it is usually adapted to the vegetative state of growth of the crop. For a tomato crop growing between mid March and the end of July (140 days), total N given during the growing season varies between 100 and 300 kg N/ha.

Phosphorus can be given as phosphoric acid, mainly in order to clear emitters; application frequency is highly variable from every other day, every week, or only on few occasions during the growing season. However, when P is given regularly as phosphoric acid, the amounts of P can reach 60 kg P/ha. Potassium is applied as potassium nitrate, giving N and K to the crop; the amount of K varies between 100 and 150 kg K/ha.

Operational Problems

Evaluation of Uniformity: Uniformity on the irrigation line is not a concern for farmers, neither for water nor for nutrients, probably because too much water is given.

Clogging of Emitters: This is a concern for farmers. Emitters are cleared with phosphoric acid or nitric acid. This is done without any pH control of water.

Water Treatment, Filtration: Water quality depends on its origin of water; deep water table is the best quality. For water of other origins, some allow a settling period before injection so that sediments can settle to the bottom of the tank, but this is done only by few farmers; some farmers use a sand-filter, but in most of the cases poor water quality often results in clogging of the emitters.

PRODUCTION, INPUT FACTORS, AND ON-FARM FUNCTIONING

Production

In 1995, the average yield in fertigated tomato was 120 t/ha and the area fertigated in Cap Bon was 60 ha. During the following years, average yield decreased to 60 t/ha in 1998, while area increased to 3100 ha. For the same period and in the same area, average yield in surface-irrigated tomato was about 30 t/ha. During the first year of its introduction in Cap Bon, fertigation was applied only in high-input farms by few growers having a good knowledge of the technique. When this technique became used by a larger number of farmers, the average yield decreased. However, when comparing yield between surface irrigation and fertigation, fertigated tomato had larger yield (Fig. 6). Even without having a good knowledge of the technique, a large number of farmers were able to increase the average yield by 50%, but this average yield can still be improved and reach what can be considered as the potential yield, in field conditions in the area of 120 t/ha.

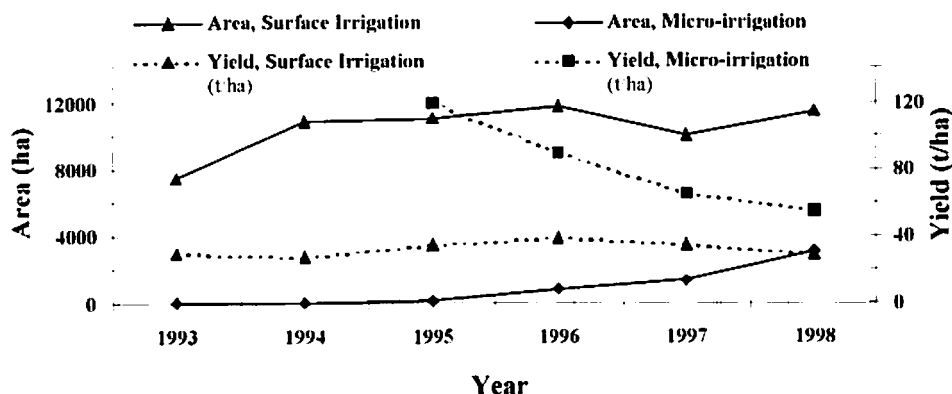


Fig. 6. Area and yield of tomato.

Input Factors

Amount of Water

As well as for yields, a large variability in the amount of water per hectare was observed. If direct measurements were made only on few occasions, consequences of water management on farming cropping systems were observed.

For some farmers, when adopting micro-irrigation, there was no variation introduced in the area they irrigated and about the same amount of water was used (about 10000 m³/ha), but with higher yield which implies an increase in water-use efficiency when expressed as production per unit of water applied. For others, modifications were observed with the introduction of micro-irrigation. In some farms, it was possible to increase the area in vegetables when using micro-irrigation with ground-water-table. Hence, the same amount of water allowed an increase in water-use efficiency through increased yield and reduction in water consumption per unit area.

Labour

In all cases, a reduction in labour when using fertigation and chemigation is observed by farmers. In some farms, there is no need to have extra labour when irrigating and the farmer can irrigate easily and save time.

Equipment

If in some farms, equipment is chosen and used by technicians, in most cases there is no choice and no control of the equipment by the farmer. When farmers buy their own equipment, they have no knowledge of micro-irrigation, but they have seen their neighbors using it. However, they learn and adapt to this new way of applying water very rapidly.

Fertilizer

When considering what is given to the crop and what are its nutrient requirements, it is apparent that too much nutrients are given. For N, provided that estimated needs in N are of 2.6 kg N per tonne of tomato fruit produced per hectare (Hamza, 1998), giving between 100 and 300 kg N/ha, without taking into account what can be provided by the soil, will probably result in leaching and losses to the water-table.

The main part of P fertilizer is given pre-plant and, P requirements being of 0.3 kg P per tonne of tomato fruit produced per hectare, that there is no need to add nutrients later. Phosphorus is given as phosphoric acid; according to farmers, the main reason is to clear emitters. However, when P is given in calcareous soil, part of it is fixed on the soil components (Arvieu and Bouvier, 1974; Barrow, 1985; Kolsi, 1999), which reduces its efficiency. When P is given as phosphoric acid on calcareous soils, although sorption on soil is observed, it has positive effects on P availability to the crop due to increased mobility of P in the rhizosphere in relation

with higher soil water content (Kolsi *et al.*, 1999), and this form of P should be encouraged.

However, when considering efficiency of applied P as tomato production per unit of P given to the crop either as phosphoric acid or as TSP, it did not differ significantly. With TSP, tomato production per unit of given P was 1.22 t/kg P, and with phosphoric acid it was 1.11 t/kg P.

Another factor is interaction between P fertilizer and manure. When soil organic matter content is increased, it increases subsequent P availability to the crop through temporary fixation of P on organic matter (Kolsi, 1999); mobility of P in the soil is also increased, thus having a positive effect on P absorption by the roots for orchard crop grown in calcareous soils.

Some negative consequences can be observed either on the crop or on the soil. Too much nutrients given at the beginning of the growth tend to increase vegetative growth instead of reproductive growth. These consequences are probably still reduced on vegetable and tomato production, but they can seriously modify fruit tree production. On the soil, in an extreme case, salinization was related to too much nutrients.

Farm Functioning

The effect of the introduction of fertigation at farm level has important consequences on yield, input factors and can have important consequences on farm functioning. Direct consequences were observed on yield, tomato production, water- and nutrient-use efficiencies. Other consequences have also to be taken into account regarding the introduction of this technique on farm functioning in Cap Bon.

When the technique is adopted and when farmers, including traditional ones, use it and are able to achieve high yields and large water- and nutrient-use efficiencies, important changes can be observed with farms becoming more specialised, relying more on irrigated vegetables. Farming systems change from mixed cropping with milk production, cereals and an irrigated area to farms with only irrigated crops, vegetables (tomato, pepper, strawberries). Even greenhouses are introduced whenever possible.

Traditional farms move from mixed cropping to more specialised high-input cropping systems. That situation allows more production and is more intensive; however, it becomes a risky situation and the farmer will have to rely on market prices.

CONCLUSIONS

Fertigation is developing rapidly; its use by farmers' attests to their adoption of this

technique. However, a lot of problems are still to be solved, and research and extension work in this area should be encouraged. If the introduction of micro-irrigation allowed increased water-use efficiency through increased production, it should now be possible to help more farmers learn how to reduce water consumption per unit area in relation with soil and weather conditions without using sophisticated methods. Weather conditions at the regional level could be used.

Nutrients are given to the crop in different forms, and in most cases the amount of nutrients could be reduced to reduce costs and pollution. For P fertilizer, lots of problems are still to be solved; knowledge of its dynamic in the soil is still limited. For water and nutrients, farmers who adopted fertigation techniques have to learn how to adapt more accurately crops needs and requirements in relation with specific soil and weather conditions.

When fertigation is adopted at farm level, farmers have to learn how to make decisions in the process of giving water and nutrients at a short scale of time, either with the help of extension services or with equipment providers. Increasing the number of farmers using micro-irrigation showed a reduction in yield. However,, when comparing traditional surface irrigation with micro-irrigation, an important increase in yield was observed even if yield is less than the potential, almost 50% of the potential was achieved when techniques are not well used. The increase in yield encourages farmers to learn and continue adopting this technique.

However, increasing the area in micro-irrigation will be done through an increase in the number of farmers using it, and keeping micro-irrigation positive effects will then be done only through an important contribution from extension services. Moreover, even if fertigation allows increasing water and nutrient-use efficiencies, some other problems may occur with modification of farm functioning and other possible consequences that should be considered more carefully on soil.

REFERENCES

- Arvieu, J.C., and O. Bouvier. 1974. Les processus chimiques de l'évolution des phosphates en sols calcaires *Société Bull. AFES* 4: 208 – 224.
- Bar-Yosef, B. 1977. Trickle irrigation and fertilization of tomatoes in sand dunes; water, N and P distribution in soil and uptake by plants. *Agron. J.*, 69: 486 – 491.
- Barrow, N.J. 1985. Reaction of anions and cations with variable-charge soils. *Adv. Agron.*, 38: 183 – 230.
- Belkhoja, K., L. Bortoli, J.P. Cointepas, P. Dimanche, A. Fournet, J.C. Jacquinet, and A. Mori. 1973. Les sols de la Tunisie Septentrionale. *Sols de Tunisie, Bull. de la Division des Sols*, 5, 1 – 185. + map
- Bortoli, L., M. Gounot, and J.C. Jacquinet. 1969. Climatologie et bioclimatologie de la Tunisie Septentrionale. *Annales de l'Institut National de la Recherche Agronomique de Tunisie*, 41, 1 – 235 + appendices. Ed.: L. Emberger and G. Long, Centre

- d'Etudes Phytosociologiques et Ecologiques, Montpellier, France.
- Commissariat Régional au Développement Agricole, Nabeul. 1998. Repartition des superficies cultures en micro-irrigation. Ministry of Agriculture, Tunis. Tunisia.
- Direction Générale du Génie Rural. 1999. Réalisations en économie d'eau d'irrigation, Ministry of Agriculture, Tunis, Tunisia.
- FAO. 1997. Irrigation in the Near East region in figures, *FAO Water Report n°9*, Rome, Italy
- GICA. 1997. Guide de la tomate. Pratique de la culture de la tomate d'industrie en Tunisie. Groupement des industries de conserves alimentaires.
- Hamza, N. 1998. Fertilization de la tomate. Doc. Thèse, INRAT. Tunis.
- Harris, G. 1998. An analysis of global fertilizer application rates for major crops.
- Jacquin, F., G. Araujo, and E. Frossard. 1983. Influence de la matière organique sur l'efficacité de la fertilisation phosphatée et sur les différentes formes de phosphore dans trois types de sol p. 581–591, 3ème Congrès International sur les Composés Phosphorés, Bruxelles, 4–6 Oct. 1983.
- Kolsi, N. 1999. Fertigation à l'acide phosphorique en sol calcaire. Thèse, Université de Gent, 230 p.
- Kolsi, N., A. Mhiri, and J. Vanderdeelen. 2000. Efficiency of phosphoric acid fertigation in fine-textured calcareous soils, IMPHOS Regional Workshop "Plant Nutrient Management under Pressurized Irrigation Systems in the Mediterranean Region" (this issue).
- Mazoyer, M., and L. Roudart. 1997. Histoire des agricultures du monde, du néolithique à la crise contemporaine, *Editions du Seuil*.
- Ministry of Agriculture. 1996a. Enquête sur les structures des exploitations agricoles Direction générale de la planification, du développement et des investissements agricoles, 1994 – 1995. Tunis, Tunisia.
- Ministry of Agriculture. 1996b. Les perspectives du secteur agricole compte tenu des mutations internationales *COMETE Engineering*.
- Papadopoulos, I. 1995. Use of labelled fertilizers in fertigation research. p. 399–410. In Proc. "International Symposium on nuclear and related techniques in soil/plant studies on sustainable agriculture and environmental preservation", Int. Atomic Energy Agency. Vienna, Austria.
- Pernin, Ch. 1998. Règles de gestion de l'eau d'irrigation des lacs collinaires tunisiens. Rapport de stage.
- Phene, C.J., D.W. Beale. 1976. High frequency irrigation for water and nutrient management in humid regions. *Soil Sci. Soc. Am. J.*, 40: 430 – 436.
- Riou, Ch. 1980. Une formule empirique simple pour estimer l'évapotranspiration potentielle moyenne en Tunisie. Cahiers de l'ORSTOM, Série Hydrologie Agricole, Vol XVII.
- World Bank. 1998. World development indicators, CD-ROM. Washington DC, USA.
- World Bank. 1999. World development report, Washington, D.C., USA.

Fertigation under Saline Conditions: Irrigation Management Minimizing Soil Salinity Risk

Gevat Kirda and Nafi Baytorun

Çukurova University, Adana, Turkey

ABSTRACT

A greenhouse experiment was carried out to determine the distribution of salts in the plant root environment. Salt accumulation patterns within the plant rooting zone underneath a drip irrigation system were measured in a greenhouse planted to cucumber. A single-line drip irrigation system, centred between 50-cm spaced, double rows of plants, fertigated with four fertilizer N concentrations (0, 100, 150 and 200 mg L⁻¹) were used to assess yield response of cucumber grown under two irrigation treatments. The irrigation treatments were defined depending on two different irrigation timing, either irrigation made at 30 or 45 kPa soil water tension, monitored with tensiometers installed at 45-cm depth midway between two plants within rows. Progressive salt accumulation within 60-cm plant rooting depth under two irrigation treatments was monitored.

Soil salinity, at the end of growing season, varied from one to five times of the initial soil salinity (≈ 0.5 dS/m), depending on relative position of plant roots with respect to dripper location under the plant-rooting zone. However, in zones within close proximity to the drippers, salt accumulation was three /five times lower than, for example, 30-cm laterally away from the drippers. The results therefore suggest that drippers, arranged either along single or double lines, can create different soil salinity environments in the plant rooting zone. At the completion of harvesting, salt had accumulated within the plant rooting zone; average soil salinity accumulated within 60-cm soil depth was nearly 30% higher under irrigation at 45 kPa, compared with irrigation at 30 kPa. The results therefore suggest that irrigation timing (i.e., irrigation frequency) could also be considered as a management technique to reduce yield reduction due to increase of soil salinity.

Although effects of irrigation water quality on salt accumulation could not be assessed because of good quality of irrigation water ($EC_i = 0.35$ dS/m) used under the present study, it would be an easy practice to leach out additional salinity which had accumulated annually as a result of irrigation water. However, one should give due consideration to salt tolerance of different crop species and vegetables to be grown under saline conditions and when good quality of irrigation water is not available.

water management
irrigation systems
soil salinity

INTRODUCTION

The world's land surface is about 13.2×10^9 ha, no more than 7×10^9 ha of which are arable and only 1.5×10^9 ha of which are cultivated (Massoud, 1981). Of the cultivated lands, about 0.90×10^9 ha (60%) have salinity and sodicity problem, existing in over 100 countries (Szabolcs, 1989). It is estimated that 20 million hectares of arable land has deteriorated and is abandoned annually as a result of salinity, in addition to already existing salt-affected lands (Malcolm, 1993).

Modifying the saline soil conditions to suit crop plants is among the basic approaches to cope with soil salinity. *Leaching excess salts from the crop rooting zone, adding soil ameliorants, improving surface and sub-surface drainage conditions, using good quality of irrigation water with proper irrigation methods and management are among the techniques which can be adopted in efforts to utilize salt-affected soils.* It should be noted, however, that in regions where soil salinity is likely to occur, scarcity of good quality of irrigation water is among the major constraints to ameliorate saline soil conditions. Keren (1990) reviewed reclamation of salt-affected soils.

Numerous experiments has been carried out earlier to assess salinity effects of drip irrigation systems on crop yields. Oron et al. (1995) used brackish water with sub-surface drip irrigation where drippers were installed at 30 and 60-cm below the soil surface to leach accumulated salts below the root zone. The field results showed that economically viable crop yields could be obtained using brackish water with sub-surface drip irrigation systems. Long-term effects of drip irrigation application treatments, from severe deficit to excess irrigation, resulted in significantly different salt accumulation within the plant root zone, indicating that plant salt injury could be minimized with excess irrigation (Hutmacher et al., 1995).

Recent improvements in both irrigation methods and fertilization practices can be utilised in sustaining good crop growths, even in saline environments. For example, a properly managed and operated drip irrigation method can open the way to utilise not only salt-affected soils but also to use saline waters with certain provisions. To this effect, this paper evaluates fertigation as an available technical option to utilise salt-affected soils.

Objectives of this work were, therefore, to measure the extent of salt accumulation and its distribution within plant-rooting zone of a greenhouse-grown cucumber crop irrigated with a drip irrigation system. The work further aimed at determining whether differences in irrigation scheduling and N fertilization would reduce adverse affects of salt accumulation on yield.

METHODS AND MATERIALS

The experiments were conducted during the growing season 1995/96 in a plastic greenhouse at Research Farm of the Faculty of Agriculture, Çukurova University,

Adana. The plastic house, oriented in north-south direction, was 12 × 24-m size and the cover material was with UV, IR, with anti-fog characteristics.

A local cucumber variety, F1 hybrid of Aksu, was used as test crop in the experiment. The greenhouse soil was classified as Palexerollic Chromoxeret, a heavy-textured soil, with medium permeability and high water-retention capacity (Table 1).

A randomised complete block experimental design, consisting of two irrigation programs, four N fertilizer concentrations (0, 100, 150 and 200 mg N /l), and of four replicates was used (Table 2). Phosphorous and K concentrations were 30 and 200 mg/l of irrigation water, respectively, and kept constant and the same for all N treatments. Total sub-plots were 32, each having 16 plants, arranged as double rows with a planting space of 50-cm in rows. Each replicate (i.e., sub-plots) contained two rows of eight plants. Fruit yields of 12 plants, excluding the two plants at extreme ends of the rows, were recorded during harvest.

Table 1. Experimental soil characteristics (0-60 cm).

Texture	Bulk Density	Organic Matter	Plant Available Water	Saturated Soil Water Content	Electrical Conductivity	pH (Saturated Extraction)
	-g/cm ³ -	----%----	mm in 100mm	cm ³ /cm ³	---dS/m---	
C	1.15	2.0	120	0.51	0.5	7.8

Table 2. Description of experimental treatments.

Nitrogen Treatments	Nutrient Concentration in Irrigation Water			Irrigation Water EC
	Nitrogen	Phosphorous	Potassium	
	-----mg/L-----			----dS/m----
N0	0	30	200	≈ 0.85
N1	100	30	200	
N2	150	30	200	
N3	200	30	200	
Irrigation Treatments	Tensiometer Reading	Number of Irrigations	Water Applied at Each Irrigation	Total Water Applied
	----kPa----		-----L/plant-----	---L/plant---
A	30	12	6	72
B	45	9	8	72

A drip irrigation system with single laterals centered between the two rows of plants was used (Fig. 1). Spacing of the drippers with 2 L/hr of flow rate was 30 cm. A wet band of approximately 70 cm width, covering the two rows of plants, was formed during irrigations. Irrigation scheduling was controlled using tensiometers, as were previously used in many other studies (e.g., Clark et al., 1991; Kirda et al., 1997). The tensiometers, set of two replicates, were installed at 15, 30 and 45-cm soil depths, midway between the two plants within rows. Additionally, neutron-access tubes were installed and centered between the two plants in rows. The access-tubes were used to measure soil water content distribution profiles using a neutron gauge (CPN 503DR).

Tensiometer readings, as averages of two replicates at 45-cm depth, were used for controlling irrigation timing. Maximum allowed tensiometer readings in irrigation Treatments A and B were 30 and 45 kPa, respectively (Table 2). The combined use of tensiometers and the neutron gauge facilitated full control of maximum wetting depth at each irrigation, which was 70 to 80 cm, with 6 and 8 litres of irrigation water applied per plant for Treatment A and B, respectively.

The greenhouse was not heated, but was protected from frost. The heating system worked only when the outside temperature was below 5 °C, as was normally practised by the growers in the region.

Gravimetric soil samples, both vertically and horizontally, were taken, the starting just below the drippers, to study the progress of salt accumulation during 210 day-growing season. Salinity, as electrical conductivity (ECe @ 25 °C) was measured in saturation extracts of air-dried soil samples, before planting, at mid-season and at harvest.

RESULTS AND DISCUSSION

Although the mode of irrigation method caused no significant fruit yield difference (Table 3), it caused significant differences in soil salinity distribution profiles. Under irrigation Treatment A, where soil water tension was kept lower (30 kPa) than that of the Treatment B (45 kPa), progress of salt accumulation under the drippers was slow, and the final soil salinity at harvest was lower than that of Treatment B with less frequent irrigation application (Fig. 2). However, soil salinity that had developed during the growing season under both irrigation treatments was not at a level which would influence the yield, because soil salinity developed throughout the growing season was hardly higher than the threshold salinity of 2.5 dSm⁻¹ to affect cucumber yield (Maas and Hoffman, 1977).

It is clear, however, that one can control salt accumulation and soil salinity distribution in plant root environment through manipulating irrigation scheduling and irrigation water quantity applied.

Fig. 3 shows that at the end of irrigation season, salt accumulation

developed was only two to three times the initial value under frequent irrigation but with lower amounts of water applied; whereas, soil salinity increased five to six times of that initial value with less frequent irrigation but with higher amounts of water applied. It should also be noted that salt accumulation under both irrigation treatments was confined within surface soil layers over 20 to 25 cm depth; at deeper zones, it could hardly be seen (Fig. 2).

The results, therefore, suggest that mulching, if proper material is cheaply available, may prevent soil evaporation and thereby reduce upward transport of salts and salinization. Wheat straw, for example, may be used for this purpose. Use of mulching can be an alternative and economic option to sub-surface drip irrigation used by Oron et al. (1995) to utilise brackish water for irrigation.

To utilise saline soils or inferior quality of irrigation water in crop production, drip irrigation systems can again advantageously be used with proper placement of the dripper lines. The lowest salt accumulation occurs just beneath the drippers; whereas salt accumulation progressively increases at locations further away the dripper. For example, in our study, the saline front at soil surface was 25 to 30 cm away from the dripper location (Fig. 3). Therefore the ideal location for planting must be as close as possible to the drip lines to utilise saline soils or brackish water for crop production. In other words, separate drip lines installed for each row of plants are essential to minimise risks of salt injury on the plants. The penalty to be paid in this case is higher material cost of the drip lines purchased for each row of plants.

However, one can use single-line drip systems safely, centred between the doubled rows of plants, if good quality of irrigation water ($EC \leq 0.5$ dS/m) is available without any risks of salt injury on the plants. In both cases, however, either one uses a single drip system, serving to double rows of plants, or separate drip lines used for each row of plants, annual or bi-annual leaching may be essential to prevent salt accumulation in areas with annual precipitation of less than 150 to 200 mm.

In summary, the experimental results reported here suggest that any adverse effects of likely salt accumulation on fertigated crops could be minimized with proper layout of the drip systems, with high-frequency irrigation practice, growing salt-tolerant crop species, and with occasional leaching of the soil profile.

CONCLUSIONS

- Salt accumulation in the plant root environment can be controlled through manipulating irrigation scheduling. Frequent irrigation with low amounts of irrigation water applied prevents salt accumulation within the plant root environment. However, increased interval of irrigation, even with high amount of irrigation water applied, causes salt accumulation with increased risk of salt

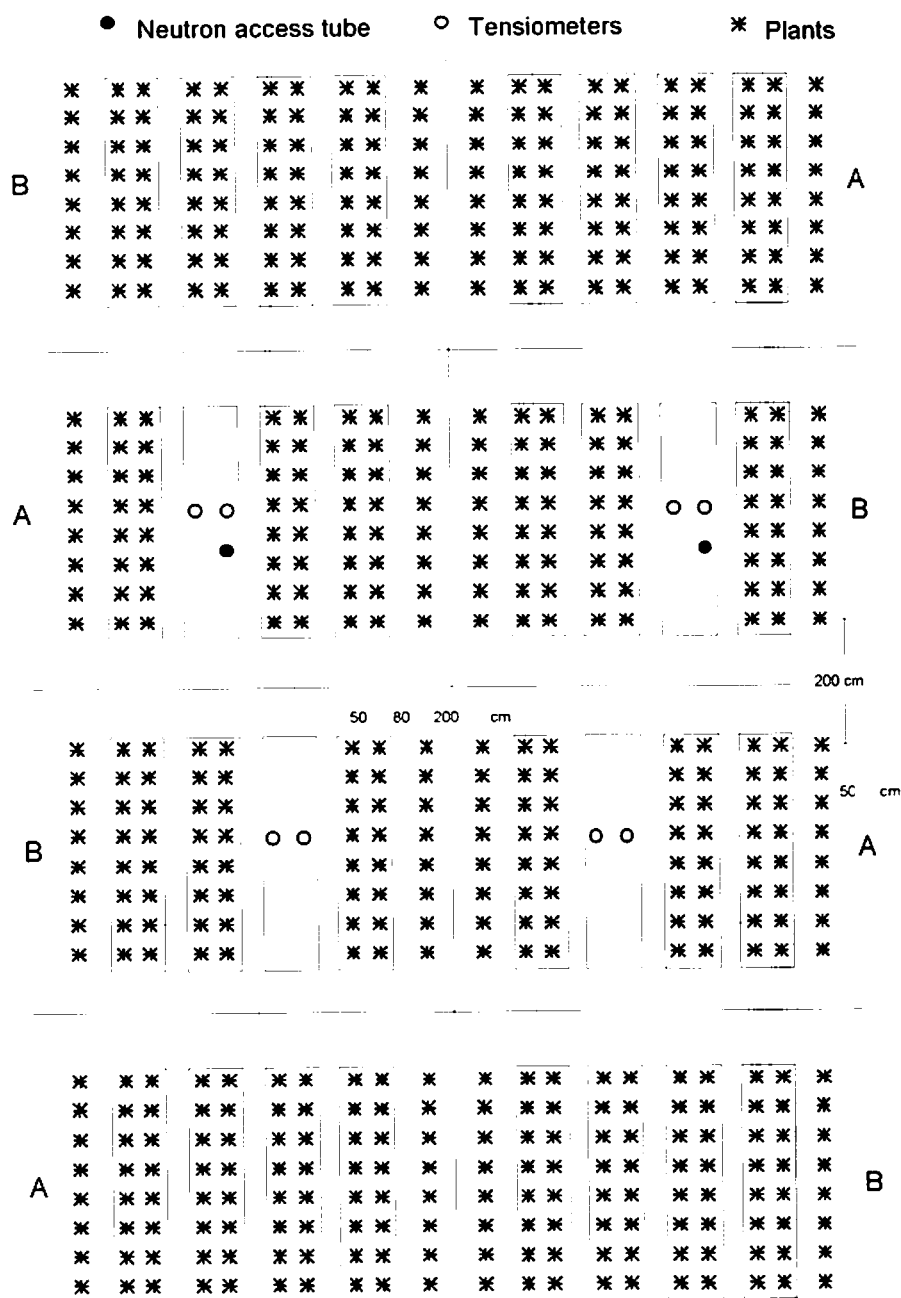


Fig. 1. Experimental design and planting arrangement.

injury on the plants. The extent of salt accumulation and salinity level depends on initial soil salinity and irrigation water quality.

- Arrangement of drip lines with reference to the location of plant rows provides a good management option to deal with salinity. One must use separate drip lines, located very close to each row of plants to minimise salt injury on the plants to utilise saline soils and brackish water for crop production.

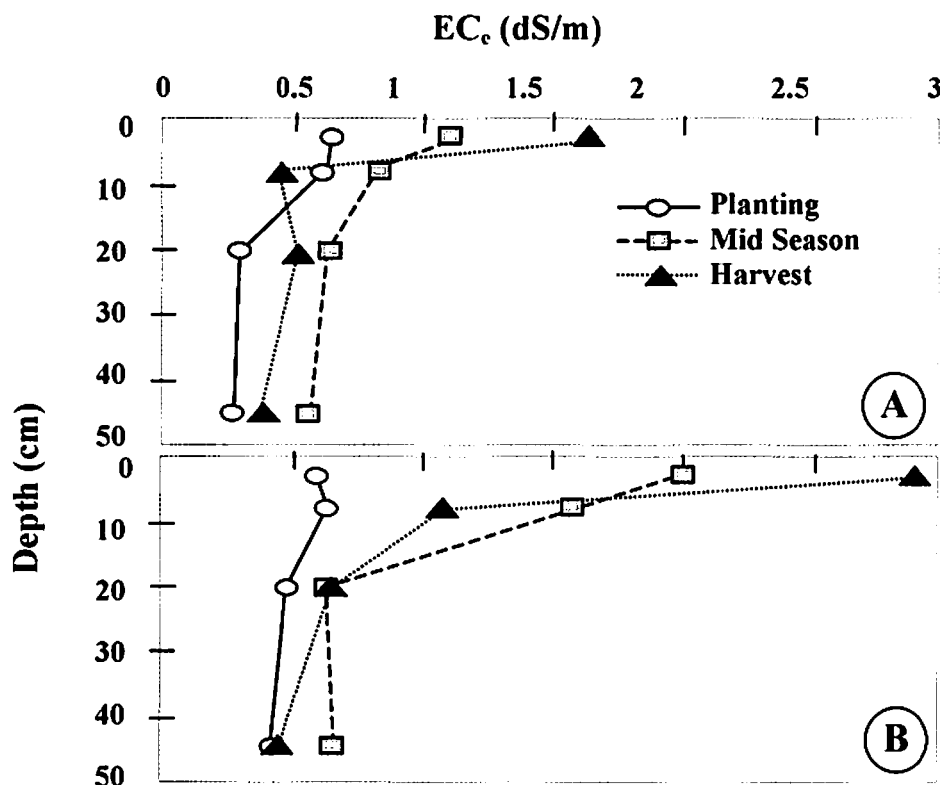


Fig. 2. Progress of soil salt accumulation within plant rooting zone with nitrogen fertilizer (200 mg/L) feeding under two different modes of irrigation practice: A) Irrigation at low soil water tension, 30 kPa; B) Irrigation at high soil water tension, 45 kPa.

ACKNOWLEDGEMENT

The work was partially supported by Turkish Scientific Research Council through a Research Contract TOGTAG-1272. The authors are also grateful for the partial support received from Cukurova University, Faculty of Agriculture, Adana, through a Research Grant, BAP-TYS-95/07.

Table 3. Cucumber fruit yield response to nitrogen fertilizer concentration of the feeding solution under two different irrigation programs.

Nitrogen Concentration (mg/L)	Irrigation Treatments		LSD _{0.05}
	A, 30 kPa	B, 45 kPa	
	-----g /plant-----		
0	6295 (170.0) ¹	5062 (136.7)	1352
100	7778 (210.0)	7578 (204.6)	
150	7575 (204.5)	7331 (197.9)	
200	7115 (192.1)	7071 (190.9)	
Average	7200 (194.4)	6800 (182.5)	NS

¹Numbers in parenthesis are calculated fruit yields in mg.ha⁻¹.

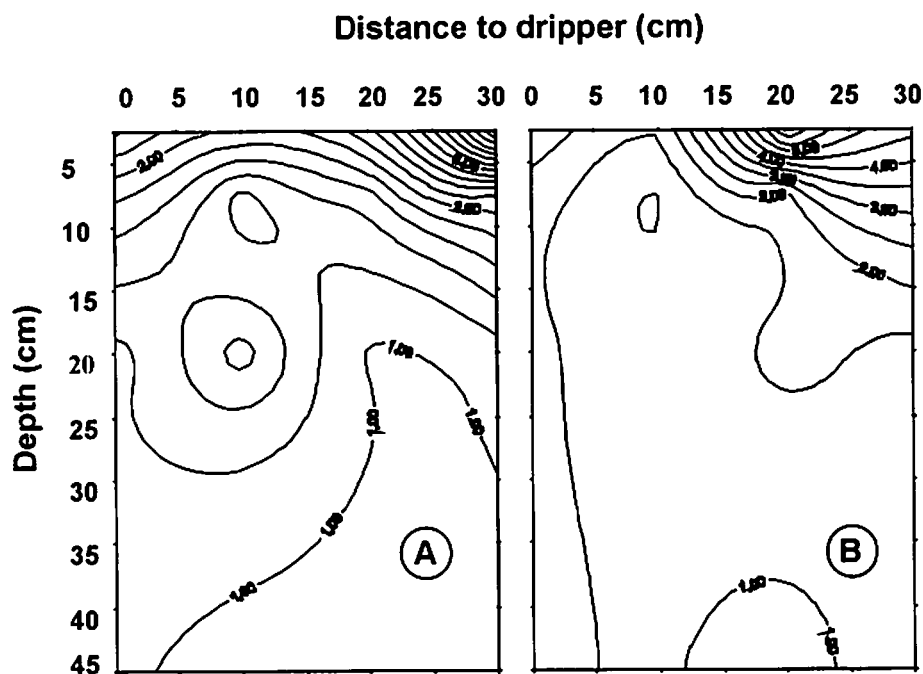


Fig. 3. Relative soil salinity contours as ratio of initial soil salinity (0.5 dS/m) to ECe (dS/m) measured at harvest, under two different modes of irrigation practice: A) Frequent irrigation at low soil water tension, 30 kPa; B) Less frequent irrigation at high soil water tension, 45 kPa.

LITERATURE

- Clark, G.A., C.D. Stanley, D.N. Maynard, G.J. Hochmuth, E.A. Hanlon, and D.Z. Haman. 1991. Water and fertilizer management of micro-irrigated fresh market tomatoes. *Trans. Amer. Soc. Agric. Engin.* 34(2): 429 – 435.
- Hutmacher R.B., H.I. Nightingale, S.S. Vail, F. Dale, D.E. Rolston, D.W. Peters, P.H. Brown, T. Pflaum, A.D. Bravo, and J.W. Biggar. 1995. Salinity and boron distribution in micro-irrigated almonds: Soil and plant accumulations. p. 110 – 115 *In Proc. 5th Int. Micro-irrigation Congr.*, April 2 – 6, 1995, Orlando, Florida
- Keren, R. 1990. Reclamation of saline, sodic, and boron-affected soils. p. 410 – 431. *In K. Tanji, (ed.) Agricultural salinity assessment and management.* Amer. Soc. Civil Engin., New York, N.Y.
- Kirda, C., N. Baytorun, Ç. Tanriverdi, R. Derici, F. Zapata, and S. Topçu. 1997. Continuous and intermitted application of fertilizers to decrease residual nitrogen fertilizer in greenhouse soils planted to tomatoes. p. 37 – 50. *In Int. Confr. on "Water Management, Salinity and Pollution Control towards Sustainable Irrigation in the Mediterranean Region"*, VI. Fertilizer and Water Quality, 22-26 Sept. 1997.
- Maas, E.V., and G.J. Hoffman. 1977. Crop salt tolerance – current assessment. *J. Irrig. and Drainage Div.*, Amer. Soc. Civil Engin., 103: 115 – 134.
- Malcolm, C.V. 1993. The potential of halophytes for rehabilitation of degraded land. p. 8 – 11. *In N.Davidson and R. Halloway, (ed.) Productive use of saline land.* Australian Center for Int. Agric. Res. Proceedings 42: 8 – 11.
- Massoud, F.J. 1981. Salt-affected soils at global scale and concepts for control. *FAO Land and Water Development Div., Tech. Paper*, Rome, Italy.
- Oron, G., Y. DeMalach, L. Gillerman, and I. David. 1995. Pear response to saline water application under subsurface drip Irrigation. p. 97 – 103. *In Proc. 5th Int. Micro-irrigation Congr.*, April 2 – 6, 1995, Orlando, Florida, USA.
- Szabolcs, I. 1989. Salt-affected soils. CRC Press, Inc. Boca Raton, Fla., USA.

SECTION IV:

ENVIRONMENTAL AND ECONOMIC ISSUES

Environmental and Health Impacts of Fertigation

Atef Hamdy

*Mediterranean Agronomic Institute of Bari,
CIHEAM/MAIB, Italy*

ABSTRACT

A growing number of world's rivers, lakes and groundwater aquifers are being severely contaminated by human, industrial and agricultural wastes. Fertilizers and pesticides are an essential component of the package of intensive agriculture, and their use is likely to increase with rapidly increasing demographic pressure, particularly in developing countries which have increased chemical inputs. An adverse impact on water quality is also likely to increase. Elevated levels of plant nutrients (i.e., nitrates), salts, and pesticides are frequently detected in agricultural soils, surface and groundwater sources, leading to increased *toxicity*, *salinity* and *eutrophication* of lakes, rivers, and coastal waters, and *groundwater pollution*. These environmental changes and, therefore, environmental management can not be excluded from human health aspects.

Irrigation schemes and intensive agriculture also carry a high risk of introducing or increasing the risk of transmission of water-borne and other diseases. In this respect, improving agricultural management, irrigation methods, and water-use efficiency will be of particular importance to protect the environment and public health. *With inappropriate planning, the threat of damage due to irrigation/fertilization is inevitable.*

Irrigated agriculture, properly planned, constructed and managed, instead of being a cause for environmental deterioration and health problems, can be an environmental and health asset. These concerns are stressed in this paper with particular emphasis on the beneficial role of the fertigation technique to reduce the environmental and health-related risks of irrigation due to *fertilizers*, *salts* and *agrochemical contamination*.

INTRODUCTION

Although population growth rates have been declining recently, by the year 2050 the planet could have as much as 10 billion people, double the number of humans it has now. The impact of this increased population on the environment will be severe. If we look at the global water resources, we see a frightening outlook.

Meeting the ever-increasing food requirements of this growing population, especially in developing countries, requires greater attention than hitherto be given to *increasing agricultural productivity on a sustainable basis*.

At the beginning of this century, 90 % of all water used in the world was for irrigation; currently it is about 70 %, and by the year 2000 it is expected to be about 60 % (Bouwer, 1993). These data indicate that we must grow *more food with less water*, using more intensive agriculture where chemicals and fertilizers will be extensively used in order to increase food and fiber production.

For years it was believed that these chemicals would either remain on the top of the ground surface of agricultural fields or would degrade before they could reach the groundwater and/or surface water. But more recent experiences have clearly shown that modern agricultural activities are contaminating water sources because of the increased use of chemicals which are being found in the surface and groundwater sources (Spalding et al., 1989; Kross et al., 1993; Fairchild, 1987). Many of drinking water supplies have been found to contain nitrate-nitrogen ($\text{NO}_3\text{-N}$) in concentrations greater than 10 mg/l, nearly all of which may have come from fertilizers (Kanwar and Baker, 1993; Kanwar, 1996).

There is no doubt that the increased use of fertilizers and agricultural chemicals has significantly contributed to agricultural productivity, but recently they have been the source of much controversy because of perceived health risks posed by the presence of *nitrate, pesticide and other compounds* in water sources. In this respect, improving agricultural management, irrigation methods and water-use efficiency will be of particular importance to protect *both the environment and the public health*. The recent popular approach of limiting fertilizer application, although might be a solution to control environmental impact, could not be considered the proper approach in enhancing agriculture production. *There is nothing wrong with the chemical fertilizers provided they are applied in the appropriate form, amount, place, and time* (Hamdy, 1989; Papadopoulos, 1996).

The role of agro-chemicals and, in particular, fertilizers and their environmental impacts will be discussed in this paper. Particular emphasis will be given to the role that fertigation techniques could play in minimizing the possible environmental side-effects.

FERTILIZATION AND THE ENVIRONMENT

Fertilization increases agricultural production. This itself represents an influence on environment: *corrective ecology*. However, the effects of fertilization on the three large environmental factors, *soil, water and air*, merit detailed consideration (Table 1). They are, in varying degrees, positively or negatively affected by fertilization activities in agriculture, just as any intervention in "nature" has a two-sided effect. Assessment therefore requires weighing advantages and disadvantages against one

another; it is especially important to establish the influence of fertilization properly in relation to other factors (FAO, 1962). Fertilization is not to blame for all relevant *damages to the environment*, nor are its effects always positive.

Table 1. Important environmental effects of fertilizers.

Soil	Water	Air
Reaction.		Improvement of air quality
Structure.	Eutrophication of surface water	Noxious substances.
Life.	Fertilizers in groundwater	Earth's ozone shield.
Toxic substances		

Nitrogen Fertilizers

Current and Future Use

Nitrogen is the most limiting nutrient for plant growth in most of the world's agricultural soils, and hence, crop production worldwide relies heavily on inputs of N from organic or inorganic sources. Plants may utilize some forms of organic N, such as amino acids and amines, although most of the N is assimilated by plants from inorganic ammonium (NH_4) and nitrate (NO_3) salts.

Consumption of N fertilizers has been increasing on a global scale. From 1967 to 1987, there was an increase in world N fertilizer utilization from 22.1 to 72.7 million (m) metric tons (FAO, 1962–1987), and by 1991 this amount had increased to 77 mt (Fert. Inst., 1993). It has been estimated that by the end of 1993, world consumption of N fertilizers will exceed 83.5 mt (FAO, 1988), and that by the year 2000 between 111 and 134 million metric tons will be produced and consumed (Newbould, 1989).

The developing countries (excluding China) use some 37 mt of fertilizer (in terms of nutrients, NPK). Such use increased fourfold in the last 20 years, though the growth rate in the 1980s was much lower than that of the 1970s. At present, fertilizer use rates have reached 62 kg/ha of harvested area (about one-half the average of the developed countries), but with very wide differences, ranging

regionally from 11 kg in Sub-Saharan African to 90 kg in the Near East/North Africa. The scope for further increases is much less than in the past. Projected fertilizer consumption in the developing countries (excluding China) may rise to some 80 mt and the application rate to some 110 kg/ha. The environmental dimensions of this prospective development will be discussed.

Nitrogen Budgets

The N cycle has numerous pathways and complex interrelationships of the processes involved. Not only are there *chemical, physical, and biological processes*, but these processes can be driven differently depending on climate, soil properties, and land management. These complexities increase the challenge, but do not diminish the need for preparing N budgets as means for evaluating ecosystem N inputs and outputs. By quantifying N in each pathway, N budgets can provide a means of assessing the impacts of *tillage, fertilizer, and crop management practices on outputs such as runoff and leaching, which affect water quality*.

Legg and Meisinger (1982) extensively reviewed the literature and noted that although there are limitations and inadequacies in N budget research, "soil N-budget principles provide a sound basis for estimating N *losses, gains, and transformations for any agricultural management system*". In a more recent literature discussion, Schepers and Fox (1989) note the difficulty in precisely quantifying N losses, but that "sound management practices can be developed to minimize nitrate leaching".

Off-Site Effects of Nitrogen Fertilization

Off-site effects of N fertilization include influences of agricultural products on people, as well as indirect influences through the environment. Some effects are *positive* and some are *negative*, but support for research generally emphasizes the negatives. Off-site effects are not necessarily economic, although economics is involved, and it is primarily economists who attempt to integrate the various facets in analyses of costs versus benefits.

The significance attached to these effects by society is reflected in the numerous recent scientific publications dealing, at least in part, with *environmental aspects of nitrogen*. These include a number of books, e.g., Prins and Arnold (1980), Brogan (1981), Stevenson (1982), International Institute for Sugar Beet Research (1983), Hauck (1984), Kang and Van der Heide (1985), Neeteson and Dilz (1985), Lambers et al. (1986), Van der Meer et al. (1986), Hargrove (1988), Jenkinson and Smith (1988), Follett (1989), Germon (1989), Welte and Szabolcs (1989), Follett et al. (1991), Addiscott et al. (1991), and Groot et al. (1991).

The principal environmental concern about N fertilizers, and about fertilizer

use in general, is the potential unfavorable impacts on human health of fertilizer-derived nitrate present in groundwater used for drinking. Of secondary concern is the enhanced growth of algae in surface waters containing extra N (and P). Algal "blooms" on surface waters are obvious and unsightly, and decomposition of the organic matter reduces the oxygen supply needed by fish and other aquatic animals. Of additional currently minor concern is the evolution of small quantities of gaseous nitrous oxide from soils and the possible contribution of the evolved nitrous oxide to the breakdown of stratospheric ozone and consequently to global warming.

FERTILIZATION AND WATER QUALITY

Fertilizers and pesticides are an essential component of the package of intensive agriculture, and their use is likely to increase with rapidly increasing demographic pressure, particularly in developing countries. With increased chemical inputs, an adverse impact on water quality is also likely to increase. Important pollutant fertilizers are N and P, which are responsible for eutrophication of surface water. Agricultural practices can also affect the quality of groundwater through leaching of fertilizers and pesticides applied to the soil surface.

Chemicals can be readily transported into the groundwater with water percolating from surface into the subsoil. Under intensive land use, the quality of water is adversely affected because of disruption of cycles of carbon and principal plant nutrients, and transport of sediments and dissolved chemicals to groundwater, rivers, and lakes.

The impact of increased use of organic and mineral fertilizers on the quality of water resources is not well investigated, especially in developing countries, where infrastructure and resources needed for monitoring and analysis are not fully available. In addition, multiple cropping based on intensive land use also leads to contamination of water resources. Intensive land use, with little or no fallow period for soil restoration, can set in motion several degradation processes with adverse impacts on water quality. However, the impact of fertilizer application on water quality is to a great extent influenced by the principal soil processes including *physical, chemical and biological ones* (Table 2).

Important among physical processes are *compaction, crusting, and accelerated soil erosion*. Physical processes are set in motion by decline in soil structure, with resultant decrease in water infiltration capacity and increase in surface runoff. Declining structural stability also increases soil erodibility and risks of inter-rill and rill erosion. Surface runoff and erosion enhances transport of dissolved chemicals and sediment-borne pollutants into natural waters.

Leaching, transport of chemicals from surface into the subsoil with percolating water, is another process affecting water quality. Concentrations of soluble

nutrients may be of several orders of magnitude higher in seepage water than in surface runoff. Leaching is generally more severe during off-season when crops are not actively growing. Active crop growth removes readily soluble chemicals, e.g., NO_3 , NH_4 , P, K, Ca, Mg, etc. Leaching can be accentuated by macropore flow or by-pass flow.

Table 2. Soil processes affecting water quality.

Soil Processes	Impact on Water Quality
Soil erosion	Transport of dissolved and suspended sediments in surface runoff.
Leaching	Movements of nutrients, agricultural chemicals, and dissolved organic carbon in percolating water.
Macropore flow	Rapid transport of water and pollutants from surface to sub-surface and into a drainage system.
Mineralization of humus	Release of readily-soluble compounds that are easily washed away or leached out.

In general, the rate and magnitude of macropore flow are inversely related to those of surface runoff. In addition to nutrient application through fertilizers, plant nutrients also become available through mineralization of humus and soil organic matter. The process of humification releases plant nutrients immobilized in organic matter and makes them readily soluble and mobile. The biomass, active and dead, is a major buffer against nutrient loss (by erosion or leaching) out of the ecosystem. Therefore, a decrease in total biomass activity and species diversity of soil fauna can have serious adverse impact on water quality.

Nitrogen Fertilization

Not all nutrients ions in a fertilizer applied to a field soil are taken up by the growing crop, and the amount remaining is very important in any discussion on the effect of their long-term intensive use. Many things can happen to these residues in the soil; they may remain in the soil, they may be removed in the water leaching thought the soil or running off the surface of the soil, or they may be lost to the atmosphere by *volatilization*. The relative importance of these depends on the physio-chemical and biological reaction the ions take part in. Although the benefits of N for plant production have been well recognized, excessive use of N fertilizers has often been indicated as a major source of nitrate in "ground and surface water in rural and suburban areas" (De Roo, 1980; Spalding et al., 1982; Schepers et al., 1984).

Sources other than soluble fertilizers and soil N also contribute to high levels of nitrate encountered in certain areas. Livestock feeding, barnyards, septic tanks, animal and human contamination are frequently associated with elevated nitrate in well waters (Stevenson, 1986). Nitrate leaching is a potential problem in urban and rural areas that are characterized by the predominance of sandy soils, abundant rainfall, frequent shallow water-tables, high fertilization rates and reliance on groundwater as a source of drinking water.

Reports from Florida, dating as early as 1916 (Collison and Walker, 1916) mentioned that $(\text{NH}_4)_2\text{SO}_4$, rather than NaNO_3 , should be the preferred N fertilizer form in the wet season to prevent leaching losses. Excessive irrigation (> 10 cm) or heavy rainfall is likely to move nitrate below the root zone of many crops grown on sandy soils in Florida (Graetz et al., 1973; Endelman et al., 1974). In humid regions and under irrigation, leaching loss can account for up to 50% of the N input (Legg and Meisinger, 1982; Keeney, 1986).

Groundwater

Groundwater is the major source of drinking water for a large percentage of the urban and the rural population. Application of excessive amounts of N fertilizers has frequently been suggested as a primary source of nitrate contamination in groundwater (Spalding et al., 1982; Schepers et al., 1984). Regions under irrigated cropland and with well-drained soils are more prone to have large areas with relatively high nitrate-N concentration. Nitrate pollution of groundwater is not a serious problem in poorly drained soils, especially if seepage to deep aquifers is small. Denitrification in the subsoil is normally an intense process of N removal under these conditions (Martin et al., 1991).

Concerns with fertilizer contamination of groundwater are growing nationally and internationally, although most of the surveys indicate that currently nitrate contaminated areas are small in proportion to the total land use (Spalding and Exner, 1993). Undoubtedly, protective measures can and must be taken so that irremediable problems are avoided in the future. Remediation of surface water pollution may be aided by naturally occurring environmental processes, such as heating and cooling, exposure to sunlight, microbial transformations, and oxidation that chemically transform pollutants. Groundwater is not subject to these processes, and thus, recovery from nitrate pollution, if it occurs at all, is expected to be slow.

Use of excessive N fertilization not only increases nitrate concentrations of groundwater but also could adversely affect the quantity and quality of crops produced. This means that farmers have to bear higher cost for fertilizers used as well as loss of revenue due to poorer quality and quantity of products. Unquestionably, the solution of the twin problems of yields and production of water quality lies in adopting better management practices.

Surface and Groundwater Pollution.. Related Factors

Surface runoff is dependent on the amount and intensity of precipitation, antecedent soil moisture, soil properties, and slope as well as management factors such as tillage, crop residue, and cropping systems. Surface runoff and infiltration are closely related. Usually *factors, which reduce runoff, increase infiltration*. Sub-surface flow can be another major pathway for water loss from a soil-plant system. Many of the factors, which reduce surface runoff promote an increase in sub-surface flow.

The impacts of tillage, crop management, and fertilizer management are quite interrelated, especially their impacts on soluble N, which is moved via sub-surface flow. These factors take on greater importance in humid climates, where greater soluble N losses usually occur with sub-surface flow than with surface runoff.

Nutrients and sediments are the major "non-point" pollutants of surface waters, but groundwater may add to this contamination (Hallberg, 1989). Excellent reviews on nitrate movement and transformation in aquifers have been published (Lowrance and Pionke, 1989; Pionke and Lowrance, 1991). Movement of nitrate with drainage water or runoff from cropped lands may contribute significantly to pollution of surface waters (Martin et al., 1991, CAST, 1992). However, soluble-N losses through surface runoff are generally small, unless high rates of N fertilizer have been applied at the surface just before heavy rains (Gilliam et al., 1974; Legg and Meisinger, 1982).

Poorly drained soils with high water-tables normally lose less nitrate to drainage water than well-drained soils (Gambrell et al., 1975). Upon drainage, nitrate movement in soils is enhanced, even in the absence of additional fertilizer N. Water draining from soils with high N-mineralization rates, in excess of crop uptake, may have a high nitrate-N content, even if no fertilization is done (Duxbury and Peverly, 1978; Miller, 1979).

Whenever N fertilizer application greatly exceeds N absorption by the crop, large losses may occur through tile outlets, and thus, excess N may enter streams or simply seep into nearby lakes (Gilliam et al., 1985). A major fraction of the N lost by surface runoff is organic N, which is associated with silt-sized particles and sediments (Schuman et al., 1973; Kissel et al., 1976). The loss of soil and subsequent problems associated with its downstream deposition have been of concern for a longer time than problems associated with N loss.

Correspondingly, there is less information concerning nutrient losses in surface runoff than is available on runoff and erosion (Sharpley and Smith, 1991). The loss of N associated with sediment is usually several times greater than soluble-N loss in surface runoff (Legg and Meisinger, 1982; Sharpley et al., 1987). Therefore, as practices are developed and implemented to reduce runoff and erosion, losses of sediment associated N and soluble N in runoff are also reduced.

Surface water contamination may be minimized by management practices such

as modification of landscape, countouring and use of structures (terraces, grass waterways, tile drains). Equally so, the improvement of water management with an appropriate irrigation scheduling and the use of pressurized irrigation systems for water distribution, as well as fertilizer application (fertigation), could significantly reduce the nitrate-N water resources pollution.

Phosphorus Fertilization: Eutrophication

The eutrophication caused by abundance of P and N in discharges is now extending to all continents. There is accelerated growth of algae stimulated by the P and N present in many discharges, including human and animal wastes, detergents and run-off from fertilizers. These two elements, when discharged into water, act as nutrients greatly speeding up the process called *eutrophication*. Excessive alga growth leads to a decline in the oxygen content of the water with adverse consequences for aquatic life. It can also impart a foul taste to drinking water. Eutrophication, first noticed in many Western European and North American lakes in the 1950s, is now leading to decline in water quality on all continents. The draining of nutrients into oceans can lead to an increase in the number of toxic algal blooms, sometimes known as “red tides”, which can make seafood unsafe to eat. Eutrophication (accumulation of nutrients) in surface water is largely due to increased P supplies since this is the most important growth-restricting minimum factor. Increased P supplies promote the growth of algae. Decomposition of dead algae masses consumes oxygen excessively, and fishes die because of lack of oxygen.

There is now no doubt that most P is supplied from domestic waste. The share of fertilization in the increased P load is highly exaggerated at one third of the total P contribution; values below 10%, would be more realistic. These figures apply primarily to mineral fertilization with phosphate. However, far higher values may occur when there is more intensive fertilization of soils close to groundwater with semi-liquid manure. The P component due to fertilizers should not be equated to the P component due to agriculture, which may be considerably larger in some areas.

Phosphate enters bodies of water through leaching and washing-off. Leaching is insignificant, at least in most soils far from groundwater. It amounts to less than 1 kg/ha of P, often only 0.1 to 0.2 kg/ha. These values apply equally to soils fertilized more or less intensively with phosphate. It is therefore completely unjustified to connect increased use of P fertilizers in agriculture with the increasingly detrimental effects on bodies of water nutrients. Damage to the environment is chiefly caused by *incorrect fertilization*.

Potential Adverse Environmental and Health Impact of Nitrogen

Some of the potential adverse effects of excess N, were listed by Keeney (1982) and shown in Table 3. The intended scope of this paper will discuss only the causative agents related to agricultural management. High nitrate levels in water are a concern because the ingestion of such water has the potential to reduce the oxygen-carrying capacity of the blood. Nitrate is reduced to nitrite (NO_2^-), which oxidizes the Fe of the hemoglobin in the blood; and methemoglobin, which cannot carry oxygen, is formed (Keeney, 1982). Infants have greater potential to suffer these ill effects than adults. In the USA, the maximum $\text{NO}_3^- - \text{N}$ level for potable water for humans has been set at 10 mg/l (USPHS, 1962; USEPA, 1973). The World Health Organization (1971) and European Economic Community (1980) have established levels of 10.2 and 11.3 mg/l of nitrate -N, respectively.

Table 3. Potential adverse environmental and health impacts of nitrogen.

Impact	Causative Agents
Human Health	
Methemoglobinemia in infants.	1. Excess nitrate and nitrite (NO_2^-) in waters and food.
Cancer.	2. Nitrosamines from NO_2^- ; secondary amines.
Respiratory illness.	3. Peroxyacyl nitrates, alkyl nitrates, nitrate-aerosols, NO_2^- , HNO_3 vapor in urban atmospheres.
Animal Health	
Environment.	4. Excess nitrate in feed and waters.
Eutrophication.	5. Inorganic and organic N in surface waters.
Materials and ecosystem damage.	6. Nitrate acid HNO_3 aerosols in rainfall.
Plant toxicity.	7. High levels of NO_2^- in soils.
Excessive plant growth	8. Excess available N.
Stratospheric ozone depletion	9. Nitrous oxide NO_2^- from nitrification, denitrification, stack emission.

Nitrites can react with amines and amides to form nitrosamines and nitrosamides, and 80% of these compounds tested have proved to be potent carcinogens in animal experiments (OECD, 1986). Certain epidemiological studies indicated a positive correlation between nitrate consumption in drinking water and the incidence of gastric cancer (Hill et al., 1973), although several authors (Addiscott et al., 1991; Bockman and Granli, 1991) state that they found very limited evidence linking stomach cancer with nitrate in water. Some evidence exists

of other health disorders, such as non-Hodgkin's lymphoma (Weisenburger, 1991), increased infant mortality (Super et al., 1981), central nervous system birth defects (Dorsche et al., 1984), and hypertension (Malberg et al., 1978).

Nitrate poisoning of animals from water is not common, but was reported in Saskatchewan where wellwater contained 626 mg/l nitrate-N (Campbell et al., 1954). In cattle, various clinical effects have been related to high-nitrate ingestion through feed (forages) and/or water. The disorders include deficient growth/health in young animals, increased abortion rates, depressed yields and milk quality (OECD, 1986). No details regarding nitrate levels in grass, feed and water were given.

Since N fertilization of forages is expected to increase in European countries and since there is higher nitrate present in the water, nitrate intake by farm animals is likely to increase (OECD, 1986). Oat (*Avena sativa*) hay or oat straw containing high nitrate levels and fed to animals have caused a loss of cattle in Canada (Henry and Menely, 1993). Excess nitrate accumulation in plants is enhanced under conditions where a sudden drought occurs.

PESTICIDE USE AND ENVIRONMENTAL HAZARD

Agricultural fields which receive application of pesticides to control insects, pests and weeds from damaging crops are considered the main "non-point" sources of pesticides in surface waters and groundwater. Soil erosion, infiltration recharge due to rain or irrigation water, and water runoff from agricultural fields treated with pesticides are the major "non-point" sources of pesticide pollution. Volatilization of pesticides from the soil or plant surface and wind erosion of dust particles can carry pesticides into the atmosphere. These pesticide particulates hang in the atmosphere until rainfall deposits them back on the land surface as a "non-point" source. Nations et al. (1993) have given a list of pesticides found in rainwater in Iowa. Obviously, the occurrence of pesticides in rainwater affects the quality of surface water.

While atmospheric transport may add small amounts of pesticides to surface water, runoff water is still the largest "non-point" source of pollution. In artificially drained areas, the movement of agrochemicals with sub-surface drainage water is important and should be considered as sources of "non-point" pollution. Pesticide movement with sub-surface drainage water is of minor importance compared to surface runoff (Baker and Johnson, 1979, 1983).

The fate and transport of pesticides applied to cropland require knowledge about their *chemical properties, their transformation, and physical transport processes* of site-specific conditions. Baker (1992) reported that four pesticide properties largely determine the tendency of pesticides to move once they are applied to the land surface. The most important properties are *adsorption*,

persistence, vapor pressure and solubility.

To minimize the side-effects of agrochemicals on the environment and, in particular, the degradation and pollution of water quality, it is extremely important to know the behavior of agricultural chemicals in the soil-water-air environment. The leaching of chemicals through the soil profile depends on complex interactions between the movement of water through the soil and the distribution of the chemical between the soil matrix and soil solution.

Most agricultural chemicals can be divided into three categories: as (1) *highly soluble* but weakly adsorbed; these chemicals can be lost to groundwater with percolating water; (2) *moderately adsorbed*, these chemicals can leach to the environment, mostly with runoff water; and (3) *strongly adsorbed*, these chemicals can be lost to the environment, mostly with sediments or soil particles.

MANAGEMENT FOR ENVIRONMENTAL AND WATER POLLUTION CONTROL

Best management practices (BMPS) are those that can be used to minimize *point* and *non-point* source pollution and are *economically, socially and environmentally acceptable*. Among these, we would like to highlight the following three approaches:

Chemical Rates and Methods of Application

Reduction in the rates and total quantity of chemicals applied could reduce the amount of chemicals available for leaching to groundwater or for runoff. Computer simulation studies indicated that higher nitrate-N losses are associated with high N application rates (Kanwar et al., 1988, Baker and Johnson, 1983). For pesticides, the rate of application is one of the dominating factors affecting pesticide losses with sediment and runoff water. If chemical application rates can be reduced, it would reduce the contamination potential to water resources, as well as save money and energy.

Placement

One of the approaches to reduce the leaching of chemicals to groundwater and/or surface water would be to incorporate the chemical with soil. A chemical's location in the soil profile and/or on the surface affects its concentration in runoff and sub-surface drainage water. If a chemical is applied broadcast, it mixes with the incoming rainfall or irrigation in a thin mixing zone (about 10 to 20-mm thick) and can either leach to subsoil layers or become part of the runoff water. If a chemical is incorporated, it is less susceptible to runoff losses.

Another approach would be to apply the chemical on a partial area through the

use of banding, where only the crop row area is treated, as opposed to a broadcast application where the whole area in the field is treated. With banding practice, the rate of chemical application can be reduced to more than 50 % or more. Appropriate placement of chemicals is a good BMP to control groundwater pollution.

Timing of Application

Appropriate timing of chemical applications can increase the efficient use of chemicals (especially N) and result in decreased leaching losses. Kanwar and Baker (1993) have shown that split-N applications resulted in lower residual N in the soil profile and nitrate-N concentrations in the sub-surface drainage water were at or below 10 mg/l during the 9-year study period. In this regard, hydrologic factors, primarily rainfall patterns, can have significant interactions with the timing of chemical applications.

IRRIGATION AND DRAINAGE SYSTEMS

Irrigation and drainage practices are typically considered as production practices rather than BMPs for water quality enhancement. Irrigation management is important in controlling water quality related problems. The rate, amount, and timing of irrigations are important considerations.

Fertigation and Environmental Effects of Agro-Chemicals

The introduction of efficient irrigation systems, such as drip and sprinkler fertigation became feasible as a means for *high yield, good quality* of the product and, even more important, *protecting environment and public health*. In this regard, the question to be raised is “Can fertigation be recommended as an appropriate means to overcome environmental problems associated with fertilization, and possibly with chemigation, under intensive irrigated agriculture?” The research findings and experience gained in this field demonstrated the superiority of fertigation techniques with respect to other conventional ones in ameliorating water quality and minimizing environmental problems related to fertilization.

Among the advantages that the fertigation technique provides are the following:

- Water-soluble fertilizers at concentrations required by crops are conveyed via the irrigation stream to the wetted volume of soil; the chemicals are placed in the desired location, the root-zone.
- Improved efficiency of fertilizer recovery (Miller et al., 1981), minimal fertilizer losses due to leaching (Bressler, 1977; Klein et al., 1989), control of nutrient

concentration in soil solution (Papadopoulos, 1986), control of nutrient forms and ratio of the various forms, particularly for N fertilizers, and flexibility in timing of fertilizer application in relation to crop demand based on development and physiological stage of crops (Snyder and Burt, 1976; Kovach, 1983).

- Fertigation reduces fluctuations of soil solution salinity due to fertilizers (Papadopoulos, 1985), thereby improving soil solution conditions, particularly for salt-sensitive crops. In general, with fertigation, protection of soil and groundwater from fertilizers on a sustainable basis can be achieved;
- Fertigation is particularly helpful to control the mobile forms of nutrients in soil. The nitrate form of N does not react with the soil exchange sites and is not held in soils. Nitrates move with other soluble salts to the wetted front. This requires that nitrate-N be applied, if possible, with every irrigation and at that concentration needed by the fertigated crop to satisfy its N requirement from one irrigation to the other (Papadopoulos, 1988; Hamdy, 1991).
- Fertigation has lately been introduced also with the furrow irrigation (Pereira et al., 1994). With such an approach, and provided that irrigation and nutrient application are based on real crop water and nutrient requirements, high efficiency of the nutrients can be reached. Apparently, under such conditions, residual fertilizers in soil are reduced and contamination of soils and groundwater by fertilizers is minimized.

The application of other chemicals with the irrigation water (chemigation) deserves particular attention. It might be a means of successful pest control but, if used without planning, it may also lead to environmental and health disaster.

CONCLUDING REMARKS AND RECOMMENDATIONS

To meet future food requirements, developing countries will have to increase their agricultural production. It is estimated that a large part of their increase will have to be secured from increased crop yields through agricultural intensification. In the context of sustainable agriculture and rural development, this intensification process will have to avoid possible environmental hazards. The necessity to increase agricultural production on a limited expandable cropping area leads to an intensification process which will require development of optimal land nutrients management, aiming to:

1. Increase agronomic and economic efficiency of sources of plant nutrients.
2. Avoid or, at least, limit nutrient losses and environmental degradation through plant nutrient depletion, thus contributing to agricultural

sustainability.

With particular reference to N management, to optimize crop nutrition and minimize losses, the following points should be considered:

- No more N for a given crop should be applied than is strictly needed, considering achievable yields, and taking into account soil mineralization, crop residues and organic sources, available N, and biological N fixation.
- Organic resources need to be considered and their use optimized, which means that quality and quantity have to be monitored. Appropriate types of fertilizers and application techniques have to be closely adapted to local conditions of crop, soil and climate.
- Irrigation techniques need to be improved, in particular to avoid *runoff*, *leaching*, *salinization* or *pounding*.
- *Environmental protection has to be integrated in any comprehensive development program*, which aims at increasing agricultural production and improving the farmer's family net incomes.
- Particular attention should be given to set up concrete recommendations, which could be accepted and promoted by any organization involved in agricultural activities.
- Sound policies and related strategies in the field of plant nutrition management will have to play a major role in the intensification process.
- To develop appropriate technologies for minimizing the impact of agrochemicals on surface and groundwater quality, it is necessary *to consider the properties of the chemical, and local agronomic and environmental conditions*. These technologies may or may not be applicable to other circumstances. What we know, and what we do not know, about agriculture's role in the water quality problems must be continually re-assessed as new research findings emerge. The following opportunities for research could contribute in bringing the contamination of water resources under control:
 1. Current ongoing research on the development of better agricultural and irrigation management practices should continue under a different set of environmental conditions in different parts of the world.
 2. More research is also needed on developing and implementing cost-effective diagnostic and monitoring methods to refine the management of soils, nutrients, pesticides, and irrigation and drainage water.

3. Research on government policies and regulations aimed at controlling groundwater pollution from agricultural sources is needed. The use of adequate computer models in predicting the behavior of irrigation practices can be developed on socio-economic impacts.
4. We have not yet fully understood the physical processes dictating the fate of chemicals and transport in soil and water system. More research is needed on the effects of microbial activity, pH, organic matter, and temperature on agrochemical behavior.
5. Research is needed to better understand the sources of pesticide contamination of groundwater. It is very important to know if the contamination resulted from *point* sources or *non-point* sources process.

REFERENCES

- Addiscott, T.M., A.P. Whitmore, and D.S. Powlson. 1991. Farming, fertilizers and the nitrate problem. C. A. B. International, Wallingford, Oxford, UK.
- Baker, J.L. 1992. *Understanding and reducing pesticide losses*. Coop. Ext. Serv., Iowa State University, Ames, IA. USA.
- Baker, J.L., and H.P. Johnson. 1979. The effect of tillage system on pesticides in runoff from small watersheds. *Trans. Amer. Soc. Agric. Eng.* 22: 554 – 559.
- Baker, J.L., and H.P. Johnson. 1983. Evaluating effectiveness of BMPs from field studies. In *Agricultural Management and Water Quality*. Iowa State University Press, Ames, IA. USA.
- Bockman, O.C., and T. Granli. 1991. Human health aspects of nitrate intake from food and water. p. 373. In M.L. Richardson (ed.) *Chemistry, agriculture, and the environment*. The Royal Soc. Chem., Cambridge. UK.
- Bouwer, H. 1987. Sustainable irrigated agriculture: Water resources management in the future. *Irrigation J.* 43 (6): 16–23.
- Bresler, E. 1997. Trickle-drip irrigation. principles and application to soil-water-management. *Adv. Agron.* 29:343–393.
- Brogan, J. C. (ed.). 1981. Nitrogen losses and surface run-off from landspreading of manures. Martinus Nijhoff/Dr. W. Junk Publ., The Hague, The Netherlands.
- Campbell, J.B., A.N. Davis, and P.J. Myhr. 1954. Methemoglobinemia of livestock caused by high nitrate contents of well water. *Carz. J. Camp. Med.* 18:93–101.
- Collison, S.E., and S.S. Walker, 1916. Loss of fertilizers by leaching. Univ. Florida, *Agric. Exp. Sta. Bull.* 132.
- De Roo, H.C. 1980. Nitrate fluctuation in groundwater as influenced by use of fertilizer. Connecticut *Agr. Exp. Sta. Bull.* 779, Univ. Connecticut, New Haven, CT.

- Dorsche, M.M., R.K.R. Scragg, A.J. McMichael, P.A. Baghurst, and K.F. Dyer. 1984. Congenital malformations and maternal drinking water supply in rural south Australia: A case control study. *Am. J. Epidemiol.* 119:473–486.
- Duxbury, J.M., and J.H. Peverly. 1978. Nitrogen and phosphorus losses from organic soils. *J. Environ. Qual.* 7:566–570.
- Endelman, F.J., D.R. Keeney, J.T. Gilmour, and P.G. Saffira. 1974. Nitrate and chloride movement in the Plainfield loamy sand under intensive irrigation. *J. Environ. Qual.* 3:295–298.
- European Economic Community. 1980. Council directive on the quality of water for human consumption. Official Journal No. 80/778, EEC L229, Luxembourg, Belgium.
- FAO (Food and Agriculture Organization of the United Nations). 1962–1987. *FAO Fert. Yearbooks*. FAO, Rome, Italy.
- FAO (Food and Agriculture Organization of the United Nations). 1988. Current World Fertilizer Situation and Outlook 1986/87–1992/93. FAO, Rome, Italy.
- Fertilizer Institute. 1993. Fertilizer facts and figures. Washington, DC, USA.
- Follett, R.F. (ed.). 1989. Nitrogen management and ground water protection. *Developments in Agricultural and Managed-Forest Ecology* 21. Elsevier Sci. Publ. Co. Amsterdam, The Netherlands.
- Follett, R.F., D.R. Keeney, and R.M. Cruse (ed.). 1991. Managing nitrogen for ground-water quality and profitability. *Soil Sci. Soc. Amer.*, Madison, WI.
- Gambrell, R.P., J.W. Gilliam, and S.B. Weed. 1975. Nitrogen losses from soils of the North Carolina Coastal Plains. *J. Environ. Qual.* 4:317–323.
- Germon, J. C. (ed.). 1989. *Management systems to reduce impact of nitrates*. Elsevier applied science, London, UK.
- Gilliam, J.W., T.J. Logan, and F.E. Broadbent. 1985. Fertilizer use in relation to the environment. p. 561–588. In O.P. Engelstad (ed.) *Fertilizer technology and use*. Soil Sci. Soc. Amer., Madison, WI, USA.
- Graetz, D.A., L.C. Hammond, and J.M. Davidson. 1973. Nitrate movement in a entic fine sand planted to millet. *Soil Crop Sci. Soc. FL.* 33:157 – 160.
- Groot, J. J. R., P. de Willigen, and E. L. J. Verberne. 1991. *Nitrogen turnover in soil-crop system*. Kluwer Academic Publ., Dordrecht, The Netherlands.
- Hallberg, G.R. 1989. Nitrate in groundwater in the United States. p. 35 – 74. In R.F. Follett (ed.) *Nitrogen management and groundwater protection*. Elsevier Sci. Publ., Amsterdam, The Netherlands.
- Hamdy, A. 1991. Fertigation prospects and problems in Italy. p. 207 – 214. In FAO Proc. "Fertigation/Chemigation". FAO, Rome, Italy.
- Hamdy, A., 1998. Fertigation prospects and problems. FAO Regional Commission of Land and Water Use in the Near East. 10 – 14 Dec. Amman, Jordan.
- Hargrove, W.L., A.L. Black, and J.V. Mannering. 1988. Cropping strategies for efficient use of water and nitrogen: introduction. p. 1 – 5. In W.L. Hargrove

- (ed.) *Cropping strategies for efficient use of water and nitrogen*. Amer. Soc. Agron., Crop Sci. Soc. Amer., and Soil Sci. Soc. Amer., Madison, WI, Special Publ. No. 51.
- Hauck, R. D. (ed.). 1984. *Nitrogen in crop production*. Amer. Soc. Agron., Crop Sci. Soc. Amer., Soil Sci. Soc. Amer., Madison, WI, USA.
- Henry, J. L., and W.A. Menely. 1993. Nitrates in Western Canadian groundwater. p. 1 – 31. Western Canada Fert. Assoc.
- Hill, M.J., G. Hawksworth, and G. Tattersall. 1973. Bacteria, nitrosamines and cancer of stomach. *Br. J. Cancer* 28: 562 – 567.
- International Institute for Sugar Beet Research. 1983. Symposium “Nitrogen and Sugar Beet.” Intern. Inst. Sugar Beet Res., Brussels, Belgium. (Soils and Fertilizers 47, Abstract 5204. 1984)
- Jenkinson, D. S., and K. A. Smith (ed.). 1988. Nitrogen efficiency in agricultural soils. *Elsevier Appl. Sci. Publ.*, London, UK.
- Kang, B. T., and J. van der Heide (ed.). 1985. Nitrogen management in farming systems in humid and subhumid tropics. Institute for Soil Fertility, Haren, The Netherlands, and Intern. Inst. Trop. Agric. (IITA), Ibadan, Nigeria.
- Kanwar, R.S., and Baker J.L. 1993. Tillage and chemical management effects on groundwater quality. p. 490–493. *In* Proc. National Conference on “Agricultural Research to Protect Water Quality”, Soil Conservation Service, Ankeny, IA, USA.
- Kanwar, R.S. 1996. Agro-chemicals and Water Management. p. 773 – 793. *In* L.S. Pereira, R.A. Feeds. J.R. Gilley and B. Lessafre (ed.) *Sustainability of irrigated agriculture*. Kluwer Academic Publ., Amsterdam.
- Keeney, D.R. 1982. Nitrogen management for maximum efficiency and minimum pollution. p.605 – 649. *In*: F.J. Stevenson (ed.) *Nitrogen in agricultural soils*, Agron. 22. Am. Soc. Agron., Madison, WI, USA.
- Keeney, D.R. 1986. Sources of nitrate to groundwater. *CRC Critical Rev. Environ. Control*, 16: 257 – 304.
- Kissel, D.E., C.W. Richardson, and E. Burnett. 1976. Losses of nitrogen in surface runoff in the blackland prairie of Texas. *J. Environ. Qual.* 5: 288 – 292.
- Klein, I., Levin I., B. Bar-Yosef, R. Assaf, and A. Berkovitz 1989. Drip nitrogen fertigation of “Starting Delicious” apple trees. *Plant Soil* 119: 305 – 314.
- Kovach, SP. 1983. Injection of fertilizers into drip irrigation systems for vegetables. *Citrus and Vegetables Magazine* 14: 40 – 47.
- Kross, B. C., G.R. Hallberg, D.R. Bruner, K. Cherryholmes, and J.K. Johnson, 1993. The nitrate contamination of private well water in Iowa. *Am. J. Pub. Health* 83 (2): 270 – 272.
- Lambers, H., J. J. Neeteson, and I. Stulen (ed.). 1986. Fundamental, ecological and agricultural aspects of nitrogen metabolism in higher plants. Martinus Nijhoff Publ., Dordrecht, The Netherlands.

- Legg, J.O., and J.J. Meisinger. 1982. Soil nitrogen budgets. p. 503-566. In F.J. Stevenson (ed.), *Nitrogen in agricultural soils*. Agron. No. 22. Amer. Soc. Agron., Madison, WI.
- Lowrance, R.R., and H.B. Pionke. 1989. Transformations and movement of nitrate in aquifer systems. p. 373 – 392. In: R.F. Follett (ed.), *Nitrogen management and groundwater protection*. Elsevier Sci. Publ., Amsterdam, The Netherlands.
- Malberg, J.W., E.P. Savage, and J. Osteryoung. 1978. Nitrates in drinking water and the early onset of hypertension. *Environ. Pollut.* 15: 155 – 160.
- Martin, D.L., J.R. Gilley, and R.W. Skaggs. 1991. Soil water balance and management. p. 199–235. In: R.F. Follett, D.R. Keeney, and R.M. Cruse (ed.), *Managing nitrogen for groundwater quality and farm profitability*. Soil Sci. Soc. Amer., Madison, WI, USA.
- Miller, M.H. 1979. Contribution of nitrogen and phosphorus to sub-surface drainage water from intensively cropped mineral and organic soils in Ontario. *J. Environ. Qual.* 8: 42 – 48.
- Nations, B.K., G.R. Hallberg, R.D. Libra, and R.S. Kanwar. 1993. Pesticide in precipitation: Implications for water quality monitoring. p. 142 – 145. In Proc. National Conference on Agricultural Research to Protect Water Quality. Soil Conservation Service, Ankeny, IA.
- Neeteson, J. J., and K. Dilz (ed.). 1985. Assessment of nitrogen fertilizer requirement. Inst. Soil Fert., and Netherlands Fert. Inst., Haren, The Netherlands.
- Newbould, P. 1989. The use of nitrogen fertilizer in agriculture. Where do we go practically and ecologically? *Plant Soil.* 115 :297–311.
- OECD (Organization for Economic Cooperation and Development). 1986. Water pollution by fertilizers and pesticides. OECD Publ., Paris, France.
- Papadopoulos, I. 1986. Nitrogen fertigation of greenhouse-grown cucumber. *Plant Soil.* 93: 87 – 93.
- Papadopoulos, I. 1988. Nitrogen fertigation of trickle irrigated potato. *Fert. Res.* 16: 157 – 167.
- Papadopoulos, I. 1996. Micro-irrigation systems and fertigation. p. 309 – 322. In NATO ARW on “Sustainability of Irrigated Agriculture” Vimeiro. March, 1994.
- Pionke, H.B., and R.R. Lowrance. 1991. Fate of nitrate in subsurface drainage water. p. 237-257. In R.F. Follett, D.R. Keeney, and R.M. Cruse (ed.) *Managing nitrogen for groundwater quality and farm profitability*. Soil Sci. Soc. Amer., Madison, WI, USA.
- Prins, W. H., and G. H. Arnold (ed.). 1980. The role of nitrogen in intensive grassland production. Centre for Agricultural Publishing and Documentation, Wageningen, The Netherlands.
- Schepers, J.S., and R.H. Fox. 1989. Estimation of N budgets for crops. p. 221 – 246.

- In R.F. Follett (ed.) *Nitrogen management and groundwater protection*. Elsevier, Amsterdam, The Netherlands.
- Schepers, J.S., K.D. Frank, and D.G. Watts. 1984. Influence of irrigation and nitrogen fertilization on groundwater quality. p. 21 – 32. *Proc. Int. Union of Geodesy and Geophysics*. Hamburg, West Germany.
- Schuman, G.E., R.E. Burwell, R.F. Piest, and R.G. Spomer. 1973. Nitrogen losses in surface runoff from agricultural watersheds on Missouri Valley loess. *J. Environ. Qual.* 2: 299 – 302.
- Sharpley, A.N., and S.J. Smith. 1991. Effects of cover crops on surface water quality. p. 41 – 49. In W.L. Hargrove (ed.) *Cover crops for clean water*. Soil Water Cons. Soc., Ankeny, IA, USA.
- Sharpley, A.N., S.J. Smith, and J.W. Naney. 1987. Environmental impact of agricultural nitrogen and phosphorus use. *J. Agric. Food Chem.* 35: 812 – 817.
- Snyder, G.H., and E.O. Burt. 1976. Nitrogen fertilization of Bermudagrass turf through an irrigation system. *J. Amer. Soc. Hort. Sci.* 101: 145 – 148.
- Spalding, R.F., and M.E. Exner. 1993. Occurrence of nitrate in groundwater - a review. *J. Environ. Qual.* 22: 392 – 402.
- Spalding, R.F., M.E. Burbach, and M.E. Exner. 1989. Pesticides in Nebraska's groundwater. *Groundwater Monit. Rev.* 9 (4): 126 – 133.
- Spalding, R.F., M.E. Exner, C.W. Lindau, and D.W. Eaton. 1982. Investigation of sources of groundwater nitrate contamination in the Burbank-Wallula area of Washington, USA. *J. Hydrology* 58: 307 – 324.
- Stevenson, F.J. 1982. Origin and distribution of nitrogen in soil. p. 155 – 215. In: F.J. Stevenson (ed.) *Nitrogen in agricultural soils*. Amer. Soc. Agron., Madison, WI, USA.
- Super, M., H. Heese, D. MacKenzie, W.S. Dempster, J. du'Pless, and J.J. Ferreira. 1981. An epidemiologic study of well-water nitrates in a group of southwest African Namibian infants. *Water Res.* 15: 1265 – 1270.
- U.S. Environmental Protection Agency. 1973. Water quality criteria. Washington, DC, USA.
- U.S. Public Health Service. 1962. Public health drinking water standards. USPHS, Washington, DC, USA.
- van der Meer, H.G., and M.G. van Uum-van Lohuyzen. 1986. The relationship between inputs and outputs of nitrogen in intensive grassland systems. p. 1 – 18. In H.G. van der Meer, J.C. Ryden and G.C. Ennik (ed.) *Nitrogen fluxes in intensive grassland systems*. Martinus Nijhoff Publ., Dordrecht, The Netherlands.
- Weisenburger, D. D. 1991. Potential health consequences of groundwater contaminations by nitrates in Nebraska. p. 309 – 315. In I. Bogardi and R.D. Kuzelka (ed.) *Nitrate contamination: exposure, consequence, and control*. NATO ASI Ser. G: Ecol. Sci. 30. Springer-Verlag, Berlin, Germany.

- Welte, E., and I. Szabolcs (ed.). 1989. Protection of water quality from harmful emissions with special regard to nitrate and heavy metals. Proc."The 5th International Symposium of CIEC". Intern. Sci. Centre of Fertilizers, Budapest, Hungary.
- World Health Organization. 1971. International standards for drinking water. World Health Organization, Geneva.

B. SHORT COMMUNICATIONS

POSTERS

Management of Fertigation of Protected Cucumber in Coastal Lebanon using Slightly Saline Water

Thérèse Atallah¹, Talal Darwish², Souhail Awad³,
and Maroun El-Moujabber³

¹*Faculty of Agricultural Sciences, Lebanese University,*

²*Lebanese National Scientific Research Council, ³Faculty of Agriculture, Holy Spirit University, Kaslik. Lebanon.*

INTRODUCTION

The use of drip irrigation is widespread in protected cultures along the coastline in Lebanon. Irrigation water, as shown in previous studies, does not present risks of salinity, according to the FAO classification (Ayers and Westcot, 1985). Water quality to the north of Beirut was satisfactory, except for a narrow strip close to the seashore (Ward, 1995). However, there is increasing evidence of the use of well waters with higher electrical conductivity at E_{cw} 0.7 - 3.0 dS/m near the sea to the south, about 25 km from Beirut, as well as in some localised areas in various production regions. This study focused on the management of fertigation when depending on slightly saline water in the production of protected cucumber, which, with tomato are the main crops. The objective was a comparison between the growers practice of alternating between irrigation water and fertigation water (Atallah et al., 1998) and the continuous application of nutrients with the water.

MATERIALS AND METHODS

The season was mainly in spring, with the growing period extending between early spring and the beginning of the summer. The crop nutrient requirements were based on results established previously in the region (Abou Jaoude, 1996). Treatments consisted of testing two irrigation frequencies: every 2 (T2) and 3 days (T3) combined with two modalities of fertigation, i.e., *continuous input with every irrigation* (C) and *discontinuous input with every other irrigation* (D), the water and nutrient inputs being otherwise equal by the end of the season. This was achieved by the use of the same stock solution with a modification of the dilution factor of the injector (Dosatron DI 16). Observations focused on the crop performance, including the number of fruits (commercial and non-commercial) as well as on the salinity buildup in the soil.

RESULTS

Irrigation water originated from a well on the site and presented an electrical conductivity of 1.13 dS/m, considered as slightly saline. In the continuously fertigated treatments, the fertigation solution reaching the plants had a constant value of 2.79 dS/m, whereas it varied between 1.13 and 4.56 dS/m in the discontinuous treatments (Table 1).

Table 1. Electrical conductivity values of solutions reaching the plants in fertigated treatments.

Treatments ¹		Electrical Conductivity	
		-----dS/m-----	
Continuously	T2C and T3C	2.79	
Discontinuously	T2D and T3D	1.13	4.56

¹See Material and Methods for details.

As a consequence of this stable salinity, the plant fertigated continuously every 2 days gave the best results. This included a larger yield contribution (30 %) compared to the other three treatments. In addition, the number of non-commercial fruits was significantly smaller, suggesting less stressful conditions. Consequently, this management practice ensured a stable, i.e., TD2 (25%), T3c (24%), and T3D (21%) salinity conditions and kept the moisture content of the soil relatively high. It provided, in fact, the better environment for the plants.

Another important aspect consisted of the soil salinity, as established on a saturated paste. By the end of the experiment, only in the T2C treatment, the soil EC was not significantly different from the beginning of the experiment; all other treatments had a significant increase in this variable. These results are remarkable considering the narrow separation between treatments. It also gives an indication of a management practice available to growers. This could, also, help to overcome the limitation due to slightly saline irrigation water.

ACKNOWLEDGEMENTS

This project was financially supported by the Lebanese National Scientific Research Council. It is also part of a regional project with the International Atomic Energy Agency, Vienna, on "Water balance and fertigation for crop improvement".

REFERENCES

Abou Jaoude, R. 1996. Fertigation of protected spring cucumber: nitrogen

- requirements (*in French*). Graduation project, Fac. Agric. Sci., Lebanese University, Beirut, Lebanon.
- Atallah T., T. Darwish, and M. Moujabber. 1998. Modality of fertigation of protected cucumber and nitrogen use efficiency under field conditions. Report in coordination meeting of RAW/5/002 "Water balance and fertigation for crop improvement" in Karadj, Iran. 31 Oct. - 4 Nov. 1998.
- Ayers, R.S., and D.W. Westcot. 1985. Water quality for agriculture Irrigation and Drainage Paper N°. 29. FAO, Rome, Italy.
- Ward, R. 1995. Cultural practices and soils fertility in greenhouses (*in French*). Graduation project, Fac. Agric. Sci., Lebanese University, Beirut, Lebanon.

Water Balance and Irrigation Scheduling of Cucumber under Protected Cropping

Maroun El Moujabber¹, Rouaida Abi Zeid Daou¹, Thérèse Attallah², Talal Darwish³, and Pierre Metri²

¹*Faculty of Agricultural Sciences, Holy Spirit University, Kaslik, Jounieh, Lebanon;* ²*Faculty of Agricultural Sciences, Lebanese University, Beirut, Lebanon;* ³*Lebanese National Council for Scientific Research, Beirut, Lebanon.*

ABSTRACT

The increased pressure on water resources in Lebanon highlights the necessity of optimizing water use, mainly for agriculture. Lebanese growers have adopted protected agriculture because it insures high productivity and an important added value to their products. Nowadays, greenhouses occupy around 1,350 ha, among which are 1,250 ha of cucumber alternated with tomato. Their production is relatively low due to poor cultural practices, mainly involving fertilizers and water application. Despite the importance of greenhouses, mainly on the coast, Lebanese growers lack the information background on water consumption and, as a consequence, on crops' fertilizer requirements.

Water requirements for greenhouse cucumber were determined and tested using mini-lysimeters (0.5 m²). The climatic demand inside unheated greenhouses was determined by the mean of small blue pans (20 cm height, diameter 50 cm) placed on a piece of wood at 10 cm above the soil. Several small pans were distributed to determine the variability of evaporation inside the greenhouse and, in several greenhouses with different crops and different vertical development of the same farm. The comparison of the evaporation in different localities on the coast completed the study. Evaporation was correlated with reference evapotranspiration.

Water requirements for greenhouse cucumber seems to be close to 250 mm. A coefficient (K) was calculated as a function of days after sowing for irrigation scheduling using these pans. Evaporation didn't differ significantly in the same greenhouse, not even in the same farm. By changing the location on the coast, the evaporation measured was almost the same. This is due to a similarity of the climate in this area, mainly radiation and air humidity. The evaporation was slightly higher in greenhouses near bare soil. The correlation between the evaporation and ETo, and the ratio Ep/ETo was equal to 0.5.

INTRODUCTION

The increased pressure on water resources in Lebanon highlights the necessity of optimizing water-use mainly for agriculture. Lebanese growers have adopted protected agriculture because it insures relatively higher productivity than conventional cropping and an important added value of their products. In addition, greenhouses allow the improvement of small land properties (less than 2 ha), which constitute over more than 46% of Lebanese farms (FAO, 1996).

Nowadays, greenhouses occupy around 1,350 ha among, of which 1,250 ha of cucumber alternated with tomato, had a total yield of 172,000 tons of tomato (127 t/ha) and 144,000 tons for cucumber (115.2 t/ha) in 1996, (Min. Agric., 1997). This production seems relatively low compared to production in other countries of the Middle East (Papadopoulos, 1995). This difference is probably due to a bad management of cultural practices, mainly of fertilizers and water application (Darwish, 1995).

Irrigation scheduling by the mean of climatic data is still generally used (Abou Khaled et al., 1988). In greenhouses, under the Mediterranean climate, the Class A pan evaporation method, as well as the radiation (FAO) and Priestley-Taylor methods, are presumed to give reliable results of water requirements of protected crops (de Graaf and Van den Ende, 1981; Doorenbos and Pruitt, 1984; Abou Hadid, 1993). The difficulty of an accurate measurement of the wind inside the greenhouse hinders the use of the Penman method (Castilla, 1993). The ease of management of the evaporation pan, without sophisticated equipment, is remarkable, but proper placement is necessary to avoid shading (El Fadl and Mounhim, 1993). However, the use of Class A pan seems to be a problem of space and circulation inside the greenhouse.

Despite the importance of greenhouses on the Lebanese coast, few studies have been carried out to determine water requirements of the protected crops. Except for Abou Khaled and Ammar (1971) and Nimah et al. (1990), Lebanese growers lack the information background on water consumption and, as a consequence, on fertilizer requirements of the crops.

MATERIALS AND METHODS

Water requirements for greenhouse cucumber were determined and tested using mini-lysimeters (0.5 m²). The climatic demand inside unheated greenhouses was determined by the mean of small blue pans (20 cm height, diameter of 50 cm) placed on a piece of wood at 10 cm from the soil, described by Westensen and Ismail, (1985). These pans were used with success in the Békaa Valley (Nimah et al., 1990). They have the advantage of small size, which avoids the problems of space and shading caused by the Class A pan. The evaporation from these pans is half of the evaporation from Class A pan.

The pan was placed in the middle of the greenhouse on the west side if the orientation of the greenhouse was north-south, and on the south side if it is east-west oriented. Attention was paid in order to avoid alga development inside the pan. Several small pans were distributed to determine the variability of evaporation inside the greenhouse on one hand, in several greenhouses with different crops and different vertical development (cucumber, tomato, and lettuce) of the same farm on the other hand.

The comparison of the evaporation in different localities on the Lebanese coast (humid area) completed the study. Finally, the evaporation of these pans was correlated with reference evapo-transpiration (E_{To}) calculated by the mean of Penman-Monteith formula. Water requirements of cucumber were determined in spring 1996; the results of the experiment over 120 days showed that total water consumption for greenhouse cucumber was close to 250 mm.

RESULTS

The actual evapo-transpiration of cucumber was correlated with the evaporation from the small pan in order to establish a coefficient (K) useful for irrigation scheduling by using these small pans. The coefficient was calculated as a function of days after sowing (Fig. 1). Potassium increased with (days after sowing) to reach a maximum of 1.5 when the plants are fully developed. This value is equivalent to a crop coefficient of K_c equal to 1.

The evaporation of the small pans distributed on both sides of the same greenhouse was almost the same (Fig 2). It is important to underline the fact that shading was avoided during all the period of observation. The evaporation of different pans distributed in different greenhouses of the same farm did not vary significantly (Fig. 3), although these greenhouses were oriented differently, and planted with different crops with different vertical development.

By changing the location on the coast (35 km distance), the evaporation measured was almost the same (Fig. 4). This is due to a similarity of the climate in this area, mainly radiation and air humidity. The evaporation was slightly higher in greenhouses near the bare soil. Doing the correlation between the evaporation inside greenhouses on the coast and the climatic demand outside in terms of reference evapo-transpiration, the ratio E_p/E_{To} varied between 0.45 and 0.55, and 0.5 on average for the whole season.

These results are a good step to establish continuity between research and agriculture development in Lebanon. These types of studies should be extended to other crops, and several experiments are needed to establish how to increase water-use efficiency in protected crops for water saving and reducing environmental hazards in Lebanon.

REFERENCES

- Abou-Hadid, A.F. 1993. Climatic factors in plastic houses and their possible effect on plant water requirements. *In* Workshop on environmentally sound use of water of agriculture under Mediterranean and arid climates. Bari, Italy.
- Abou Khaled, A., J. Van Hove, and A.R. Al Yassaki. 1988. Evapo-transpiration formulae adjusted to plastic tunnels in Egypt. Preliminary results. *FAO Tech. Rep.* No. 6653. Cairo, Egypt.
- Abou Khaled, A., and A. Ammar. 1971. Greenhouse effect of plastic tunnels. Third Sci. Meeting, 17 – 18 Dec., Lebanese Assoc. Adv. Sci., Beirut, Lebanon.
- Castilla, N., 1993. Greenhouse drip irrigation management for Mediterranean areas. *In* workshop on “Environmentally sound water of agriculture under Mediterranean and arid climates”. Bari, Italy.
- Darwish, T., 1995. Implementation and perspectives of fertigation in crop production in Lebanon. p. 235–248. Advanced short course on fertigation. 26 Nov. - 2 Dec. 1995, Beirut, Lebanon.
- Doorenbos, J., and W.O. Pruitt. 1984. Guidelines for predicting crop water requirements. FAO Irrigation and Drainage Paper 24. Rome, Italy.
- El Fadl, A., and H. Mounhim. 1993. Besoins en eau d’une culture de bananier “Dwarf Cavendish” menée sous-abri plastique. *In* workshop on “Environmentally sound use of water of agriculture under Mediterranean and arid climates”. Bari, Italy.
- FAO, 1996. Irrigation in the Near East Region in figures. *Water Reports*: 135 - 143.
- Graaf, R. de, and J.V.D. Ende. 1981. Transpiration and evapo-transpiration of glasshouse crops. *Acta Hort.*, 119: 147 – 158.
- Ministry of Agriculture. 1997. Current agricultural statistics. Beirut, Lebanon.
- Nimah, M., I. Rubeiz, and B. Miribi. 1990. A simple method for scheduling irrigation and measuring evapo-transpiration for vegetable crops. *Acta Hort.*, 278: 721 – 722.
- Papadopoulos, I. 1995. Micro-irrigation systems and fertigation. Advanced short course on fertigation, 26 Nov. – 2 Dec. 1995, Beirut, Lebanon.
- Westensen, G.L., and S.M. Ismail, 1985. Evaporation from washtubs covered by various size of screens. *Appl. Engin.Agric.* ASAE 1(2): 100 – 102.

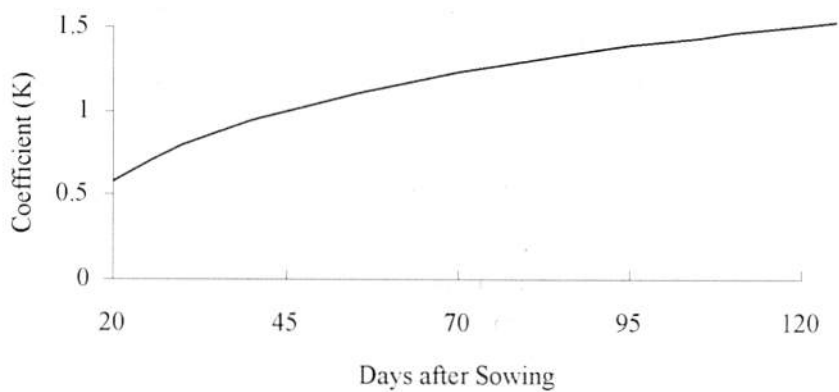


Fig. 1. K coefficient for greenhouse cucumber.

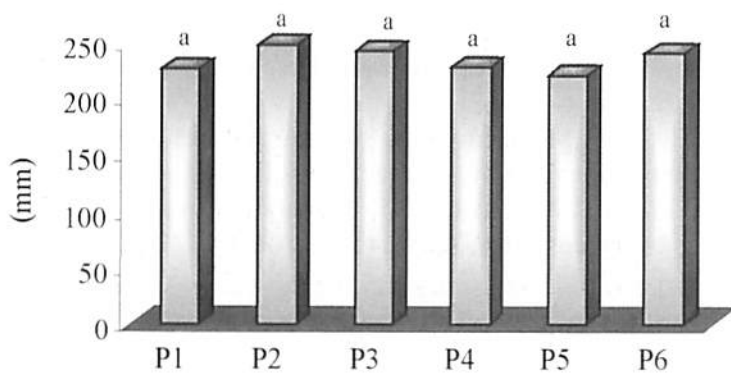


Fig. 2. Comparison of evaporation for six pans in the same greenhouse.

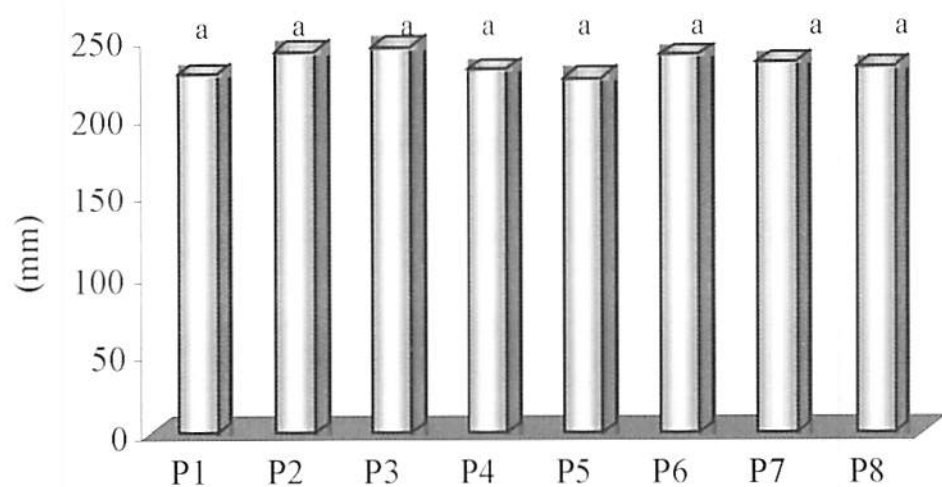


Fig. 3. Comparison of evaporation for eight pans in the same farm.

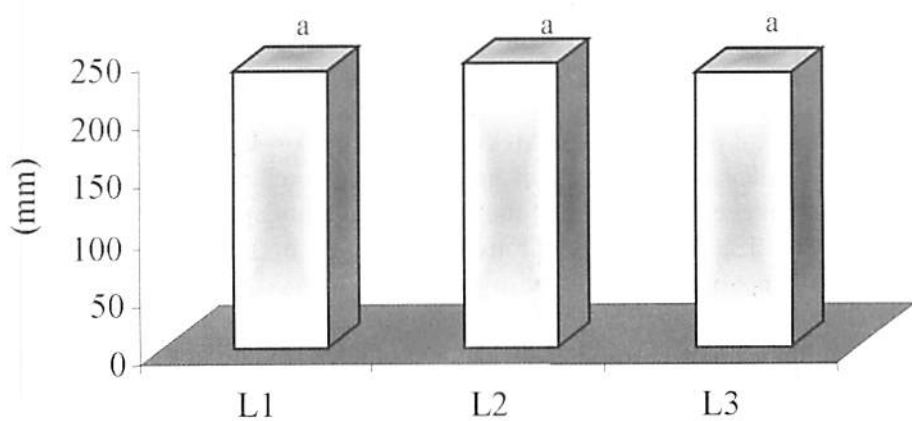


Fig. 4. Comparison of evaporation in three locations on the coast.

Irrigation Systems and Plant Nutrient Distribution with Depth in Orchard Soils

Bousselham Loudyi

Ecole Nationale d'Agriculture (ENA), Meknès, Morocco.

ABSTRACT

Phosphate (P) and potassium (K) fertilizers, which are generally applied on agricultural soils, accumulate in the top layers as a result of retention by soil constituents. In order to improve fertilizer efficiency, especially in orchards, efforts are made to have the applied nutrients placed near the root zone of trees. Such efforts include, in some cases, heavy applications before planting and attempts to localize the fertilizer at the vicinity of the plant roots in established plantings using special equipment. However, slight transport of P and K to deeper layers may occur under some conditions depending on soil properties and rainfall. This study was carried out in order to make comparisons of irrigation systems effects on major plant nutrients distribution in the soil profile, with either the traditional method of irrigation or fertigation. The nutrient levels were analyzed at three different depths (0-20, 20-40, 40-60 cm) in surface and drip-irrigated orchards.

INTRODUCTION

Average yields of orchards in the Meknes region are considered low by farmers, as well as by extension services. In general, variety selection, cultural practices, pruning are believed to be some of the reasons explaining such a situation. Strictly speaking, fertilization is not rigorously undertaken or rationally practiced, and deficiency symptoms are observed over most cultivated species. However, it is difficult to have precise information about fertilizer application. In the present study, attempt is made to evaluate the amount of applied fertilizers by measuring N, P, and K contents of irrigated orchard soils at three deep levels. Thus, evaluation of fertilizer applications effect on soil fertility is used to appreciate farmers' practices. Different tree species and two irrigation systems are compared.

MATERIAL AND METHODS

The study consisted of sampling different irrigated orchard soils in Meknes region and carrying out on fertility analyses. Soil sampling was done with auger at three

depths level: 0-20 cm, 20-40 cm, and 40-60 cm. In each cultivated field, 20 samples are taken in an area homogeneous in terms of soil and general conditions of growth. These samples were mixed to obtain composite samples for analysis. The analytical methods used are the following: phosphorus (Olsen method); potassium (exchangeable K by ammonium acetate pH 7), mineral nitrogen; and calcium carbonate (Bernard calcimeter).

RESULTS AND DISCUSSION

Data analysis are presented in two parts: Table 1 shows observed averages of different soil characteristics for different planted species without taking into account the irrigation system (Loudyi, 1998). Table 2 presents average analytical data in relation to irrigation system for all tree species, at one depth (0 – 20 cm) and average value for the deeper (20 – 40 cm; 40 – 60 cm layers).

Soil Characteristics

Most of the soils studied are characterized by a loamy texture. The upper horizon of some samples was sandy. Peaches and plums, in general, are planted on the lightest soils. In orchards soils, free calcium carbonate content varied between 1 to 20 % in most cases. In sandy soils, small quantities of free CaCO_3 are at least present in most cases.

Table 1. Soil characteristics as related to species¹.

	0-20 cm							20-40 cm	40-60 cm
	Pear	Apple	Almond	Peach	Prune	Wheat	Total	Total	Total
N, ppm	56	37	34	25	36	22	38	38	33
O. M., %	3.3	3.1	2.7	1.8	2.2	2.8	2.9	2.3	1.9
P, ppm	78	76	40	19	42	16	64	42	27
K, ppm	1206	916	312	247	329	340	769	458	331
Clay, %	26	26	23	20	22		25	26	29
CaCO_3 , %	9.8	6.0	11	5.9	4.9		7.0	8.2	9.8
PH	7.8	7.7	7.2	8.0	7.0		7.6	7.6	7.5

¹Values above 10 are rounded to nearest unit.

Soil organic matter content in this region is considered satisfactory in the Moroccan context, except for sandy soils. The average is 2.8% at the topsoil, and 2.2% for median horizon. Most (90%) of soils present had more than 2% at the top soil and more than 1.5% in the second horizon. The soils sampled can be considered to be in the Vertisol, Mollisol, Alfisol or Inceptisol orders. Their main constraints, in

some cases, are represented by high clay, sand, or CaCO_3 contents and by the occurrence of a calcic or a petrocalcic horizon in some areas.

Soil Fertility in Relation to Cultivated Species

Observed N, P and K contents change with species regardless of the considered horizon. In general, pear orchards presented higher inorganic N content than average for all horizons. A similar tendency was observed in the case of apple plantings. Nitrogen applications seem to be more important for apples and pears. For the other species, ranking changes in relation to horizons. Soil texture and organic matter contents are parameters which may contribute to explain such variations.

The observed ranking for P and K obtained values is the same in all horizons, i.e., Pearñ Appleñ Almondñ Plumñ Peach. Fertilization effects on P and K soil contents was more evident. It seems that apples and pears receive more fertilizers than the other species. In comparing orchards' soil fertility average to the average of 200 sampled wheat cultivated fields of the same region for the first and the second horizons, one may observe large differences with P and K fertilization.

Phosphorus applications were overall higher for orchards than cereals. In the case of K fertilization, apples and pears seem to be heavily fertilized compared to cereals, while for the other species such as almonds, plums and peaches; the observed results indicate lower levels. Moreover, it could be seen that depletion in the deeper horizons is appearing. At least, smaller quantities of K fertilizers than required, are used in the case of these species. Also, it was noted that P content in the deeper horizons was low compared to that of the topsoils, indicating that fertilizers are not properly incorporated into soil, and that fertilizer treatments to correct soil deficiency and improve its fertility are not practiced before tree installation.

Soil Fertility and Irrigation Systems

Tables 2 presents the averages for the parameters studied for surface (contour check) and drip irrigated orchards, considering all species confounded in one hand and apples only in the other hand. The results show that soil N, P, and K contents are high in the case of drip irrigation for all horizons, indicating more amount of applied fertilizers in this case. The apple values were higher than average confirming the tendency of farmers to use greater quantities of fertilizers for some species (apples and pears). Moreover, it seems that adoption of drip irrigation contributed more to the increase of both P and K levels in the deeper horizons.

Table 2. Soil characteristics in relation to irrigation systems¹.

	0-20 cm				20-40 cm				40-60 cm			
	Total Soils		Apple Soils		Total Soils		Apple Soils		Total Soils		Apple Soils	
	Furrow	Drip	Furrow	Drip	Furrow	Drip	Furrow	Drip	Furrow	Drip	Furrow	Drip
N, ppm	34	41	30	39	34	41	32	39	29	35	30	32
O. M., %	2.6	3.1	3.0	3.2	2.2	2.5	2.1	2.4	1.8	2.0	1.7	1.9
P, ppm	50	73	63	80	30	51	33	53	20	32	23	31
K, ppm	454	972	677	998	275	575	362	567	195	419	243	429
Clay, %	23	26	24	26	24	28	23	28	25	32	23	33
CaCO ₃ , %	6.5	7.4	6.3	5.8	8.0	8.3	9.7	6.9	8.3	10	9.6	7.9
pH	7.2	7.7	7.5	7.7	7.2	7.7	7.5	7.6	7.3	7.6	7.4	7.6

¹Values above 10 are rounded to nearest unit.

CONCLUSION

This study allows evaluation of fertilization practices in orchards in the Meknes area. The conclusion is that farmers apply more fertilizers for some species, such as apples and pears. *They do not correct soil deficiencies before planting.* Drip-irrigated orchards receive more fertilizers than surface-irrigated ones. Drip irrigation seems to contribute to the improvement of the fertility of the soil deeper horizons. The effect of fertilization on yield levels could not be quantified because of the lack of more detailed data in relation to other factors for each of the field studied. However, observations carried out in the area confirm the presence of many deficiency symptoms at different levels for several elements such as iron (Fe), zinc (Zn), copper (Cu). Such deficiencies may be related to the soil itself as well as to unbalanced nutrition resulting from inadequate fertilization.

REFERENCES

- Keeney, D.R., and D.W. Nelson. 1982. Nitrogen, inorganic forms. In A.L. Page (ed.) *Methods of soil analysis*. Chemical and microbiological properties, 2nd ed. Agron. N° 9, Part 2. Madison, WI., USA.
- Loudyi, B. 1998. Caractérisation de la fertilité des sols de la wilaya de Meknès et recommandations en matière d'emploi des engrais. DERD, MAMVA, Rabat, Morocco.

Fertigation: Useful Tool in Cyprus

Costas Hadjiparaskevas

Soils and Water Use Section, Nicosia, Cyprus

ABSTRACT

The problem with water *shortage* is expected to become more serious for many countries in the Near East in the future. Therefore, the agricultural sector, which is the main water consumer, will be adversely affected more than any other sector (UNEP, 1991/1992). The use of *modern irrigation systems* is, for the time being, the most *effective and efficient way for water and fertilizer use* (Papadopoulos, 1991). The introduction of these systems has improved water irrigation efficiency at high levels and enabled the rapid expansion of fertigation as a method of irrigation (Miller et al., 1981).

Fertigation is a very useful tool for the farmers, assuming that they are familiar with the theory and procedures of installation and implementation; otherwise, they will face various problems. It is now time to seriously consider the use of treated wastewater for agricultural purposes, because water demand for domestic purposes will increase due to the rapid development of urban and rural areas (WHO, 1989). Such water could be used safely through the modern pressurized irrigation systems. *Fertilizer industry companies* have to supply the market with suitable fertilizer types for fertigation at prices which are be affordable by their customers. Moreover, they have to investigate the market of the region for more active collaboration and expansion of their activities.

GENERAL VIEW

- In areas where there are large variations in rainfall and rain distribution from year to year, the target must be the highest possible water utilization.
- For the moment, the safest way for effective and efficient water/fertilizer can be achieved with fertigation.
- The introduction of modern irrigation systems helped the rapid spread of fertigation, especially in intensive agriculture.

cyprus

Fertigation Aims

Is not far from now the time at which “water” will be one of the most important subject of talks and discussions for many countries. Having this in mind, our duty is to find ways to prevent the problem. This can be done by obtaining maximum use of the applied water, maximum yield per unit of fertilizer and minimize environmental hazards. For the time being, the most promising method to reach the target is fertigation.

Is very well known that the agricultural sector is the main water consumer (for Cyprus, about 72%), especially in areas with arid or semi-arid climatic conditions like the Near East. In Cyprus, about 98% of the irrigated land is under the modern irrigation systems such as sprinkler, mini-sprinkler, and micro-irrigation – all compatible with fertigation. The average farm holding size is about 3.5 ha divided into 4.5 plots. This situation, of course, is not the most desirable for excellent implementation of the fertigation method.

The water shortage in Cyprus is one of the main factors for wide and rapid expansion of advanced irrigation systems. Moreover, the experimental results for many crops based on local research for fertigation helped farmers to accept the new approach, i.e., fertigation. At the same time, the Government, through the extension service, succeeded in informing farmers about its benefits in a short time, while, in a second stage persuaded them to accept and apply the fertigation method using all the existing education methods. Besides that, the government policy to subsidize the irrigation systems first, and then the fertigation systems, was a very successful effort.

Methodology

The introduction of a new methodology in an area implies the close collaboration of all sectors dealing with the subject for better results. After our experience, we are now in a position to say that the proper way to persuade farmers to accept fertigation is through education and with demonstrations at farmers’ level, i.e., the “Training and Visit System”.

The next step is to choose the proper injector for each case. There are many types in the market. Nitrogen is the element with the highest consumption due to the large quantities applied to plants. Usually, in intensive agriculture, farmers use ammonium nitrate, urea, liquid nitrogen and nitric acid. Day-by-day, more and more farmers are interested in phosphoric acid. The reason is the high soil pH value and slightly alkaline water. Monoammonium phosphate (MAP) is also widely used. With potassium fertilizers, the situation is simple because usually farmers are using potassium nitrate and only a small number is using liquid potassium. They don’t choose potassium chloride for greenhouse, floriculture and vegetable plantations due to the presence of chloride.

A great part of the fertilizer market belongs to the multi-nutrient fertilizer types enriched with trace elements. The tendency at intensive agriculture is to use “modern fertilizer types” with specific characteristics.

Why Fertigation?

There is no doubt that fertigation offers many advantages to the farmers. Cypriot farmers have accepted the method for specific reasons which are:

- There is no other method to minimize water and fertilizer losses.
- Each farmer can have a fertigation program based on crop nutrient and water requirements.
- Government and private agriculture extension service are in a position to advice anyone anywhere.
- Fertigation can be facilitated with Simple Barrel, Venturi, Dosatron (Piston System), or Fertigation Manager Computerized System.
- Irrigation Systems which are suitable for fertigation are: high-capacity sprinkler, low-capacity sprinkler, mini-sprinkler, roll line, and drip irrigation.

REFERENCES

- Miller, R.J., D.E. Rolston, R.S. Rauschkolb, and D.W. Wolfe. 1981. Labelled nitrogen uptake by drip irrigated tomatoes. *Agron. J.* 73: 265 – 270.
- Papadopoulos, I. 1991. Fertigation in Cyprus and some other countries of the Near East region. p. 67 – 82. FAO Proc. “Fertigation /Chemigation” Cairo, Egypt, 1991.
- UNEP (United Nations Environment Program). 1991/92. Environmental data report. Third Ed., Basil Blackwell, Oxford, UK.
- WHO (World Health Organization). 1989. Health guidelines for the use of wastewater in agriculture and aquaculture. *Report of a Scientific Group*. Tech. Rep. N^o. 778. Geneva, Switzerland.

Nitrogen-Water Relations of Tomato by Drip Fertigation

Sabri Oruç and Adem L. Bey

Research Institute of Rural Services, Ankara, Turkey.

INTRODUCTION

Traditional application of fertilizers with modern irrigation systems has serious limitations. Drip irrigation system, which is highly efficient in terms of water application, is also suitable for fertigation. Dissolved fertilizers, at concentrations required by crops, are conveyed through irrigation water in the wetted volume of soil where the active roots are concentrated. Fertigation is an effective means to control timing and placement of fertilizers, which improves fertilizer efficiency and reduces nutrient losses due to *volatilization*, *leaching*, and *fixation of nutrients* to less available forms.

The purpose of the research presented in this paper, based on experimental field data, is to examine the response of tomato to nitrogen (N) levels supplied through drip system, and to identify optimum N concentrations and water consumption of the crops.

MATERIAL AND METHODS

A field experiment with tomatoes (Falcon) was carried out in Ankara. Some physical and chemical properties of experimental soils were summarized in Table 1. The experimental design was a complete randomized blocks with four replicates. Treatments included five N levels which were 0, 22, 44, 66 and 88 mg N/l. Nitrogen fertilizer was supplied through the irrigation stream with every irrigation, which was operated three times in a week. Potassium (K) fertilizer was applied into the soil at 100 kg K_2O /ha during planting, while phosphorus (P) was given to the plants at 200 kg P_2O_5 /ha level through irrigation water once in the beginning of irrigation season.

In the experiment, 0.75 of evaporation from Class A pan was given as irrigation water. Each plot had dimensions of 4.8 m $\times$ 6.0 m = 28.8 m², with 120- and 50-cm spacing between and within rows, respectively. Tomato fruits were sampled periodically to analyze for dry matter, vitamin C content, and pH level. Seasonal water consumption by the crop was calculated through water depletion in

the effective rooting depth. Water-use efficiency of tomato was determined by dividing tomato yield by seasonal water consumption. At the end of the season, statistical analysis was performed to evaluate the effect of N on tomato yield.

Table 1. Some physical and chemical characters.

Soil Depth	pH	Saturation	Total Salts	Calcium Carbonate	Organic Matter	Available	
						Phosphorus	Potassium
---cm---				-----%-----		-----kg/ha-----	
0-20	8.0	54	0.5	31.8	1.10	32.0	854.1
20-40	8.1	54	0.5	28.9	0.98	26.3	725.4

RESULTS AND DISCUSSION

Tomatoes yields from individual plots are given in Table 2. Average yields were greatly increased by N as the first increment, with no further increase, i.e., from 43 t/ha with no added N to over 100 t/ha with added N. Nitrogen applications consistently increased the dry matter content of tomato fruits (Table 3). The increase obtained by 88 mg/l application was significant among consecutive N levels. A vitamin C content of tomato fruits was significantly decreased with increasing N levels. The highest vitamin C content (142.51 ppm) was in the control treatment. Increases in N application beyond 44 mg/l had no significant effects on C contents (Table 4).

Table 2. Tomato yields obtained in the experiment.

Nitrogen Level	Replicates				Mean	Mean
	1	2	3	4		
---mg /l---	-----12 m ² -----				--kg/plot--	---t/ha---
0	43.5	53.3	57.4	53.1	51.8	43
22	120.2	129.5	117.8	135.6	125.8	105
44	126.9	121.2	123.4	127.0	124.6	104
66	131.8	141.8	137.3	126.1	134.2	112
88	122.5	133.4	135.9	121.6	128.3	107

Table 3. Dry matter content of tomato fruits.

Nitrogen Level	Replicates				Mean
	1	2	3	4	
---mg /l---	-----%-----				
0	5.3	5.3	5.5	5.2	5.3
22	5.6	5.3	5.6	5.4	5.5
44	5.7	5.4	5.8	5.5	5.6
66	5.8	5.4	5.4	6.0	5.6
88	6.2	6.1	5.9	6.0	6.1

Table 4. Vitamin C content of tomato fruits.

Nitrogen Level	Replicates				Mean
	1	2	3	4	
---mg/l---	-----ppm-----				
0	141	139	147	143	143
22	115	128	116	119	120
44	105	104	105	117	108
66	98	98	97	107	100
88	98	92	94	81	91

The pH values of tomato fruits ranged from 4.4 to 4.6. In other words, these changes were within one unit. For this reason, these changes were not considered significantly different. Seasonal water consumption's and water-use efficiencies of treatments are given in Table 5. Water consumption varied from 596 to 627 mm, and water-use efficiencies were between 71 and 171 kg/ha/mm. Water-use efficiencies of all the N levels, being similar to each other, were significantly higher than the control.

Table 5. Seasonal water consumption and water use efficiencies.

Nitrogen Level	Seasonal Water Consumption	Water-Use Efficiency
---mg N/l---	-----mm-----	----kg /ha /mm----
0	609	70.9
22	606	173.0
44	596	174.3
66	601	186.2
88	627	170.6

CONCLUSION

Statistically optimum yield was obtained by the application of 22 mg N/l. Although this amount is close to that of traditional N application in the area, the yield obtained by fertigation is high enough to be an advantage of this system.

Adoption of Water-Soluble Fertilizer Technology through Micro-Injection System under Indian Conditions: Case Study

T. T. Fatif

ABSTRACT

India is emerging as one of the leading producers and exporters of fresh fruits, vegetables and flowers with use of "Hi-tech" production practices. The adoption of fertigation technology began in 1992 along with micro-irrigation systems, and both technologies are rapidly growing for precise and scientific water and nutrient management. Remarkable results have been achieved with use of water-soluble fertilizers through drip irrigation and foliar feeding in case of tablegrapes, pomegranate, banana, sugarcane, and oranges. The use of water-soluble fertilizers has also contributed significantly in improvement of yields and quality of flowers grown under controlled conditions. Foliar applications with speciality water-soluble fertilizers and micro-nutrients at critical growth and stages have also supplemented the nutritional requirements of economic crops.

Water-soluble fertilizers, being environment-friendly, have helped to preserve soil fertility by avoiding harmful salt accumulation in the soil profiles. India has vast potential to introduce and promote cost-effective, quality, speciality water-soluble fertilizers for balanced nutrition to a wide range of horticultural and field crops. I would like to project significance and impact of fertigation technology adopted by Indian farmers through a case study covering important fruit and vegetable crops.

Dr. T. T. Fatif
Director, Horticulture
Department of Agriculture
Government of India

Irrigation Water Quality and Nitrogen for Yield and Water-Use Efficiency of Barley (*Hordeum vulgare* L. Cv. Ardhaoui) in the Arid Climate of Southern Tunisia.

Kamel Nagaz¹, Nétij Ben Mechlia² and Atef Hamdy³

¹*Institut des Régions Arides, 4119 Médénine, Tunisia;*

²*INAT, 43, avenue Charles Nicolle, 2083 Tunis, Tunisia;*

³*IAM-Bari, 9 via Ceglie 70010 Valenzano, Bari, Italy*

ABSTRACT

A field study was carried out on sandy soil in the arid region of southern Tunisia to determine the effect of water quality and nitrogen (N) on yield and water-use efficiency of "Ardhaoui", a barley (*Hordeum vulgare* L.) cultivar. Two irrigation water qualities were used: canal water (3.4 dS/m) and saline water (11.7 dS/m). Nitrogen was applied at the rate of 0, 60, 120 and 180 kg/ha. Dry matter production was not significantly affected by water salinity. However, barley grain yield was significantly decreased under the use of saline water. The reduction in grain yield was mainly attributed to reduction in the number of spikes per m², number of grains per spike, and grain weight. Water-use efficiency decreased significantly with increasing irrigation water salinity. Crop yield, yield components and water-use efficiency increased with an increase in N rates. The rate of N at 180 kg/ha was appropriate to obtain good yield and efficient water-use of barley in southern Tunisia.

INTRODUCTION

Lack of adequate water is the limiting factor to crop production in the arid regions of southern Tunisia. However, most of the waters available for irrigation are frequently saline, often as groundwater. These saline waters must be used in this region, where supplemental water is needed to intensify agriculture. The salinity of irrigation water as a cause of yield reduction has been the subject of many investigations (Wagenet et al., 1980; Maas, 1990; Van Hoorn et al., 1993; Katerji et al., 1996). Barley is one of the important cereal crops of salt-affected soils and occupies a large cultivated area during the winter, and has been classified as a

hardy crop
in arid
Tunisia

irrigation water
water quality
water salinity
yield components
water use efficiency

tolerant plant (Maas and Hoffman, 1977). Kim et al. (1983) observed that irrigation with the high saline waters caused greater reduction in barley grain yield.

The performance of different barley cultivars under different N levels have been reported by Singh et al. (1985) and Singh and Chauhan (1991). These studies brought out the positive role of N fertilizer for growth, yield and quality of barley. The response of crop plants to irrigation with different water qualities and N fertilizer has been the subject of numerous studies. A field experiment conducted by Al-Tahir et al. (1997) showed that barley yields increased with an increase in N application rate up to 350 kg/ha under irrigation with fresh canal and saline waters. Substantial reduction in barley yields occurred with saline water for each N level; barley yields with fresh canal water and N rate of 250 kg/ha were comparable to yields with saline water 350 kg N /ha. However, in arid regions of Tunisia, little information is available on interaction effects of irrigation with different water qualities and N in sandy soils that are generally low in N. The present investigation was therefore undertaken to determine the effects of two water qualities and N application rates on yield and water-use efficiency of barley under arid conditions of southern Tunisia.

MATERIALS AND METHODS

The experiment was carried out at the experimental station of Arid Lands Institute at Ben Gardane, Médenine, Tunisia, during 1997-1998. The experimental soil was sandy, with electrical conductivity (Ece) range of 1.0 to 1.65 dS/m on a whole-profile basis (0–70 cm depth of soil). The total available soil water, calculated between field capacity and wilting point, was 60 mm. The climate of the region is typical of arid regions. The level of available N in the soil was very low (< 0.007 %), and thus was not taken into consideration in calculating the fertilizer for different treatments. The treatments, consisting of two irrigation-water qualities (canal and saline waters, Table 1) and four levels of N as ammonium nitrate (0, 60, 120 and 180 kg/ha), were arranged in randomized complete block design with three replicates.

Table 1. Chemical composition of irrigation waters.

Waters	Eci ¹	Ca ²⁺ +Mg ²⁺	Na ⁺	K ⁺	Cl ⁻	SO ₄ ²⁻	CO ₃ ²⁻ +HCO ₃ ⁻	SAR ² iw
	-dS/m-	-----meq/l-----						
Saline	11.7	43.5	71.5	2.0	74.0	40.0	3.0	15.3
Canal	3.4	9.9	21.3	3.0	24.0	9.0	1.3	10.0

¹Water Electrical Conductivity ° EC₁; ²Sodium Absorption Ratio, water ° SAR_{iw}.

Barley (*Hordeum vulgare* L. cv. Ardhaoui) was planted on 21 November, 1997 with seeding rate of 120 kg/ha. The plot size was 2'3 m² with row-to-row spacing of 15 cm. At planting time, 100 kg/ha each of P₂O₅ and K₂O and one-third of the N were applied as a basal dose; the remaining quantity of N was applied at tillering and stem-elongation stages. After seeding, all plots received canal water to promote germination.

Irrigation with two water qualities was initiated 2 weeks from emergence. The total amount of water applied was 402.5 mm to meet crop water requirements. In order to differentiate the treatments, the amount of irrigation water was kept the same in all treatments. This amount was the actual water requirement for irrigated barley based on a previous study at the experimental area (Nagaz and Ben Mechlia, 1998). The rainfall received during the experimental period (14, 46, and 36 mm in January, February and April, respectively) was adjusted for the irrigation water applied by subtracting from the total amount required for the particular day. Irrigation water was applied by surface irrigation. Since irrigation of barley at the study area is practised weekly and barley is drought-resistant crop, extension of irrigation for 10 days is a possibility. Therefore, irrigation frequency of 10 days was adopted in this study.

Barley was harvested on June 1, 1998. For each treatment, yield was evaluated on three sample areas. The criteria for analyzing yield were: final dry matter biomass of the aerial part of plants, grain yield, number of spikes per m², grain number per spike and 1000 grain-weight.

Water-use efficiency (WUE), defined as the yield obtained per unit of water consumed as evapotranspiration (ET) by the crop under consideration according to Doorenbos and Pruitt (1977), was calculated by the following formula:

$$W.U.E \text{ (kg/ha/mm)} = \text{Yield (kg/ha)} / \text{Water use (mm)}$$

Soil samples were collected with a 4-cm auger from 0–10, 10–20, 20–30, 30–40, 40–50, 50–60 and 60–70cm depths after the harvest of barley crop. Soil samples were analyzed for EC_e.

RESULTS AND DISCUSSION

Soil Salinity

The final salinity profiles (0-60 soil depth) indicated that average EC_e value in the upper 30 cm was 1.63 dS/m under irrigation with canal water (Fig. 1); the corresponding EC_e value with saline water was 4.0 dS/m, and all values decreased

with depth. The higher ECe values in the surface layers may be due to higher evaporation (about 7 mm/d) at the time when soil samples were collected. Similar trends in soil salinity buildup have also been reported by Elgabaly and Naguib (1965) and Bajwa et al. (1983).

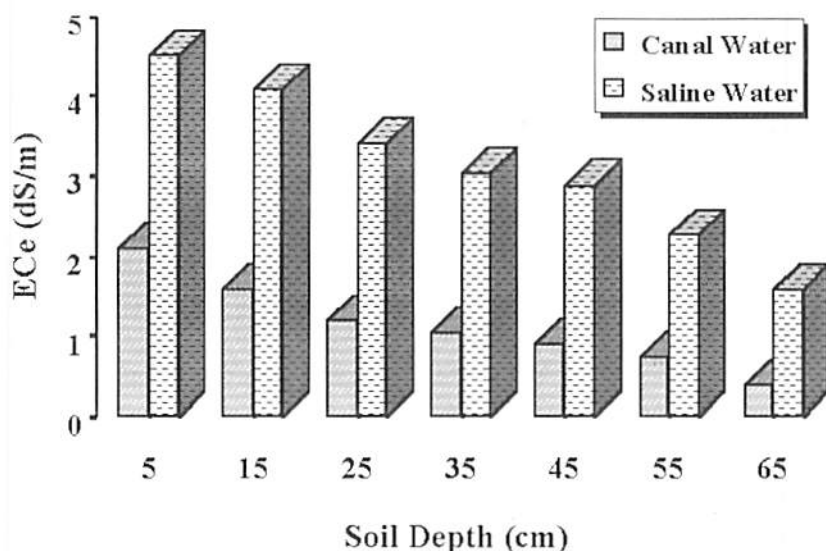


Fig. 1. Irrigation with two water qualities vs. canal and saline water soil profile after harvesting.

The mean ECe values under canal and saline water treatments were lower than the EC of irrigation waters used. Singh and Bhumbla (1968) observed that the extent of salt accumulation depended on soil texture and reported that in soils containing less than 10% clay the ECe values remained lower than the EC of the irrigation water. The leaching of soluble salts under the prevailing conditions was brought about by rainwater, occurring mainly during January to April.

Yield and Yield Components

Barley dry matter production was not significantly affected by water quality. However, grain yield was significantly decreased using saline water (Table 2). The reduction in grain yield was higher than that of dry matter production. The reduction in both parameters with saline water was 13.9 and 8.7 %, respectively, in comparison with that using canal water. The reduction in grain yield was attributed to reduction in grain number per spike, number of spikes per m² and grain weight.

Table 2. Yield and its components with varying water quality and nitrogen.

	Yield		Spike per m ²	Seed per Spike	1000-Seed Weight
	Grain	Dry Matter			
	-----t/ha-----				----g----
Water Quality					
Canal	3.39	5.97	211	49.8	47.8
Saline	2.92	5.44	195	46.6	46.5
LSD (5%)	0.38	0.81	14.2	2.1	1.3
Nitrogen (kg/ha)					
0	2.60	4.53	185	46.0	46.0
60	3.01	5.33	197	47.6	46.5
120	3.29	6.18	209	48.8	47.3
180	3.71	6.79	221	50.2	48.8
LSD (5%)	0.36	0.57	15	3.1	1.60

The crop was responsive to increasing N fertilizer level (Table 3). Yields of both grain and dry matter increased up to 180 kg/ha. The difference in grain yield was significant between different fertilizer rates, except 60 and 120 kg N /ha. However, the difference in dry matter production among various fertilizer rates was significant. The increase in yield may be attributed to improved growth and yield components due to N application.

The interaction effect between water quality and N on grain yield and dry matter production indicated that yield response to N was more pronounced under irrigation with canal water than with saline water (Table 3). It was noteworthy that under both saline and canal waters, maximum yield was obtained with 180 kg N/ha. The yield decreased as the rate of N decreased. Yields of both grain and dry matter decreased as the salinity of irrigation water increased for each N level. However, the reduction in yields due to increasing salinity was counteracted by increasing N level.

The grain yield obtained with canal water and 0 kg N/ha (2.77 t/ha) was the same as the yield obtained with saline water, when the N increased from 0 kg N/ha with canal water to 60 kg N/ha with saline water. The grain yield attained 3.06 t/ha when the N level increased to 120 kg/ha under irrigation with saline water. That yield is not significantly different from the yield obtained with canal water and 60 kg N/ha. The grain yield produced under irrigation with saline water and 180 kg N/ha was 3.43 t/ha, which is similar to the yield obtained with canal water and 120 kg N/ha, and higher than that obtained under irrigation with canal water and N level of 60 kg/ha.

Table 3. Water quality and nitrogen interaction vs grain yield and dry matter production.

Water Quality	N Application Rates (kg/ha)							
	Grain Yield				Dry Matter Yield			
	0	60	120	180	0	60	120	180
	-----t/ha-----							
Canal	2.77	3.27	3.52	3.99	4.83	5.72	6.29	7.03
Saline	2.43	2.75	3.06	3.43	4.23	4.94	6.06	6.55
LSD (5%)				0.28				7.0

For the dry matter production, the highest value (7.03 t/ha) was obtained with canal water and 180 kg N/ha. The dry matter production showed its lowest value (4.23 t/ha) with saline water and 0 kg N/ha. However, under irrigation with saline water and N levels of 60, 120 and 180 kg/ha, the yields were higher than those obtained with canal water and 0, 60 and 120 kg N/ha applications. Thus, the reduction in yields due to increasing irrigation-water salinity could be compensated by increasing N application. The findings of Hamdy and Samti (1995), Al-Tahir et al. (1997), Dregne and Mojallal (1969), Feigen (1982), Broabent and Nabashima (1971) also confirm these results.

Water-Use Efficiency

Under saline conditions, the same amount of seasonal applied water did not provide the same water-use efficiencies (Table 4). Values for grain and dry matter production were the lowest under the irrigation with saline water and the highest with canal water. Decreased WUE under irrigation with saline water is the consequence of significant yield reduction. Nagaz and Ben Mechlia (1998) reported similar results. However, WUE increased with an increase in N up to 180 kg /ha; values for grain were comparable with those reported by Bhutia and Singh (1990) and Hussain and Al-Jaloud (1998), and again are due to increased barley yields with N fertilization, as shown by Hussain and Al-Jaloud (1998).

Table 4. Water-use efficiency for grain and dry matter yield under different water qualities and nitrogen applications.

	Grain	Dry Matter
	-----kg/ha/mm-----	
Water Quality		
Canal	8.4	14.8
Saline	7.2	13.5
LSD (5%)	0.9	2.0
Nitrogen (kg/ha)		
0	6.4	11.2
60	7.4	13.2
120	8.1	15.3
180	9.2	16.8
LSD (5%)	0.9	1.4

CONCLUSIONS

Under arid conditions of southern Tunisia, the use of saline water for irrigation increased soil salinity and produced lower grain yield compared with canal water. Dry matter production was not reduced. A considerable reduction in water-use efficiency WUE of barley was observed under irrigation with saline water. Under both canal and saline waters, the effect of N fertilizer was also substantial with increasing levels. The yield, yield components and water-use efficiency increased significantly up to 180 kg N/ha. Application of N at 180 kg N/ha gave good yields and water-use efficiency in barley.

However, yield and water-use efficiency WUE increases due to fertilizer N were reduced as the salinity of irrigation water increased. The reduction in barley yields due to increasing irrigation-water salinity was compensated by increasing N rate. The significant interaction effect between water quality and N levels suggests that the N additions to barley should be related to the salinity of irrigation water. Thus, saline water could be another alternative for irrigation under similar experimental conditions especially with high N rates (120–180 kg/ha), which could eventually save more canal irrigation water for other cultivated crops.

REFERENCES

- Al-Tahir, O.A., Y.A. Al-Nabulsi, and A.M. Helalia. 1997. Effects of water quality and frequency of irrigation on growth and yield of barley (*Hordeum vulgare* L.). *Agric. Water Manage.* 34: 17 – 24.

- Bajwa, M.S., G.S. Hira, and N.T. Singh. 1983. Effect of sodium and bicarbonate irrigation waters on sodium accumulation and on maize and wheat yields in Northern India. *Irrig. Sci.* 4: 191 – 197.
- Bhutia, N.K., and G.D. Singh. 1990. Study on yield and water-use efficiency of barley in response to moisture regimes and sources of nitrogen. *Haryana J. Agron.* 6(1): 76 – 77.
- Broabent, F.E., and T. Nabashima. 1977. Effect of added salts on nitrogen mineralization in three California soils. *Soil Sci. Soc. Am. Proc.* 35: 457 – 460.
- Doorenbos, J., and W.D. Pruitt. 1977. Crop water requirements. *Irrigation and Drainage Paper 24*. FAO, Rome, Italy.
- Dregne, H.E., and H. Mojallal. 1969. Salt-fertilizer-specific ion interactions in soil. *New Mexico Agr. Sta. Bull.* 54: 66 – 70.
- Elgabaly, M.M., and N.M. Naguib. 1965. Effect of depth and salt concentration of ground water on salinization of soil. *Proc. Symp. Sodic Soils*, Budapest, 1964: 369 – 374.
- Feigen, A. 1982. Fertilization management of crops irrigated with saline waters. *Plant Soil*, 82: 285 – 299.
- Hamdy, A., and H. Samti. 1995. Interaction salinité-fertilization et son effet sur la production de la pomme de terre. Workshop on “Farm Sustainable use of Saline Water in Irrigation: Mediterranean Experiences”, 5 – 8 October, Hammamet, Tunisia, SectionA9: 1 – 24.
- Hussain, G., and A. AL-Jaloud. 1998. Effect of irrigation and nitrogen on yield, yield components and water use of barley in Saudi Arabia. *Agric. Water Manage.*, 36: 55 – 70.
- Katerji, N., J.W. Van Hoorn, A. Hamdy, and M. Mastrorilli. 1996. Effect of saline water on soil salinity and water stress, growth, and yield of maize and sunflower. *Agric. Water Manage.* 30: 237 – 249.
- Kim, C.S., J.W. Cho, and S.Y. Lee. 1993. Mechanism of salt tolerance of crop plants. *Korean J. Crop Sci.* 38(4): 371 – 376.
- Maas, E.V., and G. J. Hoffman. 1977. Crop salt tolerance - current assessment. *J. Irrig. Drainage Div.* ASCE 103: 115 – 134.
- Maas, E.V., 1990. Crop salt tolerance. p. 262-304. In Tanji (ed.) *Agricultural salinity assessment and management. ASCE Manuals and Reports on Engineering Practice* N° 71. Amer. Soc. Civil Eng., New York, USA.
- Nagaz, K., and N. Ben Mechlia. 1998. Barley production under different irrigation regimes with two water qualities. *Agric. Medit.* 128(1): 28 – 33.
- Singh, B., and D.R. Bhumbla. 1968. Effect of quality of irrigation water on soil proprieties. *J. Res. Punjab Agric Univ*, 5: 166 – 172.
- Singh, K.N., B.N. Misra, R.R. Patil, M. Prasad, and L. Lal. 1985. Response of late sown barley to nitrogen and phosphorus in northern India Plains. *Indian J. Agron.* 30: 488 – 496.

- Singh, R.V., and S.P.S. Chauhan. 1991. Response of barley to the levels and sources of nitrogen with and without zinc in relation to yield and water use under dryland conditions. *Bhartiya Krishi Anusandhan Patrika* 6: 43 – 48.
- Van Hoorn, J.W., N. Katerji, A. Hamdy, and M. Mastorilli. 1993. Effect of saline water on soil salinity and water stress, growth, and yield of wheat and potatoes. *Agric. Water Manage.*, 23: 247 – 265.
- Wagenet, R.J., W.F. Campbell, A.M. Bamatraf, and D.L. Turner. 1980. Salinity, irrigation frequency, and fertilization effects on barley. *Agron. J.* 72: 969 – 974.

The Use of Acid Fertilizers for Fertigation

Christos Tsiattalos

*Department of Agriculture, Land and Water Use, Ministry
of Agriculture. Natural Resources and Environment,
Nicosia, Cyprus*

ABSTRACT

The productivity of calcareous soils is reduced mainly due to their high pH values and due to the predominance of the Ca ions in the soil solution, (Lutz et al., 1972; Kafkafi and Bar-Yosef, 1980). A permanent solution of this problem by using appropriate soil amendments is very *difficult, time-consuming* and is *associated with high costs*. By using strong acids, in order to destroy the calcium carbonate of the soil, the soil structure will be also affected, resulting in detrimental effects on the physical and or on the chemical properties of the soil.

Through the fertigation system, the farmer has the facility to irrigate and to fertilize at the same time (Papadopoulos, 1985; Hamdy, 1991). It is now the appropriate time to learn that, by using the necessary acid fertilizers, a stock solution of strong acid character can be prepared it for fertigation. It is possible to lower the pH of the fertigation liquid, and the pH of the soil solution, the pre-supposition for better quality and higher yield. By this method, at least as long as the fertigation time lasts, the pH of the soil solution will be substantially lower than the soil pH.

Under these new conditions, during the whole fertigation time, not only the availability of the given nutrients will be safeguarded but, over and above, non-available soil nutrients will then become available (Lutz et al., 1972). The fertigation time can be increased using emitters of lower efficiency (Papadopoulos, 1995).

It is assumed that the fertilizers industry will not have any serious difficulties to produce and provide farmers with acid fertilizers at reasonable prices. The education of farmers as to how to use acid fertilizers with care and safety must be an important task of the extension service of each country and of the fertilizers industry itself.

INTRODUCTION

According to the plant physiology theory, the most intensive growth is expected under sub slightly-acid conditions, i.e., pH 6 – 7. In many Mediterranean countries

of the Near East region, Calcareous soils cover huge areas, if not the dominant soils of each country. The productivity of these soils is reduced mainly due to their high pH – values, and due to the predominance of the Ca – ions in the soil solution. The pH of these soils (soil : water = 1:5) is commonly established between 7.5 and 8.6. It is well understood that under these conditions not only the physiological plant development is affected, but also the availability of the plant nutrients will be diminished, resulting in disorders to the plant growth and adversely affecting the quality of the yield.

The most well-known reaction under these circumstances is probably the reaction of the orthophosphoric acid with the Ca ions to form tricalcium phosphates, which are not soluble, even under slightly acid conditions.

Ca-ions + Orthophosphoric acid → Calcium phosphate



As it can be easily understood, not all P applied to the soil is available to the plants, resulting in great losses to farmers in terms of high costs and low yield. Furthermore, under the high pH conditions, the availability of all plant nutrients is affected, especially that of the micronutrients. This means the root systems cannot absorb the necessary quantity of nutrients. The root system has the ability to select ions from the soil solution, even if they are in very small concentrations, but it has not the ability to exclude the absorption of those ions, which are in abundance in the soil solution. This means that when a given nutrient is in negligible quantities in the soil solution, the root system is trying to absorb it, but at the same time it absorbs greater and greater quantities of that element which is in abundance in the soil solution. New obstacles are created, resulting in disorders of the plant development in the leaves, lowering both the quantity, and the quantity of the production. The pressing question is “Can we overcome this problem?”

Acid Fertilizers: Possible Solution!

A permanent solution of this problem is very difficult. Somebody has to add large quantities of soil amendments, or to transport and deposit good quantity topsoil to cover the alkali soil, at least 35 to 40-cm depth. Both are time-consuming and associated with high costs. On the other hand, the use of strong acids in an attempt to destroy the $CaCO_3$ of the soil will destroy at the same time the structure of the soil, resulting in detrimental effects on the physical properties and the productivity of the soil. But the challenge of today, not of tomorrow, is to find a way to intensify

the production of the calcareous soil and increase its productivity, if not on a permanent basis, at least on a temporary one, securing higher yields and lowering the costs of production.

Through the fertigation system the farmer has the facility to irrigate and to fertilize at the same time. The irrigation water enriched with the necessary plant nutrients penetrates through the soil pores satisfying the water-holding capacity of the soil in the depth where the root system is active. The farmers are now accustomed to this method and they use it without any prejudice or restriction for their intensive cultivation, either under cover or not.

It is now the time to persuade them to use acid fertilizers, such as ureaphosphate, derivatives of nitric acid monopotassium phosphate, monoammonium phosphate and, if necessary, phosphoric acid, e.g., pH 5.5 – 6. Now by using this nutrient solution for fertigation of their cultivations, at least during the whole fertigation time, the pH of the soil solution will be lower. In order to increase the fertigation time, it is simply enough to use water emitters of lower efficiency. It is very important for the root system to have always enough water and nutrient at its disposal. This is why the farmers should fertigate when the water-holding capacity of the soil is almost 60% and to stop the fertigation when it will be almost 80% of its water-holding capacity. It is strongly believed that under these conditions the crop will have, during the whole fertigation time, optimum-growing conditions, and securing high yields of best quality. This method works and it can serve our targets if practical ways are found to educate the farmers to use it rationally.

The above-mentioned assumption is not a dream, or an unfeasible theory. It is now under investigation in Cyprus with promising results. But it can be an attempt by everybody in every country wishing to produce more cheaply and yields of higher quality. It is assumed that the fertilizer industry will not have any great problems or difficulties to produce and provide the necessary acid fertilizers. It should be appreciated if that would be done at reasonable prices. Certainly the use of these fertilizers demands much more awareness from the side of the users because these are more or less strong acids.

It is the common task of the fertilizer industry and of the extension services of each country to find all the practical ways to make this method popular among the farmers and to educate them to use the acid fertilizers with care and safety, securing their health and the health of their families. *Let us agriculturists of the extension service cooperate with the fertilizers industry and with the farmers of our countries to find the necessary solutions of this challenge.*

REFERENCES

- Hamdy, A. 1991. Fertigation prospects and problems in Italy. p. 207 – 214. *In* FAO Proc. "fertigation/Chemigation", FAO, Rome, Italy.

- Kafkafi, U., and B. Bar-Yosef. 1980. Trick irrigation and fertigation of tomatoes in high calcareous soils. *Agron. J.* 72: 893 – 897.
- Lutz, A.J., Jr., C.F. Genter, and G.W. Hawkins. 1974. Effect of soil pH on element concentration and uptake by maize. I: P, K, Ca; and Na. II: C, B, Zn, Mn, Mo, Al and Fe. *Agron. J.* 64: 581 – 583.
- Papadopoulos, I. 1985. Constant feeding of field-grown tomatoes irrigated with sulphate water. *Plant Soil* 88: 231–236.
- Papadopoulos, I. 1995. Micro-irrigation and fertigation in irrigated agriculture. p. 21-26. *In* Proc NATO Advanced Research Workshop. "Sustainability of Irrigated Agriculture" Mar. 1994. Vimeiro, Portugal.

Experiences on Nitrogen and Phosphorus Management under Drip Irrigation System in India

G. Dev

*Potash & Phosphate Institute of Canada, India Program,
Gurgaon 122 016, Haryana, India*

ABSTRACT

Fertilizer use under pressurized irrigation is essentially 'fertigation', which refers to fertilizer management through irrigation systems. This tool is of importance as water costs rise and issues related to environment dictate more precise control of both irrigation and applied nutrient, especially nitrogen (Dev, 1998). In India, this practice is of relatively recent introduction, and drip irrigation is of more particular interest than sprinkler systems. Currently, in India, the area under drip irrigation system covers 70,859 ha.

The practice of fertigation through drip irrigation system at field scale is being increasingly accepted by farmers in sugarcane cultivation in Maharashtra State, where the total area under drip irrigation is 32,824 ha, the maximum in any state in India, and where sugarcane cultivation covers 516,200 ha out of 21.42 million ha of total cropped area. Hapase et al. (1998) conducted a techno-economic feasibility study on drip irrigation in sugarcane and showed that this technology has great promise for success in the State.

Hapase et al. (1992) proposed that adoption of micro-irrigation techniques (as drip system) in sugarcane provides advantages over traditional flow-irrigation systems, since they enable placement of plant nutrients in liquid form at the root zone of the crop. The results from field experiments conducted over three crop seasons on the effect of different levels of N applied through drip irrigation system for yield and quality of sugarcane under surface drip are shown in Table 1 (Hapase et al., 1992).

It is seen that 75% of recommended N (250 kg N/ha viz. 25% reduction in applied N under drip system) recorded the highest cane yield (72.65 t/ha). Further, the water saving with the drip system was 45%, with 1.5 to 2 times increased water-use efficiency under drip irrigated plot as compared to control. Earlier, Kumar (1991) and Sastry (1991) also showed that fertigation through drip irrigation in sugarcane was advantageous.

Himachal Pradesh, a hilly state in north India, represents undulating topography, shallow soil depth, and has a shortage of irrigation water. However, it

represents a unique position for producing temperate fruits and off-season vegetables. The results of field experiments conducted under USAID "Hill Area Land and Water Development Project" on N use through drip irrigation (Bhandari, 1994) showed that the highest green pod yield increment (80% over the control) was obtained when N was applied through drip system as compared to 50% increase obtained with N broadcast under drip system (Table 2). The increase in yield over the control with N broadcast under the conventional irrigation system was 49% only. Similar results were obtained in tomato where yield, fruit set and total soluble solids were observed to be the highest with N applied under drip system.

Table 1. Sugar cane yield, irrigation water applied, and water-use efficiency.

Treatment		Irrigation Water	Yield	Water-Use
N % of Recommended	Irrigation	Applied		Efficiency
		---cm/ha---	---t/ha---	----t/ha/cm----
125	Drip	132.81	66.63	0.50
100	Drip	132.81	66.16	0.51
75	Drip	132.81	72.65	0.54
50	Drip	132.81	61.92	0.46
100	Conventional	248.62	66.30	0.26

(Pooled analysis of three-drop seasons)

Table 2. Green pea yields as affected by methods of fertilizer nitrogen application.

Treatment		Yield	Yield Increment
Irrigation	Application Method		
		-t/ha-	-----%------
Control		538	-
No irrigation	Broadcast	715	32.9
Drip	Broadcast	809	50.4
Flooding	Broadcast	802	49.1
Drip	Drip	970	80.3

The experiments conducted on apple showed that higher contents of N and K were maintained in the active soil root zone under drip system (Table 3), thereby increasing their availability for plant utilization. However, the depthwise mobility of P in the soil was negligible.

Table 3. Soil depthwise available nutrients under different irrigation methods.

Soil Depth	Method of Irrigation			Fertilizer
	None	Basin	Drip	
-cm-	-----ppm-----			
0-15	270	229	294	Nitrogen
15-30	212	201	299	
30-45	208	190	308	
45-60	190	188	319	
0-15	163	200	938	Phosphorus
15-30	50	59	748	
30-45	13	13	13	
45-60	14	14	14	
0-15	392	200	551	Potassium
15-30	308	225	674	
30-45	200	165	681	
45-60	192	147	392	

Effective fertigation requires an understanding of plant growth habits, nutrient requirement, rooting pattern, soil chemistry (solubility and mobility of nutrients), and water quality parameters (pH, sodium hazards, and toxic ions). Nakayama and Bucks (1986) listed different criteria that must be met with for applying nutrients through irrigation systems. The fertilizer materials must be compatible with salts contained in the irrigation water and they must not react with each other to form precipitates.

Urea is the most popular N fertilizer in Indian agriculture. It is highly soluble and when applied through a micro-irrigation system is less of a problem. Phosphorus in fertilizers is chemically converted into insoluble unavailable forms and gets fixed in both acid and alkaline or calcareous soils. The quality of water for Ca and Mg content is of great importance to avoid precipitation of applied P resulting in clogging of emitters with Ca and Mg phosphates. If P is applied in small amounts in soluble form several times during plant growth, P uptake efficiency and utilization are enhanced. This is possible with drip irrigation system.

REFERENCES

- Bhandari, A.R. 1994. Drip irrigation: An efficient system for water and fertilizer use in horticultural crops. Directorate of Horticulture, Himachal Pradesh, Shimla 171 002: 1 – 20.

- Dev, G. 1998. Fertigation: Fertilizer management through irrigation system. Lecture at Training Course on efficient management of fertilizer for increased yield and quality of field crops, fruit crops, vegetables and agro-forestry. Haryana Agricultural University, Hisar: 1 – 11.
- Hapase, D. G., D. G. Pawar, V. P. Patil, V. Arve, S. I. Shaha, and K. L. Khanna. 1998. Proc. Agric. Energy Round Table, India and Deccan Sugar Institute, Pune, India.
- Hapase, D. G., A. S. Deshmukh, and P. P. Shinde. 1992. *Proc. National Seminar on Drip Irrigation*. Oxford and IBH Publ. Co. Pvt. Ltd.: 55 – 65.
- Hapase, D. G., 1992. *Proc. FAI Seminar: Fertilizer and Food Security*. S V2: 1–5.
- Kumar, A., 1991. *Proc. National Seminar on Drip Irrigation*, Baroda: 16–21.
- Nakayama, F. S., and D. A. Bucks. 1986. Trickle irrigation for crop production. p. 317 – 340. Elsevier Sci. Publ., Amsterdam, The Netherlands.
- Sastry, K. S. 1991. *Proc. National Seminar on Modern Irrigation Techniques in Sugarcane Farming Systems*, Pune, India.

A Schematic Approach for Fertilization Scheduling

Medany, M.A.¹, M.A. Cadel-Rabl¹ and A.F. Abou-Hadid²

¹*The Central Laboratory for Agricultural Climate, Giza,*

²*Department of Horticulture, Faculty of Agriculture,
Ain Shams University, Cairo, Egypt*

ABSTRACT

The current work represents a method for calculating a crop fertilization program utilizing the agro-meteorological information. The procedure is implemented using special software called FERTICLAC which produced by the Central Laboratory for Agricultural Climate (CLAC). It aims at estimating fertilizer scheduling, mainly nitrogen, potassium, phosphorus and magnesium, as well as iron and manganese. The program has several forms, including *crop*, *location* and *soil* (to calculate water requirements), in addition to *previous crop*, *soil problems* (salinity, alkalinity and carbonates), *available fertilizer* (organic and inorganic) and *nutrient response curve*. The program can be linked to other software developed in CLAC to estimate potential evapo-transpiration and other agro-meteorological applications.

The user will have the option to select from a list any available fertilizers to estimate units of each individual nutrient form in that fertilizer, as well as its physical and chemical properties. The user also will be capable of editing the response curve for the above - mentioned nutrients. The program calculates the fertilization schedule according to the crop type and age, soil type, location, and available fertilizers. The software has options to run, in Arabic or English, with capabilities to be adapted to any other languages after translating a list of words from English during installation.

In fertigation systems, the software will provide the end-user with the quantity of fertilizers that should be utilized according to the selected type of fertilizer. Any fertilizer that has sufficient chemical analysis of nutrients can be used. The selection of fertilizer depends on availability in the market, price, and solubility. The following flow chart shows the sequence used in the procedure to estimate the daily nutrient requirements of N, P and K fertilizers.

Figure 1 shows the daily nutrient and fertilizer requirement for maize using FERTICLAC as a function of *yield goal*, *previous crop*, *soil and water analysis* and *plant age*.

Fertilizer Requirement Process Chart (FERTICLAC)

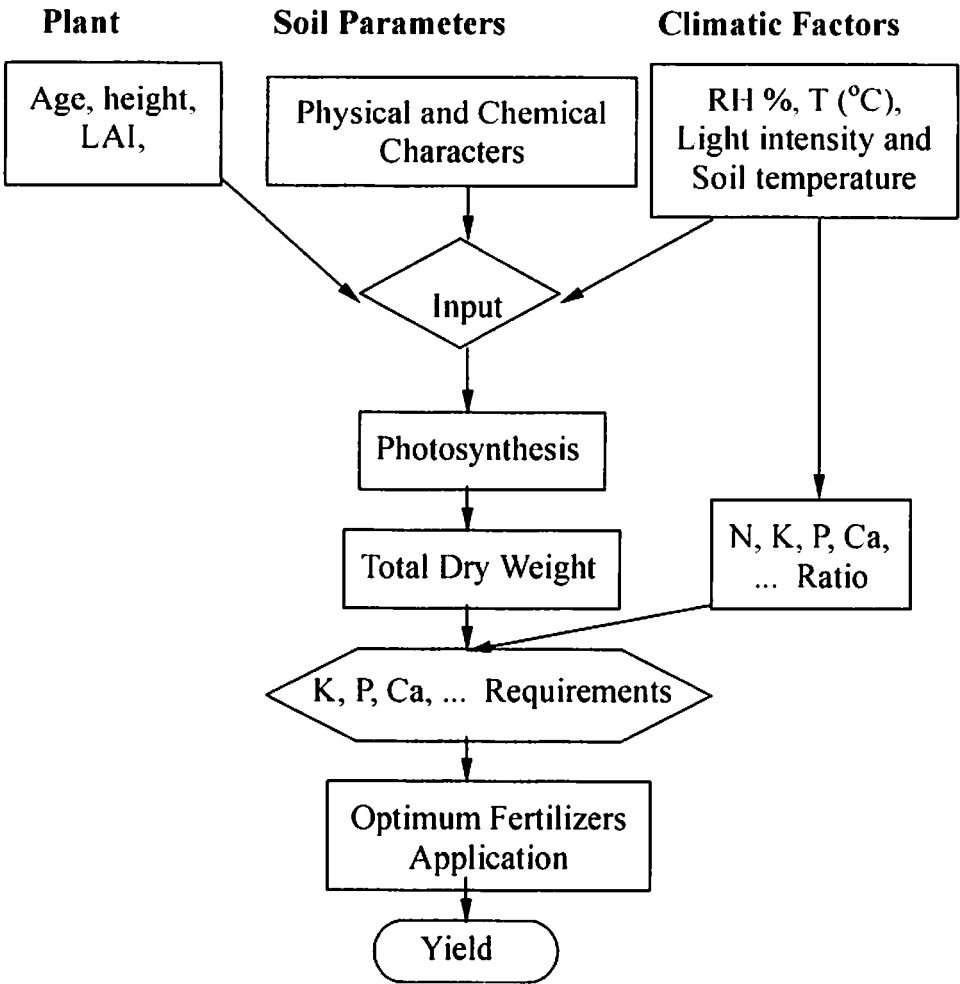


Figure 1. The daily nutrient requirement for maize using FERTICLAC as a function of yield goal, previous crop, soil and water analysis and plant age.

Efficiency of Phosphoric Acid Fertigation in a Fine-Textured Calcareous Soil

Naïma Kolsi¹, Ali Mhiri¹, and Jan Vanderdeelen²

¹*Institut National Agronomique de Tunisie (INAT), Tunis, Tunisia,* ²*Dept. Applied Analytical and Physical Chemistry, Faculty of Agricultural and Applied Biological Sciences, University of Gent, Belgium*

INTRODUCTION

Phosphorus fertilization shows low mobility and availability when applied as a solid form onto the soil. In calcareous and fine-textured soils, a complex set of sorption and precipitation processes reduces mobility, thus affecting P in the rhizosphere. Phosphoric acid fertigation is aimed at supplying P to plants in available form at appropriate times according to the specific crop requirements. The aim of this brief study was to compare the phosphoric acid fertigation efficiency compared to that of triple superphosphate (TSP).

MATERIALS AND METHODS

The soil used in the study was calcareous (40% CaCO₃) and fine-textured (37 % clay) in the Mornag area and a loamy clay in the Tunis area. Experiments in columns and field plots were conducted to determine the P mobility when applied as phosphoric acid. Comparison between phosphoric acid fertigation and TSP application was done using ryegrass (*Lolium multifolium* var. *Lemtal*) in pot experiments using 1 kg of soil per pot. In the field, drip-irrigated plots involved tomato (*Lycopersicum esculentum*. Mill. var. *Rio Grande*). The Mornag soil, containing 10 to 21 ppm P, was used for both crop experiment.

For the tomato crop, a control (T) and one application at 59 kg P /ha was used either in the solid form (S), while the liquid was added at once (L) or in split application (F). Fertilizer TSP was mixed into the upper 10-cm layer for each tomato plant. For the pot experiment, two rates (50 and 100 mg /kg soil) as solid (S₁ and S₂) and liquid form (L₁ and L₂), including the control (T), were used. The two fertilizers were labelled (³²P), while the TSP was finely ground (0.16 mm) and mixed with the soil. Ryegrass was harvested after 6, 11, and 15 weeks, Olsen P was determined at the end of the experiment. For the tomato crop, P content, yield, and P uptake were recorded.

calcareous soils

Availability of P Added as Phosphoric Acid

As P concentration in the fertigation solution increased, the P sorption rate increased and the available P decreased. This P concentration has to be optimized to improve the phosphoric acid fertigation efficiency. *Permanent soil wetting and additional irrigation* improved the P availability, with an increase of 51 to 89 kg P/ha in the top layer of the soil. Subsequent irrigation after fertigation showed a low P concentration (0.2 to 0.3 ppm P) in the leachate. When soils have a low organic matter (OM) content (1.28 %), increasing the OM content will positively affect P in the leachate, and is likely to induce a higher percolation rate probably due to soluble organic P components. In these conditions, 12% of the P added is leached. In the soils, the P movement shows P *mobility* attaining 30 cm in the column experiment and 50 cm in the field.

Yield and Fertigation Efficiency

In field plots under tomato crop and greenhouse pots with ryegrass, both the phosphoric acid and TSP fertilization displayed a significant effect on yield (Table 1). The solid form seems to be superior for tomato in relation to yield. For ryegrass, the two fertilizers behaved almost similarly. It was observed that fertilizer-use efficiency was higher and more available P in the soil at the end of the experiment using the phosphoric acid (Table 2). Also, the fertilizer-use efficiency was higher as well as the pool of available P more extended, showing a clearly positive tendency towards the beneficial effect of the liquid as a starter fertilizer.

Table 1. Tomato fruit yield characteristics ¹.

Treatments	P Uptake	Yield	Fruits/Plant	Fresh Fruit/ Plant	Fruit Weight	P Uptake
	-kg P/ha-	-t fruit/ha-	---No.---	----g----	---g---	-mg /plant-
Control	11.2 b	37.3 b	20.8 b	1195 b	57.1 a	360 b
Solid	22.1 a	71.9 a	38.9 a	2292 a	59.0 a	708 a
Liquid	18.3 ab	58.9 ab	31.7 ab	1894 ab	60.1 a	588 ab
Split application	20.1 ab	65.3 ab	36.4 ab	2085 ab	57.2 a	665 ab

¹ Mean with same letters not significant (Duncan's Multiple Range Test).

Table 2. Phosphorus distribution in ryegrass and fertilizer-use efficiency.

Treatments	Derived from Fertilizer				
	Plant P Derived From Fertilizer	Olsen P	Non-Available Soil P	Fertilizer-Use Efficiency	
	-mg P/pot-	-----% of P added-----			---%---
Control	0.565	11.4	24.7	63.9	11.0
Solid ₁	3.866	7.7	7.4	84.8	7.5
Solid ₂	7.230	7.2	4.0	88.8	6.9
Liquid ₁	4.602	9.2	11.9	78.9	8.9
Liquid ₂	7.981	8.0	6.7	85.3	7.7

CONCLUSION

Phosphoric acid fertigation seems to improve the P mobility in the calcareous and fine textured soils, resulting in a homogeneous P distribution in the soil volume. However, the yield does not seem to be affected because TSP is highly soluble, and moreover, it is properly distributed in the soil as well. As a higher P available pool will be build up in the soil, the beneficial effect of the liquid fertilizer is obvious. Probably, the difference between both fertilizers will become more evident when properly applied under field conditions.

Efficiency of Phosphate Rock as Fertilizer in Irrigated Saline Conditions of the Algerian Sahara

Amor Halitim¹, N. Abdenbi¹, and A. Masmoudi²

¹University of Batna, ²University of Biskra, Algeria

ABSTRACT

The availability of phosphorus in soil depends strongly on its behaviour (phenomena of *retrogradation* and *precipitation* limit its availability). However, several works indicate that Saharian soils are deficient in this component, which compromises their level of fertility and production potential. Algeria has important phosphate rock (PR) resources (Djebel Onk). The success of direct application of this product in order to overcome this soil P deficiency depends both on some factors related to phosphate rock and on some factors related to soil. Generally, phosphate rocks are recommended for acid and slightly alkaline soils. However, in Sahara, there are large areas, which are either saline soils or the soils irrigated with saline water.

In order to provide research relating to direct application of phosphate rock in agriculture on a range of soils, the objective of this work was to study the phosphate rock efficiency as a fertiliser in irrigated Saharian soils in comparison with triple superphosphate (TSP). Indeed, we carried out the experiment in the laboratory as well as in the greenhouse and in the field, with or without a crop i.e., barley.

The results of laboratory experiments show that the process of dissolution is clearly influenced by salts (Fig. 1). Similarly, we noticed that sodicity contributed variably towards the solubility of phosphate rock. The best solubility was obtained with a high sodium absorption ratio (Fig. 2, 3).

The results obtained in the fields and trials pots show that, the triple superphosphate have rapid action and give good results in short term (Fig. 4). Where as action of phosphate rock is slow and modest in the same period in comparison with TSP, but becomes very positive in the long term (Fig. 5).

In Saharian sandy soils, which have permanent irrigation with a salty water (EC = 5.37, sodic, SAR = 8.9), TSP solubilization and its removal from root area, despite the richness of soil in Ca⁺⁺ cation, is promoted. Phosphate rock, under the same conditions, is subjected to a slowing down and continuous dissolution. At the end of the study (harvesting), the contents of soluble P of soils were very near in different treatments with two kind of fertilizers (triple superphosphate and phosphate rock).

REFERENCES

- Curtin, D., F. Sells, and H. Stephun. 1992. Influence of salt concentration and sodicity on the solubility of phosphate in soils. *J. Soil Sci.* 153: 409 – 416.
- Halitim, A. 1988. Sols des régions arides d'Algérie. Ed. OPU.
- Lehr, J.J., and J.C. Van Wesemael. 1952. The influence of neutral pH on the solubility of soil phosphate. *J. Soil Sci.*, 3: 125 – 135.
- Robinson, J.S., and J.K. Syers. 1990. A critical evolution of the factors influencing the dissolution Gafsa phosphate rock. *J. Soil Sci.*, 41: 597 – 605.
- Starostka, R.W., and W.L. Hill. 1955. Influence of soluble salt on the solubility of and plant response to dicalcium phosphate. *Soil Sci. Soc.* p: 193 – 198.

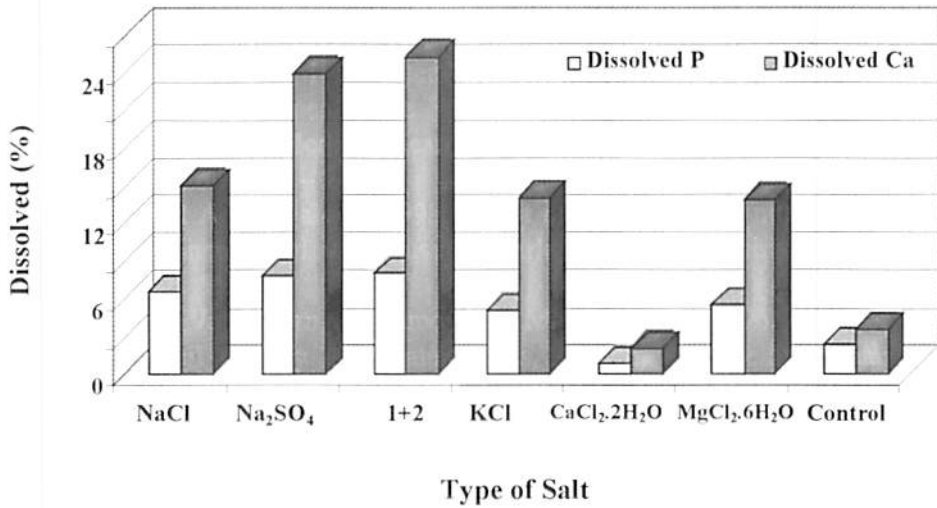


Fig. 1. Effect of the different types of salts on the solubilisation of phosphate rock (D.O 20 %)

phosphate fertilizers
phosphores
irrigated farming
algeria, deserts

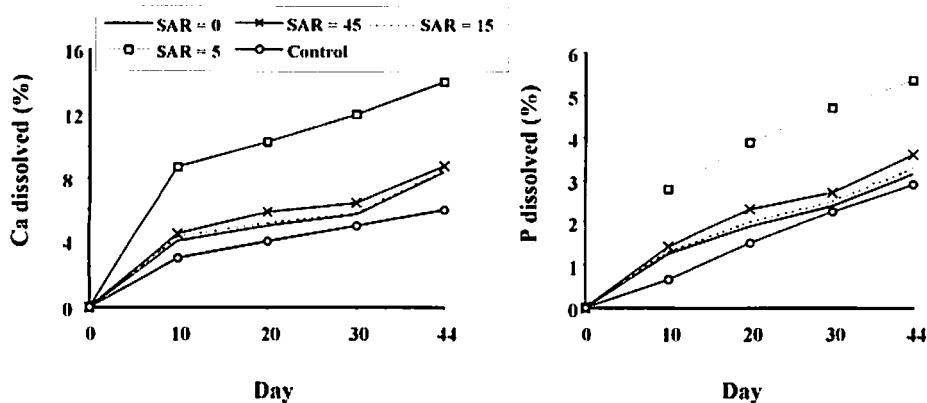


Fig. 2. Effect of the sodium absorption ratio on the solubilization of phosphate rock to an EC=2dS/m.

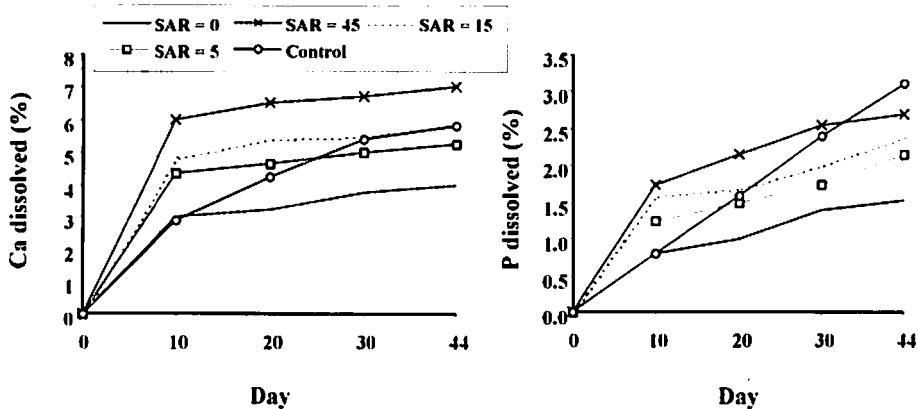


Fig. 3. Effect of the sodium adsorption on the solubilization of the phosphate rock to an EC=2dS/m.

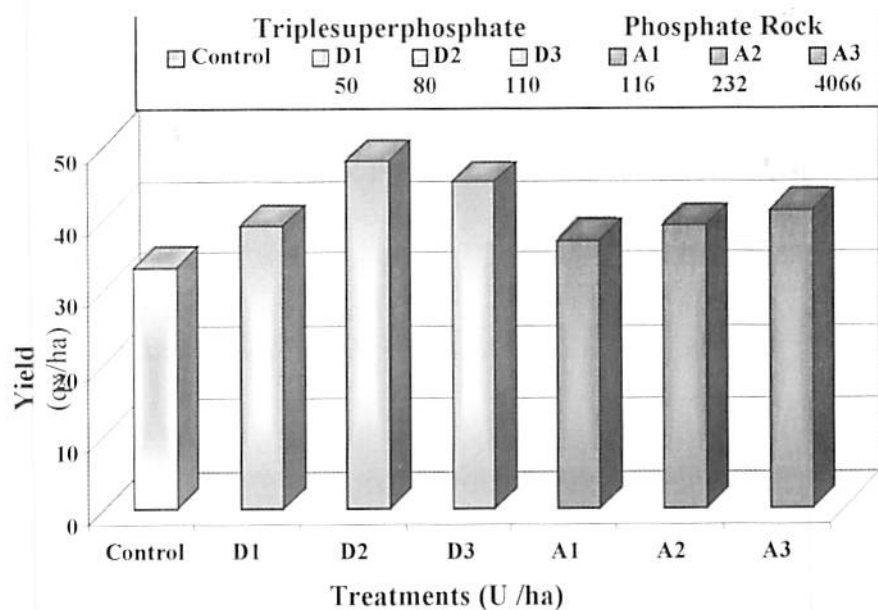


Fig. 4. Effect of triplesuperphosphate and phosphate rock at barley tillering.

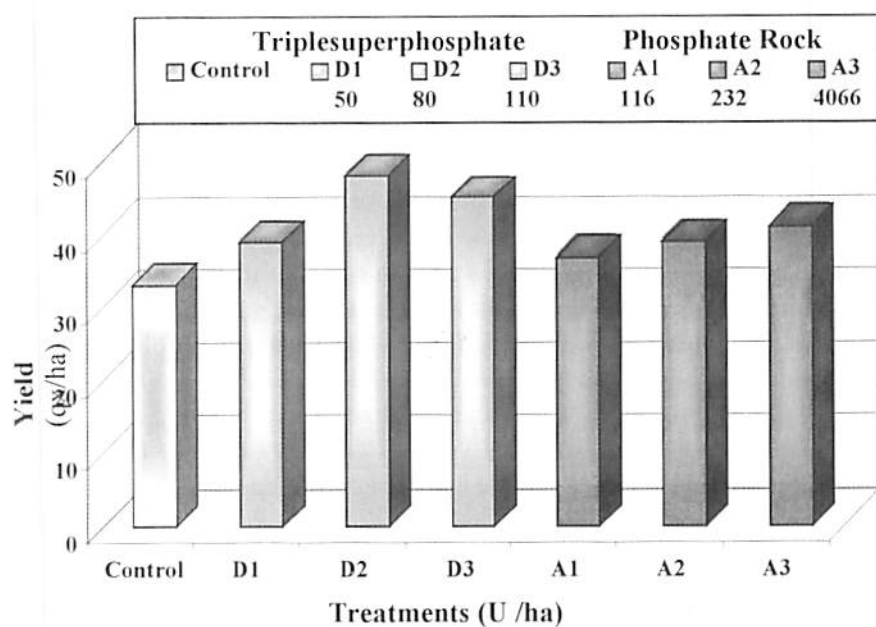


Fig. 5. Evolution of the yield of barley.

Cotton Fertigation Practices in Syria: Nitrogen and Water Effects

¹Moussadak Janat and ²George Somi

¹*Atomic Energy Commission of Syria, Agriculture Department, and* ²*Ministry of Agriculture and Agrarian Reform, Irrigation Directorate, Damascus, Syria*

INTRODUCTION

Fertigation is the precise application of irrigation water and plant nutrients through the irrigation system to match the current demands of the crop. It has been recently introduced to Syria, and is likely to be a promising practice for the most economical crops. The advantages of introducing fertigation are many. The most important are: minimizing losses of water and plant nutrients (Papadopoulos, 1985), improving fertilizer-use efficiency (Papadopoulos, 1992, 1988; Miller et al., 1982), supplying plant nutrients directly to the root zone and, therefore, optimizing the nutrient balance in the soil (Bresler, 1977), minimizing the use of soil as a storage reservoir for nutrients and water (Phene and Beale, 1976), having flexibility in timing fertilizer application in relation to crop current demand (Bresler, 1977), and improving yield and water-use efficiency (Radin et al., 1992).

In the arid and semi-arid zones, where water is scarce and costly, water-use efficiency must be an important economic consideration in order to benefit from the few available sources. Drip irrigation as a mean of water management is the most promising practice to be considered. It has been extensively used on cotton (Halevy and Kramer, 1986; Smith et al., 1991; Mauney and Henderix, 1988; Radin et al., 1992; Papadopoulos and Stylianou, 1988; Ibrahim et al., 1997); in most cases, improved cotton yield and/or water and fertilizer-use efficiency occurred. The objectives of this study were to assess yield of cotton, water-use efficiency, and nitrogen (N) requirements under surface and fertigation practices.

MATERIALS AND METHODS

The study was conducted at the Tezeen's Agricultural Research Station of the Ministry of Agriculture and Agrarian Reform (MAAR), Irrigation Directorate, near Hama, from 1995 to 1998. The soil was clayey throughout the profile (100 cm). Other properties were consistent with depth, i.e., pH 8.0, EC < 0.36 dS/m; and

cation exchange capacity, 36 meq/100g. Some properties in the top 25 cm decreased with depth, e.g., available P, 13.8 to 6.3 ppm; CaCO_3 , 7.4 to 4.8%; and organic matter, 1.1 to 0.4%.

Cottonseeds (Aleppo 33/1) were hand-planted in early April each year and irrigated immediately thereafter. The fertigation system was installed on the surface of the appropriate experimental units. Irrigation was established at 80% of the field capacity in the upper 45 cm until peak flowering; otherwise, the effective root depth was 75 cm until the end of the growing season for 1995. Since 1996, the effective root depth was changed to 30 cm from planting until peak flowering and 60 cm till the end of the growing season. Rows were spaced 75-cm apart, with 18 cm between holes. After establishment, stands were hand-thinned to two plants per hole.

Treatments consisted of five N rates for the drip irrigation (0, 60, 120, 180, and 240 kg N/ha) and only one N rate, 180 kg N/ha, for the surface irrigation applied in three unequal split applications according to MAAR recommendations (30% before planting, 50% at thinning, and 20% before flowering). Nitrogen fertilizer was injected in eight equal split applications for the fertigated cotton through the drip system every third irrigation whenever possible. Sub-plots (1.0 m²) for both irrigation methods were established in the central row of each experimental unit, and fertilized with ¹⁵N labelled urea. Phosphorus fertilizer was added according to the soil P availability index to ensure adequacy.

Each experimental unit for both surface and fertigation practices was 75.0 m², which provided five rows of 20 by 3.75 m each. Lateral drip lines had 50 emitters, a discharge of 4 l/h. Volumes of water applied by irrigation for surface and drip-irrigated cotton were monitored by two in-line propeller-type flow meters. Two neutron probe tubes were installed in each experimental unit to monitor the soil moisture content and to provide feedback data for irrigation scheduling. Amounts of irrigation water were applied uniformly to all N treatments of drip-irrigated cotton. The surface irrigated cotton plots were irrigated uniformly at 80% of field capacity using a neutron probe.

All fertilizer N for drip-irrigated cotton was supplied as a solution of urea (46% N) and injected directly into the irrigation water by proportional micro-tubes with the same flow rate corresponding to the N treatments (spaghetti tubes), using proportional-type injector. Whole above-ground plant samples were collected from the labelled sub-plots at physiological maturity. Plant samples were separated immediately into stems, leaf petioles, leaf blades and fruiting forms, which included squares, flowers, immature bolls, seeds and burs. Mature bolls were weighed, and seeds and burs were dried and ground; they were mixed uniformly with the other fruiting components.

The experimental design was a randomized complete block design with six replicates. Seed cotton yield of all treatments was determined by two hand-picking from the yield of sub-plots of the corresponding treatments at maturity. The first

picking was started when almost 70 % bolls were open, and the second picking was 15 days later.

Total dry matter production, seed cotton yield, and earliness were subjected to analysis of variance and mean separation using Duncan's Multiple Range Test at 5% level of confidence. All N treatments under drip irrigation received a total amount of 7578, 4768, 5111, and 5445 m³ /ha of irrigation water for 1995, 1996, 1997, and 1998, respectively; otherwise, under the conventional surface irrigation the amount of irrigation water applied was 14630, 14739, 10124 and 10944 m³ /ha for 1995, 1996, 1997, and 1998, respectively.

RESULTS AND DISCUSSION

Seed Cotton Yield, Earliness, and N Uptake

The effects of N fertilization and irrigation methods on seed cotton yield and earliness are given in *Table 1*. Increasing N rate significantly increased seed cotton yield, and the most pronounced response was in most cases due to the higher N rate for the fertigated cotton, i.e., a positive interaction between drip irrigation and N rate. However, the response varied with the year, e.g., it reached a maximum at 240 kg N in 1995, but only attained a plateau at 120 kg N in 1997. *Drip irrigation was superior to the surface irrigation under the N level compared.*

Table 1. Nitrogen application rates and irrigation methods in relation to cotton seed yield and earliness of maturity.

Nitrogen Irrigation		1995		1996		1997		1998	
		Yield	Earliness	Yield	Earliness	Yield	Earliness	Yield	Earliness
kg /ha		kg /ha	--%--	kg/ha	--%--	kg/ha	--%--	kg /ha	--%--
0	Drip	3791 f	85 a	3283 e	77 ab	4059 c	85 a	3827 d	93 a
60	Drip	4810 d	84 a	4095 d	80 a	4439 b	83 a	4559 c	91 b
120	Drip	5556 c	79 b	4774 c	74 b	5364 a	75 b	5157 ab	88 c
180	Drip	5837 b	78 b	5056 b	77 ab	5173 a	77 b	4869 ab	87 c
240	Drip	6058 a	78 b	5561 a	77 ab	5223 a	76 b	5389 a	88 c
240	Surface	4362 e	72 c	3291 e	76 b	4233 c	73 b	3958 d	91 b

Means followed by the same letter within a column are not statistically different at 5% level of confidence according to DMR test. Earliness is defined as the relative amount of cotton harvested at the first picking compared to the overall cotton harvest. Nitrogen tended to delay earliness, i.e., a lower percentage at first picking. However, the effect varied with the season, e.g., values were decreased

with added N up to 120 kg /ha in all except 1996 when no consistent effect was observed. There was no further decrease beyond the second N application rate. There was no consistent effect of irrigation method (drip vs. sprinkler) on the maturity date.

Nitrogen uptake (Table 2) increased consistently with added N under drip irrigation, the exception being in 1998 when there was no difference between the 120, 180, and 240 kg N /ha rates. Similarly at the 240 kg /ha N rate where drip and surface irrigation was compared, uptake was always higher under the drip system. Nitrogen-use efficiency was thus increased two to three fold by drip irrigation.

Table 2. Nitrogen application rates and irrigation methods vs. N uptake by cotton.

Irrigation	Nitrogen	1995	1996	1997	1998
		-----kg /ha-----			
Drip	0	96	109	161	207
Drip	60	91	251	377	348
Drip	120	110	227	436	481
Drip	180	134	347	459	446
Drip	240	123	395	514	440
Surface	240	124	167	352	326

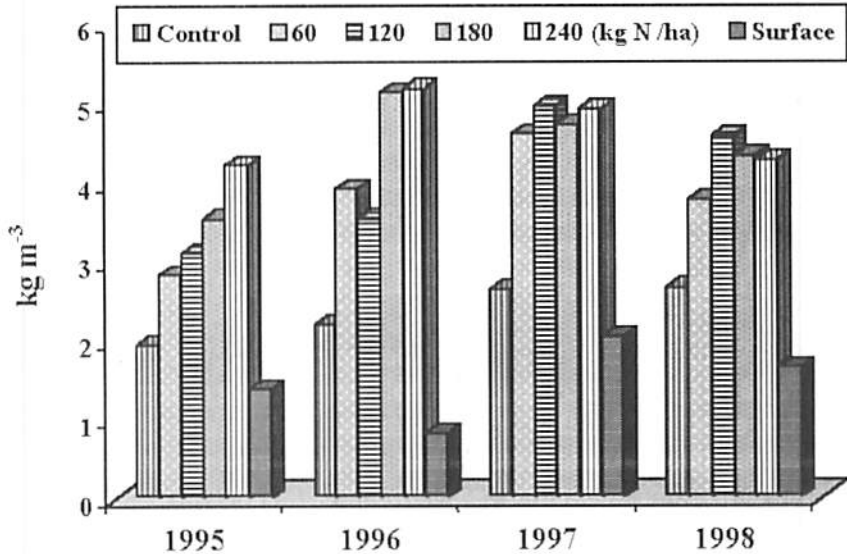


Fig. 1. Irrigation practices in relation to water-use efficiency for cotton.

Water-Use Efficiency

Water-use efficiency, defined as the crop yield (vegetative dry matter plus cotton seed) per unit of water, was substantially increased each year by added N, and even more so by the method of irrigation (Fig. 1).

In some years, the increased in water-use efficiency increased up to the highest N application rate (1995) while in the other years it reached a plateau at the 60 to 120 kg N/ha rates. At the N rate (180 kg) where the irrigation methods were compared, the drip method was three to four times more efficient in terms of water use than surface or flood application.

REFERENCES

- Bresler, E. 1977. Trickle- drip irrigation: principles and application to soil water management. *Adv. Agron.* 29: 343 – 393.
- Halevy, J., and O. Kramer. 1986. Nitrogen fertilizer management of cotton grown under drip irrigation in a Grumusol. *Irrig. Sci.* 7: 63 – 72.
- Ibrahim, M., A. M., Z. M. El-Sirafy, S. A. El-Gohary, and L. S. Willardson. 1997. Interactive effect of irrigation and nitrogen fertilization on cotton, soil, and groundwater nitrogen. *Commun. Soil Sci. Plant Anal.* 28 (1&2): 173 – 187.
- Mauney, J.R., and D.L. Henderix. 1988. Responses of glasshouse-grown cotton to irrigation with CO₂- saturated water. *Crop Sci.* 28: 835 – 838.
- Miller, R. J., D. E. Rolston., R. S. Rauschkolb, and D.W. Wolf. 1982 . Labeled nitrogen uptake by drip-irrigated tomatoes. *Agron. J.* 73: 265 – 270.
- Papadopoulos, I. 1992. Fertigation of trickle-irrigated potato. *Fert. Res.* 31: 9 – 13.
- Papadopoulos, I. 1988. Nitrogen fertigation of trickle-irrigated potato. *Fert. Res.* 16: 157–167.
- Papadopoulos, I., and Y. Stylianou. 1988. Trickle irrigation of cotton with treated sewage effluent. *J. Envir. Qual.* 17: 574 – 580.
- Papadopoulos, I. 1985. Constant feeding of field-grown tomatoes irrigated with sulfate water. *Plant Soil* 88: 213 – 236.
- Phene, C. J., and D.W. Beale. 1976. High-frequency irrigation for water nutrient management in humid regions. *Soil Sci. Am. J.* 40: 340 – 436.
- Radin, J. W., L.L. Reaves, J. R. Mauney, and O. F. French. 1992. Yield enhancement in cotton by frequent irrigation during fruiting . *Agron. J.* 48: 551 – 557.
- Smith, R .B., J. D. Oster, and J .C. Phene. 1991. Sub-surface drip irrigation produced highest net return in wasteland area study. *Calif. Agric.* 45(2): 8 – 10.

C. WORKSHOP FINDINGS

SESSION CHAIRMEN'S REPORTS AND SUMMARY OF DISCUSSION

Chairman: J.K. Syers.

Members: Session Chairmen: A. Ghosheh, C. Kirda, I. Papadopoulos, G. Hamdallah, and J. Ryan.

Rapporteur: A.E. Johnston

This report includes the edited reports of the Session Chairmen and a summary of both the discussion which followed each report and the general discussion at the end of the session.

Keynote Addresses

Chairman: A. Ghosheh. Rapporteur: M. Badraoui

The three presentations in the opening session gave an overview of intensive cropping under pressurized irrigation systems, with emphasis on water-use efficiency, fertilizer-use efficiency, and some environmental aspects related to this technology. All the papers strongly emphasised the fact that fertigation is *no longer a luxury, but a necessity for countries with limited rainfall and water for irrigation.*

In his comprehensive presentation on the present situation and prospects for fertigation, Papadopoulos stressed the importance of water conservation through *appropriate design and management of drip irrigation. If well designed, this technique could save water, fertilizers, energy, and improve water-use efficiency through increased yields.*

Problems associated with drip irrigation, such as the build-up of salinity in the soil and the clogging of emitters, can be avoided with proper selection of equipment, type of fertilizer and operating conditions.

Research on fertigation should be intensified in order to provide data on which to base recommendations for implementing an economically and environmentally sound fertigation program. Particular attention should be given to fertigation systems under saline conditions and economic benefits from micro-irrigation compared to soil application of fertilizers. *Nutrient deficiencies cannot be corrected by attempting to supply nutrients from biological sources alone.*

The quality of fertilizers, addressed by Hamdallah, is a key aspect of fertigation, permitting farmers to obtain large financial returns in ways that are friendly to the environment. *Guidelines for assessing the quality of fertilizers for fertigation* were reviewed, and the need for properly evaluating techniques for

mixing fertilizers were highlighted. Hamdallah emphasized the need for cooperation and *effective linkages* between *farmers, researchers, extension specialists, and fertilizer producers* in order to use water and fertilizers in an efficient, economical, and environmentally friendly way.

With respect to irrigation systems, Nimah stressed the fact that efficient fertigation requires efficient irrigation. Successful fertigation requires the proper selection and design of the irrigation system and proper water and fertilizer management. A set of guidelines and safety measures were presented to help ensure the efficient use of both water and fertilizer and to protect the environment.

Session I: Water Management

Chairman: C. Kirda. Rapporteur: M. Rusan

There were five papers in this session on water management and the following major points were highlighted:

- Water-use efficiency (WUE) must be defined on the basis of the gain in crop yield or crop quality per unit of water used. From such data, it is possible to estimate the financial benefits to the farmer of using a range of costs for inputs and crop values.
- *Between 30 and 50% of irrigation water can be saved by drip irrigation compared to surface application.* To further increase WUE, there must be a better understanding of the different components of the water balance. This will involve hydrological studies together with the analysis of agro-climatological data. This should lead to better cropping systems and improved nutrient-use efficiency. For example, nitrogen (N) applied through fertigation can decrease the need for N by 50% compared to surface application, thus *saving on the cost of fertilizer N.*
- Improving WUE will require the development of *user friendly computer programmes for the integrated management of both water and nutrient inputs.* The water component will require better estimates of crop water requirements. In irrigated agriculture, these estimates are complicated by advection (heat transfer by horizontal flow of air) at the macro scale, by only partial soil coverage by the crop during the early stages of growth, and by the complexity of determining the boundary conditions required to estimate individual crop coefficients (K_c) required to convert the evapotranspiration of a reference crop (ET_0) to that of the crop being grown (ET_c).
- Improved water management also requires a better knowledge of the level to which available soil water can be allowed to decrease before further irrigation

is applied, without adversely affecting yield.

- Successful water and nutrient management in fertigation requires a *knowledge of both water and fertilizer quality*. Poor water quality can lead to precipitation of solids within the irrigation system, while the presence of insoluble residues in the materials used to supply nutrients can lead both to clogging of the irrigation pipes and the drip emitters. Any soluble salts in the water must not react with the nutrient sources to produce insoluble residues.
- Future research and advisory efforts could well concentrate on quantifying the benefits of fertigation by improving the efficient use of fertilizers. Research must also improve water use efficiency and produce user-friendly computer programs to manage fertigation in a cost-effective way.

Session II: Nutrient Management Requirements and Interactions

Chairman: I. Papadopoulos. Rapporteur: A.E. Johnston

From the four papers presented in Session II, within the framework of nutrient management requirements and interactions, a number of general points emerged:

- In all cropping systems, the final objective is to provide the plants with the necessary nutrients so that they achieve their optimum economic yield with minimum adverse environmental impact. There are, however, important differences between open field, rainfed agriculture, and irrigated crops, with or without the addition of nutrients in the irrigation water.
- Because the plant acquires its nutrients from the soil solution via the roots, the distribution and function of the root system is particularly important. Under ideal conditions, different plant species have different root structures, which suggests genetic control. However, in most field situations, it is the chemical and physical environment within the soil which controls root distribution and hence the ability of the plant to acquire the necessary nutrients at a rate and in a quantity to satisfy the varying demand during growth.
- The total amount of nutrients needed by a crop is related to its yield. Hence, in comparable situations, irrigated crops yield more than non-irrigated crops and will require more nutrients within the wetted zone of the soil. The benefit of fertigation is that nutrients are applied with the water and hence are in the zone of maximum root growth and nutrient uptake.

These considerations lead to the need to estimate soil nutrient availability and

methodologies to assess whether plants are getting sufficient nutrients. Data on soil analysis from a large number of farms indicate a wide range of values for the nutrient being tested. This is clearly related to past fertilization practices. This highlights the need to know about the soil nutrient-supplying capacity when determining current nutrient requirements. This is related to the critical value of a soil nutrient such as phosphorus or potassium. Below the critical value, there is a loss of yield and above the critical value there is little or no response. This raises the question as to how and where to sample a soil in a field in which irrigation will only wet a small volume of soil. It also raises the equally interesting question of how to determine the N requirement of irrigated crops.

Plant analysis has a more important role in the nutrition of fertigated crops than in rainfed agriculture. This is because if deficiencies can be identified soon enough, then there is a reasonable chance that the deficiency can be rectified because the nutrient is supplied in a plant-available form in the water supply. To optimise this potential benefit requires knowledge of the critical nutrient concentration within the plant at different growth stages. This could be a topic for further research.

Session III: Fertigation with Phosphatic Fertilizers

Chairman: G. Hamdallah. Rapporteur: A. Fardous

Five papers were presented in this session, which specially addressed the topic of P fertilizers for fertigation.

The need for specific attention to P is due to a number of reasons. These include: (1) the complexity of the reactions which occur when water-soluble forms of P are added to soil, especially calcareous soils, which are widespread throughout the West Asia and North Africa (WANA) region; (2) 'placement' of P within the wetted zone of the soil with fertigation; and (3) the relation between soil solution P and soil P in soil that remains continuously moist throughout the growing season. Thus, there is interest in comparing different P fertilizers to see which might maintain a larger concentration of P in the soil solution and over what period of time. Acidic P fertilizers, like urea phosphates, have given larger yields than other water-soluble phosphates. However, it is not clear what proportion of the beneficial effects came from the urea or the phosphatic component of the fertilizer. What is certain is that on well-buffered calcareous soils, the use of acidifying fertilizers will have only an ephemeral effect in lowering soil pH.

Not only yields but the economics and management skills required to supply water and nutrients by fertigation systems must be compared with systems using slow-release fertilizer formulations and sprinkler irrigation.

The importance of soil and plant analysis, and the determination of critical P levels for both soils and plants as an aid to deciding the quantity of P to apply at

different growth stages, were highlighted. So too was the need to better *integrate irrigation scheduling and nutrient supply*.

There was uncertainty about the value of foliar P application if deficiency was suspected. The general lack of agreement suggested that there was need for research on this topic which should include the role of *adjuvants*, chemicals usually added in small amounts to the solution, which help retain the liquid on the leaf surface and/or facilitate the uptake of nutrients from the solution.

Salt-affected soils occur on some 23% of the 1500 million ha of soils suitable for agriculture. Preventing, modifying, or coping with salinity is therefore important. The possibility and benefits of biological amelioration, improved irrigation techniques, and the possibility of modifying saline soils need to be assessed, especially the possibility of using comparatively simple procedures like different configurations of the drip lines to maximize the benefits of irrigation and minimize any possible adverse effects from salt accumulation.

Session IV: Environmental and Economic Issues

Chairman: J. Ryan. Rapporteur: M. Nimah

It was a matter of considerable regret that the speaker on economic issues was unable to attend due to unforeseen circumstances. While economics was alluded to as a recurring theme throughout the meeting, clearly a thorough in-depth assessment of the economic principles and parameters associated with pressurized irrigation systems was much in need. Thus, there was only one paper on environmental issues which summarised current knowledge and concerns about the loss of nutrients to rivers, lakes, and groundwater aquifers.

The global concerns with pollution and associated increases in human populations was presented as a background to potential and actual pollution risks from fertilizer use. Agriculture has to be seen as linked to, and a part of, the environment. The increased use of nitrogen and phosphorus on a global scale, especially in developed countries, while contributing to enhanced agricultural output, has also brought with it a range of problems, especially those off-site.

Leaching and runoff of N have negatively impacted on groundwater aquifers and rivers and lakes, with a consequent effect of eutrophication and biological degradation of surface water sources, and contamination of used for drinking water lakes. Such effects are associated with excessive nitrate levels, with its attendant hazards for human health. The various forms of N as pollutants in soil, water, and air were highlighted.

While also a potential pollutant, P could cause damage off-site when erosion of the soil has occurred. With higher levels of available P in soils as a result of excessive fertilizer use, some P may be also lost via runoff. Similar to N and P, a

range of agricultural chemicals (insecticides, herbicides, etc.) could have adverse environmental effects if moved from farmers fields to water bodies.

With intensification of agricultural production systems, the potential pollution hazard from fertilizers and agricultural chemicals also increases, especially in irrigated agriculture. However, improved management of nutrients and water could mitigate such losses from the farmers' fields, where they are a resource, to off-site areas where they pose environmental threats. *Fertigation, if properly managed, could greatly reduce, or indeed eliminate, such losses and minimize environmental damage.*

Summary of General Discussion

Fertigation is no longer a luxury but a necessity in semi-arid and arid climates. It is one way of capitalizing on soil fertility and increasing crop production by improving both water- and nutrient-use efficiency. Such improvements will benefit both the farmer and the environment as well as help ensure increasing food security, especially where population growth is rapid. Drip irrigation can be practised on arable land where other forms of irrigation could do irreversible damage to the agricultural resource through soil erosion.

The present challenge is to *understand and solve the problems of fertigation.* It is no longer necessary to develop and promulgate the concept of fertigation. However, *fertigation requires large initial investments.* So cost is an issue, especially for resource-poor farmers. Giving them access to long-term funding on acceptable terms needs to be addressed.

There is a need to focus on the *economics of fertigation* and make valid comparisons with other methods of applying nutrients and water. Initially, it is essential to design the most suitable fertigation system for each installation if subsequent maintenance costs are to be minimized.

Appropriate forms of fertilizer and their quality are increasingly important. It is essential to develop specific criteria if manufacturers are to produce acceptable materials for use in fertigation systems. Among the appropriate criteria are *solubility, lack of impurities, compatibility of nutrient sources, appropriate nutrient ratios* for different crops, and materials with a *low salt index*, which are both *easy to handle* and add to the fertigation system.

Fertigation is the most flexible and efficient method of applying both nutrients and water, especially to meet changes in crop demand for different amounts of the various nutrients during periods of active growth. However, efficient fertigation requires, in part, an understanding of the principles on which the technique has been developed. Through a good extension service, this understanding can be communicated in an appropriate format to farmers to help them improve their management skills.

For both extension personnel and farmers, it is vital to develop manuals for fertigation practice and user-friendly computer programs at an appropriate level for ease of understanding and use. Thus co-operation and effective links are required through the chain from research to education, extension, and the farmer.

To prepare good advice for the farmer, it is essential to have *excellent analytical services readily available* to do plant, soil and water analyses and check that fertilizers meet the *appropriate quality standards*. The effective use of analytical data will require research to define critical levels of soil pH and the nutrient status; salinity levels for different crops, so that these levels are not exceeded when soluble salts are added to saline irrigation water; and critical levels of nutrients at different stages of plant growth, so that deficiencies can be corrected by increasing the concentration of a nutrient in the irrigation water.

Session V: Conclusions and Recommendations

J.K. Syers and A.E. Johnston

Important Issues Addressed by the Workshop

Within the WANA region, there is a growing concern for the agronomically effective and economically efficient use of scarce water resources and nutrients for *enhanced agricultural production* set against increasing environmental concerns for the quality of natural resources, particularly water. Although the concept of fertigation is accepted, the current challenge is to *identify, understand and overcome the problems involved in fertigation* so that its use will be more widely adopted by farmers and growers.

Fertigation offers real advantages over conventional soil application of nutrients and water. But there are several realities and limitations which should be considered:

- Greater capital costs and more efficient management are required for fertigation compared to open field, rainfed agriculture.
- Crop yield per unit of water applied is more important than yield per unit area and present and future land use must take full account of this.
- Soil nutrient supplying capacity must be given adequate consideration in developing fertigation practices.
- The uniformity of nutrient application cannot be better than the uniformity of the water application.
- Do not fertigate unless the right type of fertilizer is available.

- Specific fertilizers are required for specific needs and also consider the practicalities of mixing fertilizers.
- The form of a fertilizer is important (particularly with phosphorus), as is purity and possibly acidity for calcareous soils.
- The comparative costs of fertilizers suitable for fertigation and those for surface broadcast application are an important consideration.
- The time of application of nitrogen and potassium fertilizers may be different with irrigation compared to rainfed conditions.
- Salinity (water quality) is a major problem. There is a conflict between the need to remove accumulated salts at the end of the growing season with the risk of removing nitrate, a possible pollutant.
- There is a need to develop cost-effective technologies to maintain the productivity of existing saline soils and prevent further salinisation of existing low-saline soils.
- The use of poor quality water and inefficient fertigation practices *cause the* deterioration of the resource base on which future productivity depends.
- Technologies for monitoring water quality exist but small farmers cannot meet the cost. Who should pay?
- There is a critical need to know more about the pattern of nutrient uptake because this affects the timing and ratio of nitrogen, phosphorus and potassium applications, particularly at critical growth stages.
- There is a need to separate the reasons for foliar application and the reasons for soil application. Foliar fertilization should be seen as being complementary to fertigation.
- From research findings to implementation. Advisory and extension services are essential to get current updated information to farmers.

Summary and Recommendations

Within the WANA region, there is an urgent need to increase crop yield and crop quality. This increase must come mainly from an *intensification of production on existing agricultural soils*. Importing countries are setting increasingly high standards for the food they import. It is, therefore, important to achieve high quality in exported agricultural products to gain access to these markets. To achieve this in the most economically viable and environmentally friendly way, it is essential to optimize the efficiency of water and nutrient use. This requires a better understanding of root growth and distribution, and the patterns of water use and

uptake of different nutrients during the growing season.

The workshop therefore recommends that:

- Data on the seasonal pattern of nutrient uptake by different crops be evaluated and synthesised, and used as a basis for *formulating fertigation practices*, particularly in relation to the *nutrient-supplying power* of the soil and the *composition of irrigation waters*.
- Integrated studies of nutrient dynamics and root distribution and activity in different cropping and irrigation systems are undertaken.
- There should be improved cooperation between research workers and fertilizer manufacturers to develop and produce the most suitable fertilizers for use in fertigation systems for both soil and foliar application.
- Existing research information on fertigation be reviewed, evaluated and integrated to *develop effective management packages for water and nutrient use*. These management packages can be used to train extensionists who will then be able to provide the best possible advice for farmers.

LIST OF WORKSHOP PARTICIPANTS

List of Workshop Participants

A

A. ABED,

University of Jordan (UOJ);
Jordan

Salameh ABED,

Jordan Phosphate Mines Co., Ltd.
(JPMC) /P. O. Box 30, Amman;
Jordan,
Tel: 962 6 607 141
Fax: 962 2 69 12 90

Rima ABED-HALEM,

Jordan Phosphate Mines Co., Ltd.
(JPMC) /P. O. Box 30, Amman;
Jordan,
Tel: 962 6 607 141
Fax: 962 2 69 12 90

Bruce A'BEAR,

Marketing Speciality Products, Omnia
Fertilizers /P. O. Box 69888
Bryanston 2021;
South Africa,
Tel: +27 11 6604079
Fax: +27 11 6604079
e-mail: babear@omnia.co.za

Ayman ABOU HADID,

Professor & Director, Central
Laboratory for Agriculture climate,

Agriculture Research Center /P. O.
Box 296 Imbaba, 12411 Giza;

Egypt,

Tel: 202 3490053

Fax: 202 3490053

e-mail: ruafah@rusys.eg.net

K. ABU-GANAM,

Private Sector;
Jordan

Sultan ABU-ORABY,

Yarmouk University;
Jordan

Azmi ABU-RAYAN,

Jordan University;
Jordan

Ghaida ABU-RUMMAN,

Assistant Professor, Jordan University
of Science and Technology (JUST),
Irbid 22110;
Jordan,

Tel: 962 2 7295111 ext. 2331,
2379

Fax: 962 2 7295018

e-mail: akhdair@just.edu.jo

Hassan ABU-SEIDO,

Private Sector;
Jordan

Talib ABU-SHARAR,

Head, Department of Environment and
Desertification, Jordan University;
Jordan

M. ABU-ZREIG,

Assistant Professor, Dept. of
Agriculture Engineering &
Technology /P. O. Box 3030, Irbid;
Jordan,

Tel: 962 2 295 111 ext. 2381

Fax: 962 2 295 018

e-mail: majed@just.edu.jo

Nassim AL-ABED,

Assistant Professor, Jordan University
of Science & Technology,
Department of Agriculture
Engineering and Technology /P. O.
Box 3030, Irbid 22110;

Jordan,

Tel: 962 2 295111 ext.2344

Fax: 962 2 295018

e-mail: nassim@just.edu.jo

Taleb AL-ANNY,

Mu'tah University;
Jordan

Mohammed AL-DAWOOD,

Agronomist, Saudia Basic Industries
Corporation SABIC /P. O. Box
59090, Riyadh 11525;

Saudi Arabia,

Tel: 966 1 401 203 – 406 9900

Fax: 966 1 401 2033

Wafa AL-HALSEH,

Ministry of Agriculture /Ministry of
Agriculture Field Crop Department,
Damascus;

Syria,

Tel: 963 22 17 403

Fax: 963 22 18 020

Jamal AL-HUMAIDI,

Head of Studies & Research
Jordan Dead Sea Industries, /P.O. Box
941260, Amman – 11194;

Jordan,

Tel: 962 569 59 41

Fax: 962 569 59 39

Ghazi AL-KARAKY,

Jordan University of Science and
Technology;
Jordan

JAMEEL AL-LAHAAM,

Yarmouk University;
Jordan

Salem ALLUZI,

Arab Organisation for Agricultural
Development /P. O. Box 19082,
Amman;

Jordan,

Tel: 079 6 535396

Fax: 079 6 566 2836

Lyla AL-NIMRUJ,

Abdallah AL-RAWASHEDH,

Mu'tah University;
Jordan

Issam AL-SHOUNQ,
Yarmouk University;
Jordan

Ragheb Al-TAHHAN,
Jordan University of Science and
Technology; Irbid.
Jordan

Jumah AMAYREH,
Assistant Professor, Jordan University
of Science and Technology (JUST),
Agriculture Engineering &
Technology Department, Faculty of
Engineering /P. O. Box 3030,
IRBID 22110;
Jordan,
Tel: 962 2 295111 ext.2346
Fax: 962 2 295018
e-mail: jumah@just.edu.jo

A. ARABIAT,
Head of Senate, NGO;
Jordan

Roberto ARINGHERI,
Researcher, National Research Center
(C.N.R.) Inst. for Soil Chemistry
/Via F. Corridoni 78 - 56125 PISA;
Italy,
Tel: 39 50 48337
Fax: 39-50-500631
e-mail: aringhieri@ict.pi.cnr.it

J. ASHOUR,
Assistant Professor, Dept. of
Agriculture Engineering &

Technology /P. O. Box 3030, Irbid
22110;
Jordan,
Tel: 962 2295111
Fax: 9622295018
e-mail: jamals@just.edu.jo

Therese ATALLAH,
Faculty of Agriculture Sciences /P.O.
Box 13, 5368 Beirut (Chouran);
Lebanon,
Tel: 961 1483306 – 05 924359
Fax: 961 1785427; 01 483307
e-mail: luag2@cnrs.edu.lb

Bassim AWAD,
Directeur General, Adritec Maroc Zone
Industrielle, El Jadida;
Morocco,
Tel: 03 35 17 94
Fax: 03 35 17 95

Rafaa AZABI,
Head of Soil & Water Research
Department, Agricultural Research
Center /B.P. 2480, Tripoli;
Libya,
Tel: 218 21 361 4993
Fax: 218 21 361 4993

B

Swapnil BACHCHHAV,
Chief, Speciality Fertilizer Project, EPC
Industrie Ltd. /B-20, MIDC,
AMBAD, Nashik Maharashtra
422010;

India,

Tel: 91 253 381285 – 383241

Fax: 91 253 382975

e-mail:

epccorp@bom3.vsnl.net.in

Mohamad BADRAOUI,

Professor of Soil Fertility, I.A.V. –

Hassan II, B. P. 6202 Rabat-

Institutes;

Morocco,

Tel: 212 7 79 17 80

Fax: 212 7 79 17 80

Nabil BATTA,

Jordan Phosphate Mines Co., Ltd.

(JPMC) /P. O. Box 30, Amman;

Jordan,

Tel: 962 6 607 141

Fax: 962 2 69 12 90

Anwar BATTIKHI,

President, University of Hashimat;

Jordan

Amar BOUJAMAA,

Coordinator for Europe & Near East

Program, World Phosphate

Institute(IMPPOS), 3 rue

Abdelkder Al Mazini, B. P. 15963

Casablanca 20001;

Morocco,

Tel: 212 2 48 41 22 /24 /25

Fax: 212 2 48 41 21

e-mail: imphos@casanet.net.ma

A. BOULAD,

NCARTT;

Jordan

Loudyi BOUSSELHAM,

Professor, Ecole National d'Agriculture

de Meknès (ENA) 5000 BP. S/40;

Morocco,

Tel: 212 5 300239

Fax: 212 5 300238

C

M. CHAOUI,

Market Research Manager, O.C.P

/Angle Route d'El Jadida et Bd. de la

Grande Ceinture Casablanca 02;

Morocco,

Tel: 212 2 23 00 25 – 23 04 24

Fax: 212 2 23 06 35

D

Lana DABBAS,

Jordan Phosphate Mines Co., Ltd.

(JPMC) /P. O. Box 30, Amman;

Jordan,

Tel: 962 6 607 141

Fax: 962 2 69 12 90

I. DAKKOURI,

General Manager, Consolidated

Suppliers Company /P. O. Box 609,

Amman 11941;

Jordan,

Tel: 962 6 551 6530

Fax: 4962 6 551 0416
e-mail: CSCO@GO.COM.JO

Yaser DASSIN,

Jordan Phosphate Mines Co., Ltd.
(JPMC) /P. O. Box 30, Amman;
Jordan,
Tel: 962 6 607 141
Fax: 962 2 69 12 90

G. DEV,

IPI Canada /Sector 19 Dundahera,
Gurgaon, Haryana 122016;
India,
Tel: (Res) 91 124 340 302
(Off) 91 124 341 849

Faisal DODIN,

Jordan Phosphate Mines Co., Ltd.
(JPMC) /P. O. Box 30 Amman;
Jordan,
Tel: 962 6 607 141
Fax: 962 2 69 12 90

E

Mohammed EL-FOULY,

Professor /Head, Agriculture & Biology
Research Division, National
Research Center /El-Tahrir Street,
Post Code 12311 Cairo, Dokki;
Egypt,
Tel: 202 337 12 11
Fax: 202 361 0850
e-mail:
nrcmicro@mailier.datum.com.eg

B. EL-HAJ ,

Deputy Manager, Commercial
Department, Compagnie des
Phosphates de Gafsa/GCT /7-9 Rue
du Royaume d'Arabie
Séoudite1002 – Tunis;
Tunisia,
Tel: 216 1 840 663 – 797 296
Fax: 216 1 785 859/794 670

Maroun EL-MOUJABBER,

Director of Research, Faculty of
Agriculture Sciences, Holy Spirit
University, /Kaslik, P. O. Box 446,
Jounieh;
Lebanon,
Tel.: (Off) 961 9 640 664
(Res) 961 3 771 116
e-mail: marounm@xnets.com.lb

F

Abdel-Nabi FARDOUS,

Director of Water Resource and
Irrigation Management Program,
NCARTT /P.O. Box 639, Baqaa,
Amman;
Jordan,
Tel: 962 6 4725411
Fax: 962 6 4726099
e-mail: director@ncartt.gov.jo

H

Costas HADJIPARASKEVAS,

Agricultural Officer, Soils and Water

Use Section, Agricultural Research
Institute, Nicosia,
Cyprus,
e-mail:
hadjipa@spidernet.com.cy

Amor HALITIM,
Professor, Université de Batna, Institut
d'Agronomie, Université de Batna;
Algeria,
Tel: 213 4 85 43 39

Ghassan HAMDALLAH,
Regional Soil Officer, Food &
Agriculture Organization, Regional
Officer (FAO/RNE) /11, El Eslah El
Zerai St. Dokki, P. O. Box 2223,
Cairo;
Egypt,
Tel: 202 331 6172
Fax: 202 349 5981
e-mail:
ghassan hamdallah@fao.org

Ali HAMDI,
Secretary General, Arab Fertilizer
Association (AFA) /P.O. Box 8109,
Nasr City 113371, Cairo;
Egypt,
Tel: 202 417 2347
Fax: 202 417 3721
e-mail: info@afa.com.eg

Atef HAMDY,
Director of Research, CIHEAM-IAM-
Bari /Via Ceglie, 970010 Valenzano
(BA);
Italy,

Tel: 39 080 46 06 236
Fax: 39 080 78 06206
e-mail: hamdy@iamb.it

Boutros HATTAR,
University of Jordan (UOJ);
Jordan

Yasser HOLEIL,
Economical & Agricultural
Department, Arab Fertilizer
Association (AFA) /9 Ramo
buildings P. O. Box 8109, (11371)
Cairo;
Egypt,
Tel: 202 417 2347
Fax: 202 4 173721
e-mail: info@afa.com.eg

J

H. JABR,
President, Agricultural Union;
Jordan

Mussadak JANAT,
Atomic Energy Commission,
Department of Agriculture /P. O.
Box 6091, Damascus;
Syria,
Tel: 963 11 611 1926
Fax: 963 11 611 2289

Maher JEBRIL,
Consolidated Suppliers Company /P. O.
Box 609, Amman 11941;

Jordan,
Tel: 962 6 551 6530
Fax: 4962 6 551 0416
e-mail: CSCO@GO.COM.JO

Arthur E. JOHNSTON,
Lawes Fellow, Soil Science
Department, IACR, /Rothamstead,
Harpenden, Herts;
U.K.

K

Farida KABBAJ,
Technical Studies Section Manager,
O.C.P /Angle Route d'El jadida et
Bd. de la Grande Ceinture
Casablanca;
Morocco,
Tel: 212 2 23 00 25 – 23 04 24
Fax: 212 2 23 06 35

Riyad KALBOUNEH,
Jordan Phosphate Mines Co., Ltd.
(JPMC) /P. O. Box 30, Amman;
Jordan,
Tel : 962 6 607 141
Fax: 962 2 69 12 90

Fawzi KARAJEH,
Senior Water Resources Scientist,
Natural Resources Management
Program, ICARDA /P. O. Box
5466, Aleppo;
Syria,
Tel: 963 21 22 13 477

Fax: 963 21 22 13 490
e-mail: f.karajeh@cgiar.org

Sayed KHATTARI,
Professor of Soil Fertility and Plant
Nutrition, Faculty of Agriculture,
University of Jordan;
Jordan,
e-mail: uoj@nets.com.jo

Fayez KHASAWNEH,
President, Yarmouk University;
Jordan

Adnan I. KHDIAIR,
Assistant Professor, Jordan University
of Science and Technology (JUST),
Irbid 22110;
Jordan,
Tel: 962 2 7295111 ext. 2331, 379
Fax: 962 2 7295018
e-mail: akhdair@just.edu.jo

H. KHORI,
University of Jordan;
Jordan

Taoufik KHOUAJA,
Commercial Manager, Compagnie des
Phosphates de Gafsa /GCT /7-
9,Rue du Royaume d'Arabie
Séoudite1002-Tunis;
Tunisia,
Tel: 216 1 798 660–216 1 785313
–216 1 842 019–216 1 783
495

Grevat KIRDA,

Professor, Cukurova University, Faculty
of Agriculture /01330 Adana;

Turkey,

Tel: 90 322 338 7014

Fax: 90 322 338 6386

e-mail: krda@pamuk.cu.edu.tr.

Sami KRICHAN,

Jordan Phosphate Mines Co., Ltd.
(JPMC) /P. O. Box 30, Amman;
Jordan,

Tel: 962 6 607 141

Fax: 962 2 69 12 90

Khanna KRISHEN LAL,

Chairman, EPC Industry Ltd. /B-20,
MIDC, AMBAD, Nashik,
Maharashtra 422010;

India,

Tel: 91 253 381285

Fax: 91 253 38 29 75

e-mail:epccorp@bom3.vsnl.net.in

L

Kawther LATHIRI,

INRGREF /BP. 10 2080 ARIANA

Tunis,

Tunisia,

Tel: 216 1 719 630

Fax: 216 1 717 951

e-mail:

latiri.kawther@iresa.agrinet.tn

Cisse LEMAMOULAYE,

Head, Agronomy Division, World

Phosphate Institute (IMPHOS) /3,
Rue Abdelkder Al Mazini, BP.
15963 Casablanca 2001;

Morocco,

Tel: 212 2 48 41 22 /24 /25

Fax: 212 2 48 41 21

e-mail: imphos@casanet.net.ma

R. LUBANI,

Marketing Department, Arab Potash
Company (APC) /Shemisani, P.O.
Box 1470, 11118 Amman,

Jordan,

Tel: 962 5 666165

Fax: 962 5 673105

e-mail: apc@nol.com.jo

M

Michel MARCHAND,

Chief Agronomist, International Potash
Institute /SCPA, 2 place du Gle DE
GAULLE, TSP 1170, 68053,
Mulhouse, cedex;

France,

Tel: 00 33 3 89 36 36 14

Fax: 00 33 3 85 36 37 86

e-mail: Marchand M@scpa.fr

Mahmoud MEDANY,

Researcher, Central Laboratory for
Agriculture Climate (CLAC), /6,
Al-Nour Street Nadyel-Syed, Dokki
Giza 12411;

Egypt,

Tel: 202 336 72 74

Fax: 202 336 8059

e-mail: rumedany@rusys.eg.net

Abboud MED-TAHAR,

Head of Research Center, Compagnie
des Phosphates de Gafsa/GCT
/Centre de Recherche 2113
Metlaoui, Tunis;

Tunisia,

Tel: 216 4 241 350

Fax: 216 4 241 350

Ali MHIRI ,

Professor, Institut National
Agronomique de Tunisie (INAT)
/43, Av. Charles Nicole, 1082
Tunis;

Tunisia,

Tel: 216 1 28 71 10

Fax: 216 1 79 93 91

e-mail: mhiri.ali@inat.agrinet.tn

Munir J. MOHAMMAD,

Assistant Professor, Jordan University
of Science and Technology /P.O.
Box 3030, Faculty of Agriculture,
Irbid;

Jordan,

Tel: 9622295111

Fax: 00962 2 295123

e-mail: mrusan@just.edu.jo

Pierre MOUTONNET,

Technical Officer, Soil Fertility,
Irrigation and Crop Production
Section, Joint FAO/IAEA Division
of Nuclear Techniques in Food and
Agriculture, International Atomic
Energy Agency /Wagramer Strasse
5, P.O. Box 200, A-1400 Vienna;

Austria,

Tel: 43 1 2060 ext. 21645 /21647

Fax: 43 1 26007

e-mail: P.Moutonnet@iaea.org

Tayeb MRABET,

Secretary General, World Phosphate
Institute (IMPHOS) /3, Rue
Abdelkder Al Mazini, BP. 15963
Casablanca 2001;

Morocco,

Tel: 212 2 48 41 22 /24 /25

Fax: 212 2 48 41 21

e-mail: impfos@casanet.net.ma

A. MUSA,

Dean of Faculty of Agriculture, NGO;
Jordan

N

Kamel NAGAZ,

Researcher, Institut des Régions Arides
/4119 Médenine, Tunis;

Tunisia,

Tel: 216 5 633 006

e-mail:

houcine.khatteli@ira.rnrt.tn

Kolsi NAIMA,

Assistant, Institut National
Agronomique de Tunisie /43, Av.
Charles Nicole, 1082 Tunis;

Tunisia,

Tel: 216 1 28 71 10

Fax: 216 1 79 93 91

e-mail: mhiri.ali@inat.agrinet.tn

Musa NIMAH,

Professor, Faculty of Agriculture &
Food Sciences, American
University of Beirut, Lebanon, and
850, 3rd Ave. N.Y 10022, New
York;
USA.

Tel: 961 3222 153
Fax: 961 1 744 460
e-mail: nimah@aub.edu.lb

O

A. OBEIDAT,

Head of Cabinet, NGO;
Jordan

Sabri ORUC,

Agricultural Engineers, Ankara
Research Institute of Rural Services
/P. O. Box 253, Bakanliklar,
Ankara;
Turkey,

Tel: 903 12 28 73 581
Fax: 903 12 28 76 783
e-mail: ankara@khgm.gov.tr

P

Ioannis PAPADOPOULOS,

Senior Researcher, Agricultural
Research Institute /Nicosia;
Cyprus,

Tel: 357 2 305101
Fax: 357 2 316 770
e-mail: papado@arinet.ari.gov.cy

T. PATIL,

Chief Executive Officer, Nutri Ahar
Speciality Products (INDIA) /PVT
LTD, PUNI3 Chandrama, Prabhat
Road, Lane 8, PUN, 411004;
India,

Tel: 91 20 37 98 73
Fax: 91-20-37-70-15
e-mail:
piencc.agritech@yems.ven.rdn

Q

W. QAWASMIH,

NCARTT;
Jordan

Amjad SALEH QAZAQ,

Chemical Engineer, Research and
Development for Fertilizers,
Jordanian University of Science
and Technology (J.U.S.T) /P.O.
Box 230064, Irbid -21122;
Jordan,

Tel: 00962 2 7411359
Fax: 00 962 2 244293
e-mail: AQAZAQ@hotmail.com

R

Zahir RAWAJFEH,

Jordan University of Science and
Technology, Irbid;
Jordan

Leena RISTIMAKI,

Kemira Agro Global /P. O. Box 330

FIN-00101 Helsinki;

Finland,

Tel: 358 10 862 1485

Fax: 358 10 862 1663

Dina RYAN,

Jordan Phosphate Mines Co., Ltd.

(JPMC) /P. O. Box 30, Amman;

Jordan,

Tel: 962 6 607 141

Fax: 962 2 69 12 90

John RYAN,

Soil Fertility Specialist, International
Center for Agricultural Research in
the Dry Areas (ICARDA) /P. O.
Box 5466, Aleppo;

Syria,

Tel: 963 21 22 13 477

Fax: 963 21 22 25 105

e-mail: J.Ryan@CGIAR.ORG

S

Samer SALT,

NCARTT; Amman

Jordan

Hashim SHBOUL,

Minister of Agriculture;

Jordan

Pasquale STEDUTO,

Crop Eco-Physiologist, CIHEAM-

IAM-Bari /Via Ceglie, 970010

Valenzano (BA);

Italy,

Tel: 39 080 7806224

Fax: 39 080 7806206

e-mail: steduto@iamb.it

Keith SYERS,

Professor, Dept. of Agricultural and
Environmental Sciences, Faculty of
Agriculture and Biological Science,
University of Newcastle-upon-
Tyne,

U.K.

Tel/Fax: +4419 122 225 677

e-mail:

j.k.syers@newcastle.ac.uk

T

Awni TAIMEH,

Director General, NCARTT;

Jordan

Kassim TELFAH,

Jordan Phosphate Mines Co., Ltd.

(JPMC) /P. O. Box 30, Amman;

Jordan,

Tel: 962 6 607 141

Fax: 962 2 69 12 90

NAZIEH TOUQAN,

Jordan Phosphate Mines Co., Ltd.

(JPMC), /P. O. Box 30, Amman;

Jordan,

Tel: 962 6 607 141

Fax: 962 2 69 12 90

Christos TSIATALOS,

Ministry of Agriculture, Natural
Resources and Environment,
Department of Agriculture Land &
Water Use;

Cyprus,

e-mail: doagrg@cytanet.com.cy

V

C. VENEGAS,

Agricultural Director, SQM Mexico,
S.A DE C.V. /Bosques de Ciruelos
180 -5LO, Mexico D-F 11700;

Mexico,

Tel: 52 5 245 1011

Fax: 52 5 251 8390

e-mail: cvenegas@csi.com

Z

Mabrouk ZARZAH,

Assistant Professor, Soil & Water
Department, Faculty of Agriculture
/C/O B. Baruni P.O. Box 14380
TRIPOLI;

Libya,

Tel: 218 21 3600439

Fax: 218 21 604121

S. ZURIEQI,

NCARTT, Amman;
Jordan

