

Handbook

Approaches and strategies for sustainable wheat production

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Executive Summary

This handbook provides practical information on wheat production. It aims to inform the work of policy makers, agriculture agencies, extension agents, non-governmental organizations, universities and research organizations, both in developing countries and worldwide, who are responsible for delivering national and global food security.

It summarizes the key aspects of wheat production that planners and producers need to consider for the effective management and expansion of wheat growing areas or improvement of wheat crop productivity, including:

- Common challenges and constraints to optimal wheat production
- Overview of common wheat farming systems
- Current wheat technologies and practices, such as improved varieties, seed systems, best rotation systems, conservation agriculture, nutrient management methods, integrated pest management and irrigation methods
- Future directions and recommendations to increase wheat productivity per unit area while conserving the natural resource base

Wheat is the most widely grown and consumed food crop accounting for 20% of humanity's food. In the past decade, some 620 million tons of wheat was produced on 220 million hectares, with productivity levels of 3 tons/hectare. After the quantum leap of the Green Revolution, wheat yields have been rising by only 1.1% per year, a level that falls far short of the demand of a global population growing by 1.5% or more annually.

Some estimates reveal that global wheat production must increase at least by 1.6% annually to meet a projected yearly wheat demand of 760 million tons by 2020. By 2050, with the world population estimated to be 9 billion, the global demand for wheat is estimated to exceed 900 million tons.

Meeting this demand is very challenging and is complicated by factors including: climate change; increasing drought/water shortages; soil degradation; reduced fertilizer supply and increasing costs; increasing demand for bio-fuels; and the emergence of new virulent diseases and pests that attack wheat crops.

To address these challenges the global development, agricultural research and extension community needs to better understand the drivers of past wheat production trends and future challenges. They need to build on this perspective to design effective strategies that harness the latest technologies, farming practices, enabling policies, and continually engage in global knowledge sharing in new networks and research for development partnerships.

In preparing this handbook, the authors hope that the expertise and learning shared here inform national and international strategies that stimulate the continuous improvement of wheat production – to boost food and nutrition security.

1. Introduction

1.1. Importance of wheat to food and nutrition security

Originating in the Fertile Crescent about 10,000 years ago, bread wheat is currently the most widely grown crop, and after rice the 2nd most important food crop in the developing countries. Wheat provides about 19% of the calories and 21% of protein needs of daily human requirements at the global level (Braun et al., 2010). Wheat has played a fundamental role in human civilization and has contributed to improving food security at global and regional levels. Some have argued that the price hikes in wheat in 2008 contributed to the political instability in a few regions in the world where wheat is a staple crop, including the recent unfortunate development in some Arab countries (Shiferaw et al, 2013).

Cultivated wheat is classified into two major types; the hexaploid bread wheat ($2n = 6x = 42$, AABBDD) and the tetraploid durum wheat ($2n = 4x = 28$, AABB). Currently, at the global level, bread wheat accounts for 95% of all the wheat produced. Based on growth habit, wheat is classified into spring wheat and facultative/winter wheat, covering about 65 and 35% of the total global wheat production area, respectively (Braun et al., 2010; Braun and Saulescu, 2002).

The flour of bread wheat is used to make French bread, Arabic bread, Chapati, biscuits, pastry products and for the production of commercial starch and gluten. Durum wheat is specifically grown for the production of semolina for use in pasta and macaroni products. In North Africa, durum wheat is preferred for the preparation of couscous and bulgur. It is also widely used to prepare a hybrid bread by mixing both bread and durum flours together.

1.2. Trends in wheat production

Wheat production at the global level has increased dramatically from the 1960s through to 2013 without much change in the total area grown to wheat. . According to FAO (2014), in 2013, about 732 million tons of wheat was produced on average on 218.5 million ha with a productivity level of 3.3 t ha⁻¹, which is a highly significant increase from wheat production in 1961, which stood at 222 million tons with a productivity level of only 1.2 t/ha. The dramatic increase in wheat production both vertically and horizontally is attributed to the adoption by farmers of Green Revolution technology packages, especially improved high yielding varieties having better response to inputs, improved irrigation systems and improved use of fertilizers and pesticides as well as better management practices, coupled with conducive policies and stronger institutions.

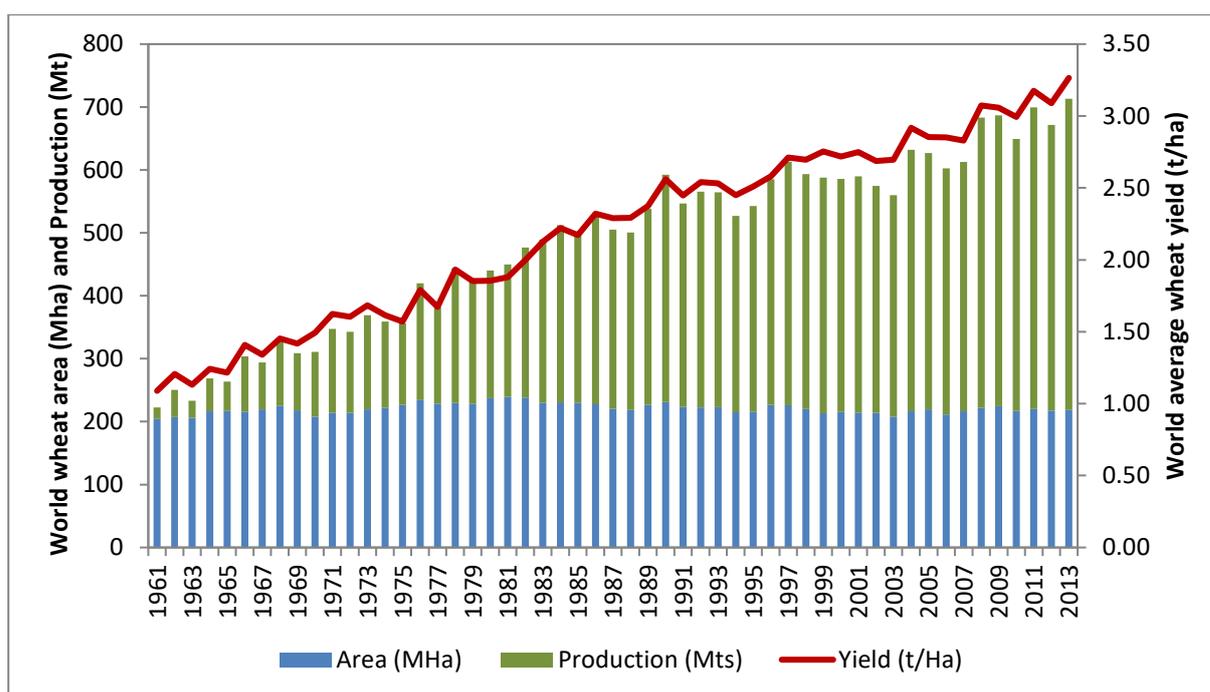


Fig.1. World wheat yield, production and area from 1961 to 2013 (FAO 2014).

1.3. Current gaps in wheat production and consumption

Wheat is the most traded agricultural commodity at the global level with a trade volume of 144 MT, with a total value of 36 billion US dollars (2010 data (Shiferaw et al, 2013)). Many of the developing countries that depend on wheat as a staple crop are not self-sufficient in wheat production, and accordingly, wheat is their single most important imported commodity. Wheat also accounts for the largest share of emergency food aid (Dixon et al., 2009). An average of 138 MT of wheat have been imported every year during the period 2007-2011 with a total value of 33 billion \$US/year. Among North African countries, Egypt is the largest importer with 9 million tons of wheat imported per year. At the global level, the demand for wheat has quadrupled since the 1960s and doubled over the last four decades. The total global annual demand for wheat has grown at the rate of 2.24% per year since 1960s, but slowed down to about 1% in the last decade (Shiferaw et al., 2013). The demand for wheat is growing fast in new wheat growing regions of the world such as Eastern and Southern Africa (5.8%), West and Central Africa (4.7%) and South Asia and Pacific (4.3%). Demand is also growing in the traditional wheat growing regions of Central Asia (5.6%), Australia (2.2%) and North Africa (2.2%) (Shiferaw et al, 2013).

1.4. Major wheat growing environments and geography

Wheat is a widely adapted crop, growing in diverse environments spanning from sea level to regions as high as 4570 m.a.s.l. in Tibet (Percival, 1921). It grows from the Arctic Circle to the equator, but most suitably at the latitude range of 30° and 60°N and 27° and 40°S (Nuttonson, 1955). Based on the availability of source of water availability, the global wheat production area can be divided into irrigated and rain-fed environments.

1.4.1. Irrigated wheat environment

The temperate irrigated environment is the most important agro-ecological zone for wheat production in the developing world. This environment includes large areas in India, Pakistan, Nepal, Bangladesh, China, Afghanistan, Iran, Turkey, Syria, Iraq, Saudi Arabia, Egypt, Zimbabwe, South Africa, Mexico and Chile (Trethowan et al., 2005). Irrigated cultivation accounts for more than 50% of the wheat production area in the developing world.

1.4.2. Rain-fed wheat environment

Wheat production in this environment basically depends on rainfall, which can be very variable. Most wheat production in the developed world is rain-fed. In the developing world, it includes high rainfall areas such as the Southern Cone countries, parts of the Andean region, Ethiopia, some areas in North Africa and in the Himalayan region of Asia. Production areas with temperate, low rainfall include areas in North Africa, West Asia, parts of Pakistan and Afghanistan, northern India and north-central China, and areas in Latin America including the central Mexican highlands (Rajaram et al., 1995).

1.5. Challenges to wheat production

1.5.1. Climate change: increased heat, drought, emerging diseases and pests

Climate change affects wheat production by increasing both abiotic stresses (heat, drought, cold, salinity and waterlogging) and biotic stresses (aggressive diseases and insect pests). With the current climate change effects, it is anticipated that new pests and diseases will emerge as already exemplified in the recent epidemics of stripe/yellow rust across the Central & West Asia and North Africa and the Ug99 stem rust epidemic in East Africa countries (Solh et al., 2012). The effect of climate change is also affecting the quality of wheat as increasing CO₂

may negatively affect protein quality and content and increasing temperatures can negatively affect grain size. Modelling results indicate that wheat production will be more affected by climate change in the developing countries than the developed countries (Dixon et al 2009).

1.5.2. Limited availability and high price of inputs

As has been clearly witnessed as a result of the Green Revolution, increasing yield per unit area has been achieved mainly through the application and utilization of inputs such as improved varieties, irrigation, fertilizers and chemicals. However, the costs of these inputs are also rising and are sometimes becoming unaffordable to poor farmers in developing countries. Rising energy costs for example have contributed to higher fertilizer prices, directly because the costs of natural gas used to produce ammonia is increasing, and indirectly through higher transportation costs. Such rapid increases in input costs offset wheat production and pose a disincentive to wheat producers (Fig 2).

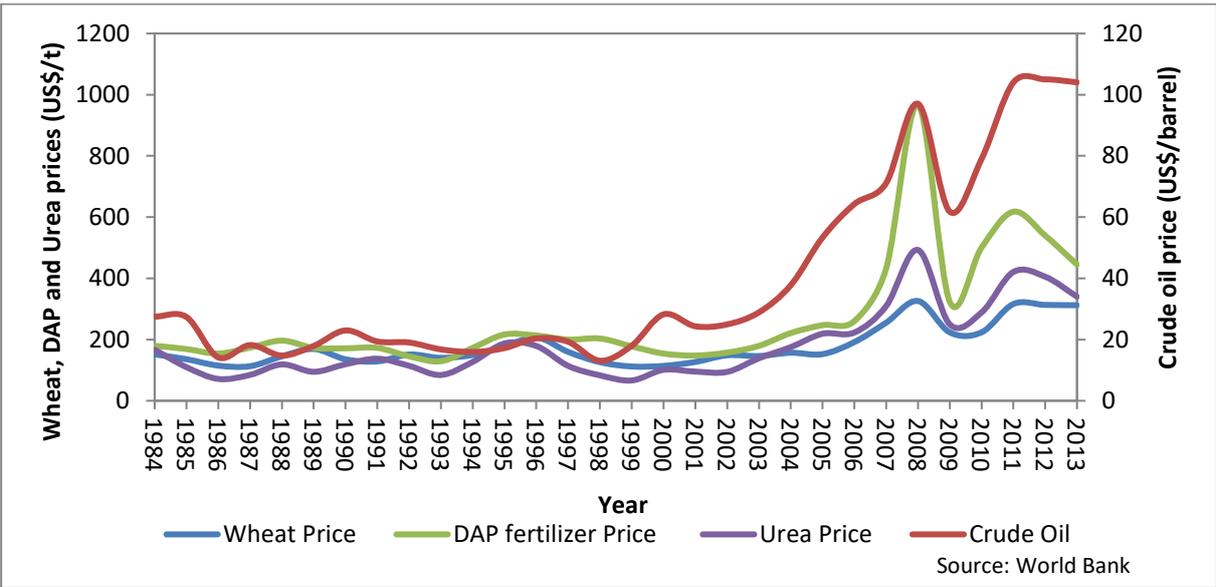


Fig. 2: Trends in world prices of wheat, fertilizer and crude oil.

1.5.3. Increasing demand for biofuel

Though many factors contributed to the “silent tsunami” of food price spikes in 2008, the most recent analysis highlights biofuels expansion as a significant driver of the food price spike (Hayes et al., 2009). Due to high fuel prices and government policies favoring the production of renewable fuel, farmers shift to more productive and high energy value crops such as corn and soybeans on acreage traditionally planted to wheat, resulting in reduced wheat production and an increasing wheat farm price (Table 1).

Table 1: Impact of policy support for biofuel production on wheat, corn and soybean production and prices.

	Commodity	High Energy Price	High Energy Price and No Biofuel Tax Credit	Low Energy Price and No Biofuel Support	High Energy No Bottleneck
Production	Wheat	-2.33	0.10	2.60	-6.98
	Corn	11.03	-0.82	-8.69	35.02
	Soybean	-8.24	0.09	3.51	-29.14
Trade	Wheat	-6.79	0.60	7.11	-21.20
	Corn	-23.36	0.56	23.91	-56.10
	Soybean	-19.57	0.93	10.17	-76.81
Prices	Wheat, farm price	9.36	0.93	-8.98	20.73
	Corn, farm price	19.56	0.65	-18.39	50.72
	Soybean, farm price	8.87	-0.47	-9.87	22.71

Source: Adapted from Hayes et al., 2009

1.5.4. Stagnating yield and increasing world population

After the quantum leap in wheat production attributed to the Green Revolution, wheat yields have recently been rising by only 1.1%/year, which falls far short of demands of a global population that is growing at 1.5% or more, annually. Some estimates show that global wheat production must increase at least by 1.6%/year to meet a projected yearly wheat demand of 760 million tons by 2020. In the year 2050, the world population is estimated to be 9 billion, while the demand for wheat is estimated to reach more than 900 million tons (Dixon et al, 2009).

Fulfilling this demand is challenging amid reports of yield stagnation in major wheat growing regions of the world. Yield stagnation is a complex issue, which might be the result of a combination of factors, such as reaching a genetic ceiling in wheat improvement, declining soil fertility, unfavourable policies and marketing, biotic and abiotic stresses associated with climate change and other factors. Some authors have attributed yield stagnation to having reached a genetic ceiling in India and Europe (Nagarajan, 2005) while others have reported the presence of genetic gain in both spring wheat (Manes et al., 2012; Sharma et al., 2012) and facultative winter wheat (Tadesse et al., 2013). However, it is evident that the potential of new cultivars have not been fully utilized in most of the developing countries due to poor agronomic management, application of incomplete packages of inputs, reduced incentives

and unstable market prices. Recent yield gap analysis at global level in wheat indicated that the range in the difference between potential yield and farm yield in most countries is narrowing (26-69%) with an average of 48% (Fisher et al., 2014).

2. Farming systems

2.1. Commonly practiced farming systems in irrigated environments

2.1.1. Wheat-rice rotation system

The wheat-rice cropping system is the most dominant wheat cropping system in the irrigated environment, particularly in the developing world. In south Asia, it is estimated that the rice-wheat system covers more than 13.5 million ha annually, mainly in the fertile, alluvial Indo-Gangetic Plains of Bangladesh, India, Nepal and Pakistan (Imtiaz et al., 2012). In China, more than 10 million hectares of rice-wheat system is practiced, especially in the central areas of the Yangtze River Valley. In this rotation system, wheat is planted during the cooler and drier winter season after rice, which is normally grown in the warm, sub-humid monsoon, summer months. Both crops are grown during a one calendar year. Other crops, particularly in the winter, are also grown including pulses, oilseeds, potatoes, vegetables, fodders and sugarcane. In recent years, efforts have been made to diversify the rice-wheat system through the replacement of rice with pigeonpea (Ali and Kumar, 2001) and/or by the introduction of short duration pulses such as mungbean as catch crop in summer season in South Asia (Ali and Kumar, 2004). Inclusion of mungbean in rice-wheat cropping system is quite advantageous in terms of physical, chemical and microbiological properties of soils besides higher yield from the system.

2.1.2. Wheat-cotton rotation system

The wheat-cotton rotation system exists as double-cropping in the irrigated environments of South Asia, mainly in India and Pakistan covering annually about 3 and 4 million ha, respectively (Mayee et al., 2008). Such a system also exists in Egypt, Turkey, Uzbekistan and others. The late harvesting time of cotton pushes the wheat planting late into December, which in turn exposes wheat to heat stress during grain-filling in late April and May. The biggest challenge for this rotation comes from cotton residues, immobilizing key nutrients such as nitrogen, sulfur, phosphorus and potassium.

2.1.3. Wheat-maize system

The wheat-maize rotation system is common in the irrigated environments of China, especially in the North China Plain (NCP), which is one of the most important agricultural production regions in China. The NCP, with a dominant winter wheat and summer maize double-cropping system, provides more than 50% of the nation's wheat and about 33% of its maize production.

2.2. Commonly practiced farming systems in rain-fed environments

2.2.1. Legume-wheat rotation system

Legumes are playing an increasingly important role in rain-fed wheat production environments, especially in soils with low N content by enriching soil N through biological N fixation, enhancing water use efficiency (WUE) and breaking the cycle of weeds, pests and diseases, which affect wheat production. Grain legume species and varieties growing in the same location differ significantly in dry matter production, N accumulation, N₂-fixation, N-balance and residue quality (Evans et al., 2001). These differences may be the main factors determining the residual N contribution to subsequent crops. Among the legumes, faba bean is the best nitrogen fixer with a mean of 100kg N/ha, followed by groundnut and soybean (Table 2) (Smil, 1999). Many trial experiments have shown that the introduction of legumes, such as faba beans, chickpea, and field bean, in wheat-based cropping is a viable strategy for reducing the application of inorganic fertilizer and thus reducing the costs for resource poor small and medium scale farmers.

Table 2. Estimates of N₂ fixation per unit area (kg/ha) of the most commonly cultivated legume crops)

Legumes species	N ₂ fixation (kg N/ha/year)		
	Minimum	Mean	Maximum
Common bean	30	40	50
Chickpea	40	50	60
Pea	30	40	50
Lentil	30	40	50
Faba bean	80	100	120
Other pulses	40	60	80
Groundnut	60	80	100
Soybean	60	80	100

Source: Smil (1999)

Winter wheat–summer fallow is the predominant cropping system in the dry areas of the world. Fields are commonly left fallow over summer, as insufficient moisture prohibits the reliable production of rainfed summer crops in the Middle East and North Africa. With the development of short duration varieties of legumes, long fallows (winter plus summer) have been largely replaced by cropping legume crops to increase production through intensified land use (Tutwiler et al. 1997; Pala et al. 2007). The use of food legumes to replace the summer fallow phase of the traditional fallow-wheat system is one of the key components for obtaining a reduced or negative carbon footprint (Gan et al. 2014) besides increased wheat yields, enhanced soil fertility, increased water use efficiency, as well as decreased losses in yield and quality from weeds and soil borne disease (Miller et al. 2002). Typical rainfed wheat-based cropping rotations include food (chickpea, lentil, faba bean, field pea) and feed (*Medicago sativa*, *Vicia sativa*) legumes (Cooper et al. 1987; Pala et al. 1999; Ryan et al., 2008).

In the highlands of Ethiopia, food legume crops are often grown in rotation with cereals or as intercrops to minimize the risks of drought and to manage soil fertility (Higgs et al., 1990; Hailu et al., 1989; Amanuel et al., 2000). In the Bale region of South eastern Ethiopia, two rainy seasons, the Belg (March – July) and the Meher (August-Nov) are available. Both seasons are suitable for wheat production but drought stress is encountered frequently in the marginal rainfall zones in the short season of Belg. Most farmers prefer to plant wheat in the Meher season to minimize the risk of grain sprouting, and keep fallow in Belg season in spite of the experimental data proving that field pea, chickpea, lentil, and faba bean can be planted in the Belg season (Tanner et al. 1994). In a two-year cropping system, wheat after faba bean significantly outyielded wheat-wheat and wheat-barley rotation. According to Assefa et al (1997), faba bean-wheat rotation system has resulted in the increase of wheat yield by up to 77% , and in the reduction of fertilizer N application for wheat production.

Similarly, introducing forage legumes into existing cropping systems at medium altitudes of Ethiopia has provided the opportunity to substitute fallowing of fields and fallow grazing as livestock feed source. Forage legumes such as *Vicia* and *Medicago* species have shown high potential for sequential cropping with wheat. A study indicated that wheat yield could be improved by 55-128% by incorporating vetch or vetch/oat mixtures in the rotation (Keftasa, 1996). This is comparable or slightly higher than the rotation with horse beans, the common rotation crop in the region.

Intercropping

Growing crops in mixtures is a common practice in traditional agriculture in various parts of Ethiopia (Georgis et al., 1990). With the adoption of high yielding semi-dwarf varieties of wheat, wheat monoculture has gained the ground for the past five decades. Despite this, a recent recourse by farmers in northern Ethiopia from growing a pure crop of improved varieties of semi-dwarf wheat to mixed intercropping of wheat with a small population of each of faba bean and field pea has attracted attention from research and development stakeholders. The farmers' reason for such a practice is land shortage coupled with the need to produce a cereal crop in the main and some pulse as an additional benefit, enabling land intensification where arable land scarcity is fast becoming very crucial. In South Asia, systematic research on inter/mixed cropping of wheat + legumes with emphasis on genotypic compatibility and spatial arrangement has led to identification of efficient intercrops, such as chickpea/lentil with wheat. These intercrops, in a particular row ratio significantly increased total productivity and land use efficiency besides improving soil health (Ali and Singh 1997). Studies on wheat + chickpea intercropping revealed that 2:2 row ratio allowed more light interception and transmission to the lower canopy and recorded significantly higher yield and LER than either of the sole crops.

2.2.2. Wheat-fallow cropping system

The Wheat-Fallow (WF) system has been practiced for many years in the semi-arid Western Great Plains of the USA, Russia, the Central Plateau of Turkey and west Iran. The practice is a definite improvement over continuous cropping, as it stabilizes yields and provides farmers with a reliable income from year to year. However, the wheat-fallow cropping system is an inefficient user of annual precipitation in regions where water is the major limiting factor. Production of wheat can be enhanced in this cropping system and more intensive rotations can be sustained by maximizing water storage and building soil residue to trap snow, absorb more rain, reduce runoff and minimize evaporation, as well as perform complete weed control at critical times in the production cycle.

2.2.3. Wheat – oil-crops rotation

Rotation of oil crops, such as canola, rapeseed, sesame and sunflower, is important in the North America, Australia, Asia, and Africa. Such a system provides the opportunity to clean out some grassy weeds that are difficult to control in a continuous wheat production system, to loosen and soften the soil, because of the deep taproots of the oil crops, break disease and insect pest cycles and reduce the risk to farmers through crop diversification.

2.3. Wheat cultivation system

2.2.4. Traditional system

In the traditional system of wheat cultivation, farmers are totally dependent on their traditional know-how, and on the tools and resources available at their disposal. They use the land, rainfall, seeds, tillage methods and power sources they can access to produce whatever nature can offer. Conventional processes are used to till the land, select and plant seeds, protect plants from competing fauna and flora and gather the harvest. Surpluses are marketed through nearby outlets. The productivity of such systems is usually poor and depends primarily on the natural fertility of the soil and the availability of rainfall.

2.2.5. Improved system

Unlike the traditional system, the improved cultivation system relies on the development, accessibility and utilization of innovation, such as modern agricultural inputs, tools, knowledge, resources, technology, management, investment, markets and supportive government policies. Agricultural extension (also known as agricultural advisory services), along with innovation, plays a crucial role in promoting agricultural productivity, increasing food security, improving rural livelihoods, and promoting agriculture as an engine of pro-poor economic growth. Many countries such as Mexico, India, China, Pakistan, Turkey, Iran, Syria, Egypt, have complemented extension services and conducive policies with demonstrated and diffused improved wheat technology packages, including improved varieties, fertilizers, herbicides, fungicides, , modern irrigation systems , mechanization, markets, information improved access to credits.

In Syria, for example, the utilization of agricultural technologies and inputs (improved varieties, fertilizer, irrigation, etc) through enabling government policy and close collaboration between agricultural research and extension system has helped to increase wheat production and

productivity especially after 1992 (Fig 3). As a result of sustainable intensification of wheat production, Syria as formerly wheat importer in the 1970's, and early 1980's became self-sufficient – and an exporter of wheat in 2000's in spite of keep the wheat area almost the same. Between 1991 and 2004 wheat production rose from 2.1 million to about 4.5 million tons, and it reached with a combination of new high-yielding varieties, supplemental irrigation technology and supportive policies. In spite of the very serious drought starting 2008, Syria continued to achieve relatively high productivity and high production. This was due to enabling Government policy, improves varieties (32%), supplemental irrigation (27%), fertilizers (18%) and crop management and other inputs (23%) including herbicides and mechanization. As a result the yield gap between farmers yields and yield potential was narrowed down as shown in Fig. 4..Majid Jamal (2014) has clearly indicated the role of cooperation between the National Research System and several international and regional organizations especially ICARDA has played a major role in capacity developments and joint research to release the famous Sham series of bread and durum wheat varieties which are adapted to both rainfed and irrigated environments in Syria.

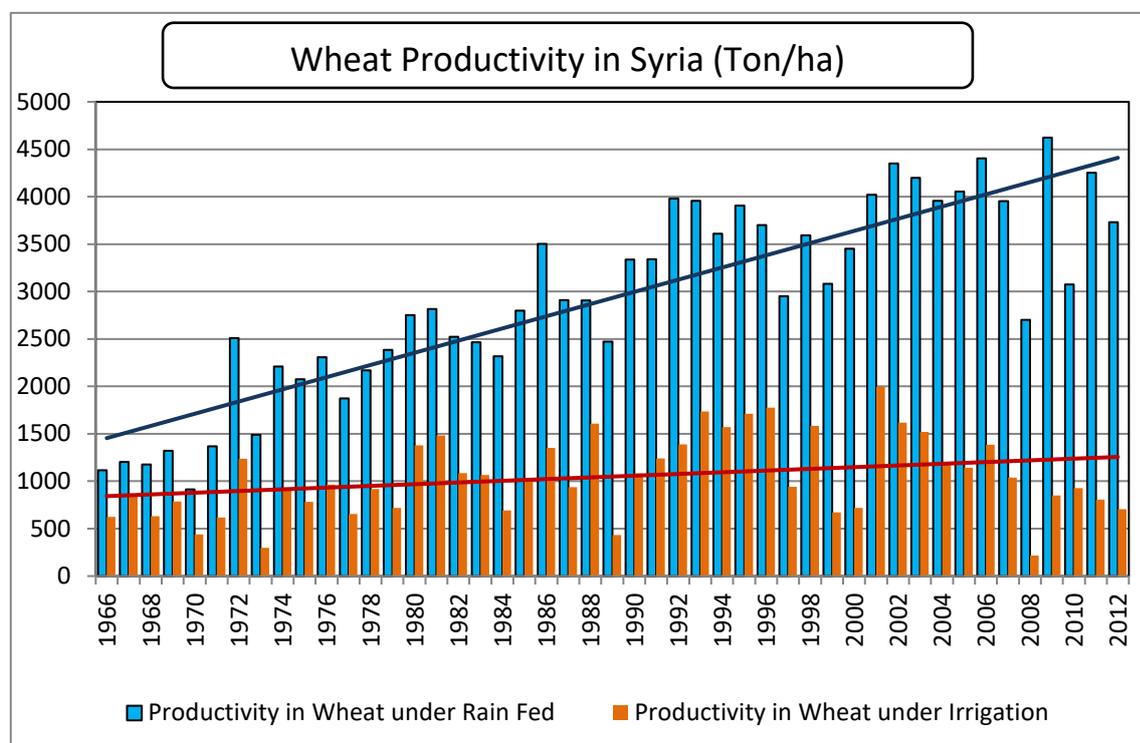


Fig. 3: Wheat production, yield, and area from 1966-2012 (Majid Jamal, 2014)

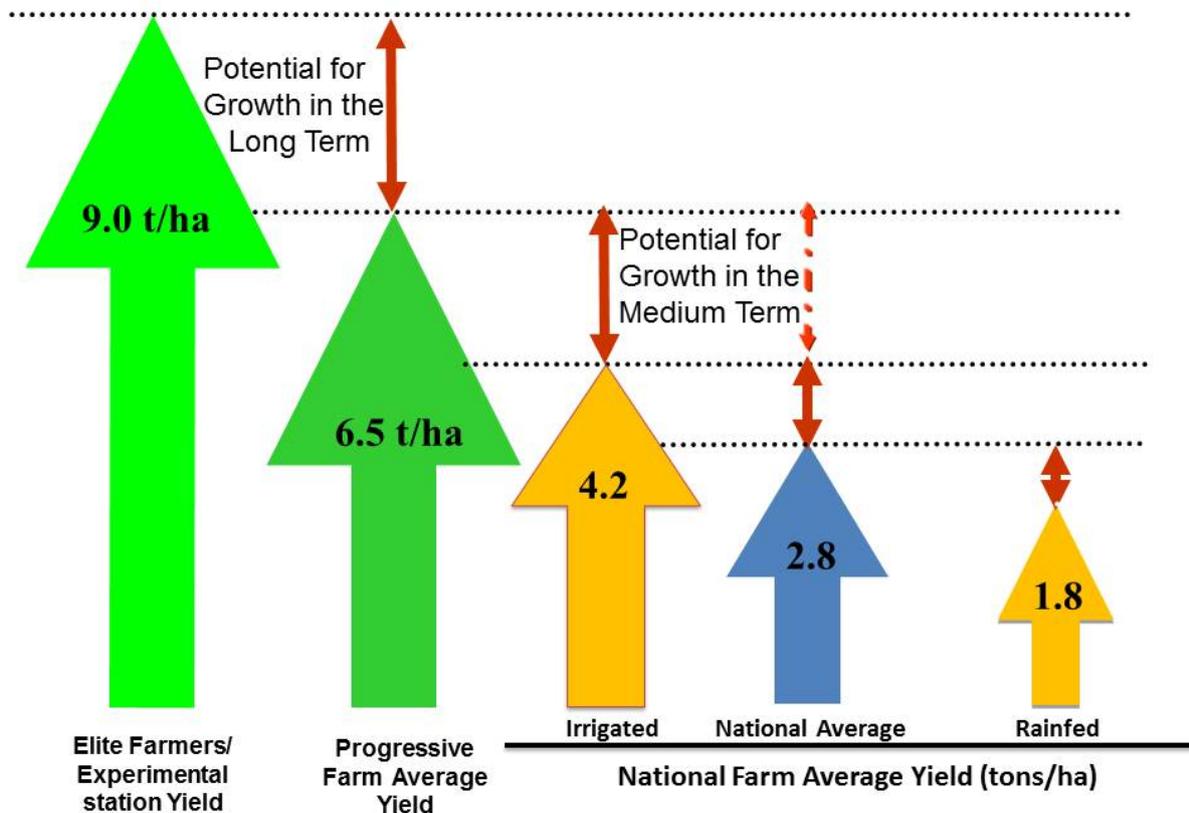


Fig. 4. Bridging yield gap in Syria.

Wheat system intensification by non-governmental organizations has also played a significant roles in demonstrating and diffusing wheat technologies, increasing wheat productivity and bolstering food security. This has been clearly demonstrated by the ICARDA-led food security project for Arab countries.

The project sought to improve wheat production and yields in wheat-based agricultural systems in nine countries: Algeria, Egypt, Iraq, Jordan, Morocco, Sudan, Syria, Tunisia and Yemen. Different adapted approaches were followed in each country to disseminate improved wheat packages (e.g. improved varieties, fertilizers, irrigation frequency and raised-bed management). Yield results of participating farmers in all the countries showed that increases under all production systems (i.e. irrigated, supplementary irrigated or rain-fed systems) were achievable through sustainable intensification of wheat production using improved

technologies as compared to the use of farmers' own practices. An average increase of 28 % was achieved in the fields of participating farmers across all countries involved. Taken separately, the maximum average increase per ha was achieved in Sudan (68% under irrigated wheat systems), and the minimum average increase was recorded in Morocco (8% under rain-fed wheat systems) (Table 3). An impact assessment study conducted in the El Sharkia governorate project site in Egypt showed that after the implementation of the project, there was an increase in the total amount of certified seeds sold to farmers (+21%), in the total area sown in wheat (+8%), in the area of wheat grown under raised beds (RB), in the average productivity (+16%), and, as well as in total amount of wheat sold to the government (+36%). Wheat yield increased from 6.2 t/ha to 7.2 t/ha (+16%). The improvement in yield led to the increase in Al-Sharkia's total wheat amount sold to the Ministry of Supply from 557,030 t in 2009 to 755,496 t in 2013 (+36%). The increase has been estimated to be worth about 36,000,000 US dollars at the conservative wheat price of 180 US dollars per ton (Habib Halila, 2014). In Syria, research results including the new released varieties, fertilizers recommendations, supplemental irrigation methods and total agricultural practices packages were demonstrated with pioneer farmers through extension service and with the help of ICARDA and other organizations. Demonstrations through field days were conducted and the new technologies were spread between farmers. Such an approach has enabled the country to achieve self-sufficiency in wheat and even to export the surplus production (Majid Jamal, 2014).

Table 3. Grain Wheat Yield (t/ha) in demonstration fields versus farmers' fields in selected Arab countries (2010-2014).

Country	Egypt	Jordan	Morocco		Palestine	Sudan	Syria			Tunisia		Yemen	Overall mean
Production system **	I	R	R	SI	R	I	R	SI	R	SI	SI		
Improved practices	8.28	2.24	2.85	6.00	2.02	3.62	1.90	5.11	3.20	5.75	4.03	4.09	
Framers' practices	6.65	1.75	2.53	4.83	1.74	2.17	1.63	4.53	2.60	4.46	2.58	3.22	
Average increase (%)	25	28	13	24	16	67	17	13	23	29	56	28	
Maximum yield	10.35	3.45	4.30	7.50	2.17	5.37	2.96	6.96	4.36	7.90	5.14	5.50	
	56	97	70	55	25	147	82	54	68	77	99	75	

*I=irrigated; R=rain-fed; SI: supplemental irrigation

Another example of intensification is the work conducted by ICARDA and its partners on wheat production improvement in Africa through the SARD-SC (Support to Agricultural Research for Development of Strategic Crops in Africa), a R4D project funded by the African Development Bank (AfDB) and involving 12 low-income regional member countries (Eritrea, Ethiopia, Kenya, Lesotho, Mali, Mauritania, Niger, Nigeria, Sudan, Tanzania, Zambia, and Zimbabwe). A special focus is made in the Project on 3 typical or “hub” countries (Ethiopia, Nigeria and Sudan) where wheat is traditionally grown or consumed to a greater extent; while collaborative research and training is also implemented in the other 9 “partner” countries on a more focused scale to address the specific needs of each of these countries, with all countries benefitting from all project results, through ICARDA-arranged joint planning and coordination meetings, workshops, training events, and exchange of visits and experiences.

During the first two years of the Project, ICARDA and its partners were able to raise awareness among farmers, farmer organizations, decision and policy makers, and a large number of other stakeholders of the wheat value chain. Eighteen Innovation Platforms (IPs) were established and operationalized in the 3 hub countries, where the IPs provided an excellent forum for co-learning, exchanging experiences, and for dialogue among the different stakeholders of the wheat value chain, including policy makers, especially in field days organized during the cropping season. What proved even more exciting is the rapid validation, demonstration and dissemination among farmers and other stakeholders of the impressive performance of the demonstrated technologies, including high-yielding varieties and improved agronomic practices.

The impressive performance of ICARDA’s developed improved and heat-tolerant wheat varieties with yields of 5-6 t/ha— significantly more than 1-2 t/ha average of traditional varieties – convinced policy makers and generated a key policy shift in Nigeria. Accordingly, wheat has been included as a priority in the Nigerian Government's Agricultural Transformation Agenda (ATA) and domestic production is targeted as a solution for curbing ever growing import dependence and for ensuring food security. Within the Government's ATA Initiative, the Government launched a nation- wide scaling up program to expand the land devoted to wheat production— from the existing 70,000 ha to 340,000 ha over the coming five years. Through a wider adoption of improved & heat tolerant wheat varieties, Nigeria set a target to produce around 1.5 million tons of wheat in 2017, guaranteeing a 45-50% reduction in Nigeria’s unsustainable import burden. At current market rates, this reflects a saving of close to \$2 billion each year in import costs.

The IP approach has also proved extremely successful in Ethiopia, Sudan, and other project partner countries to disseminate the new technologies in their own areas. Project researchers and other stakeholders alike are convinced of realizing the targeted transformational impact of increasing domestic wheat production and strengthening food security in their countries, thus significantly reducing the unsustainable wheat imports in the near future.

Similarly, System of wheat Intensification (SWI) approaches have been implemented in Nepal by Mercy Corps, a non-governmental organization, under the EU-FAO Food Facility Programme. As indicated in Table 4, SWI practices using modern wheat varieties raised wheat yields by 91%, reaching a yield of 6.5 ton/ha, compared to the control (3.4 t/ha) (Khadka and Raut, 2011).

Table 4: System of wheat intensification effect on the agronomic traits and grain yield of wheat in Kailali, Nepal, 2010/11

SN	Treatments	Maturity days	# of grains per spike	1000 grain weight (g)	Grain yield (kg ha ⁻¹)
1	Seed priming + row planting	157	75.0	62	6516
2	Seed priming + broadcasting	153	69.6	58	4525
3	No seed priming + broadcasting	145	53.2	52	3738
4	Local seed + local practice	135	44.3	48	3406

Source: Khadka and Raut, 2011

3. Soil health

Soil health is an integrative property that reflects the capacity of soil to respond to agricultural intervention, so that it continues to support both agricultural production and the provision of other ecosystem services. The major challenge within sustainable soil management is to conserve ecosystem service delivery, while optimizing agricultural yields. Various cultural practices, including the use of cover and rotational crops, organic manures, tillage systems, and others have been promoted as management options for enhancing soil quality and health. Soil fertility, soil texture and health have a significant effect on wheat productivity, as it is with other crops.

3.1. Effect of crop rotation with legumes

A traditional element of crop rotation is the replenishment of nitrogen through the use of legumes in sequence with cereals and other crops. It also helps to improve soil structure, and reduces the build-up of diseases, insects and weeds.

3.1.1. Rotation with legumes improves soil fertility, controls soil-borne diseases and nematodes

Wheat-legume rotations are desirable as wheat benefits from the nitrogen fixed by the *Rhizobium* associated with the legume crop, and the legume benefits from the residues produced by the wheat. The advantages of crop rotation include improvement of soil fertility, controlling weeds, pests and diseases, and diversified production, which reduces the risk of total crop failure in cases of drought and disease outbreaks (Wright et al., 2007).

3.1.2. Cover crops as green manures

Cover crops protect the soil from wind and water erosion, suppress weeds, fix atmospheric nitrogen, build soil structure and reduce insect-pests. Green manures also contribute to conserve nutrients from the topsoil as well as the subsoil. The presence of appropriate cover crops increases wheat N uptake and wheat yields, even when the biomass production of cover crops was modest. Late-season cover crops enhance the following season's wheat yield and facilitate reduced tillage in organic crop production (Cicek et al., 2014).

3.2. Integrated soil nutrient management

Researchers and policy-makers must consider several soil and plant nutrient management options to sustain soil fertility, which includes Integrated Nutrient Management (INM) and involves the conjunctive use of fertilizers and organic sources. Eight years of research on INM in a rice-wheat system at Jabalpur (India) revealed that conjunctive use of 5 t/ha Farm Yard Manure (FYM) and 6 t/ha green manure with 90 kg N/ha not only sustained the productivity of wheat, but also saved nearly 90-100 kg/ha fertilizer N (Singh et al., 2001).

3.2.1. Chemical fertilizers

The Green Revolution, which was based on the intensive use of high-yielding varieties of wheat coupled with other inputs like chemical fertilizers and irrigation water was successful in boosting food supply and reducing food prices (Stevenson et al., 2011). Critics of the Green Revolution, however, argue that the excessive application of chemical fertilizers has caused an imbalance in soil health by reducing soil fertility and increasing soil alkalinity. The challenge remains for scientists and farmers to work together to maintain soil health while increasing wheat production to meet growing demand.

3.2.2. Organic fertilizers

Organic manures are traditionally used to supply nutrients to plants. However, the volume of organic manure required to fertilize a unit area of land and other operational problems discourage their use. Organic manure provides nutrients in an efficient way along with improving the soil conditions. Application of farmyard manure (FYM) helps to increase the yield and nutrient uptake by wheat. Incorporation of mustard/taramira + FYM and FYM at 10 t/ha has shown a significant increase in the grain yield wheat across years (Regar et al., 2005).

3.2.3. Site-specific nutrient management

Recent approaches to increasing wheat and other crop yields include site-specific nutrient management (SSNM), which “feed crops” with nutrients as and when they are needed. This specific tailoring for nutrient demand and supply under different production systems contrasts with the blanket recommendations used in conventional approaches. The principles of SSNM are well established and have produced yield and quality improvement in wheat across soils and regions. In Southern India, Biradar et al. (2006) revealed that nutrient application on the basis of SSNM principles resulted in higher wheat grain yields (3.7 t ha⁻¹), which was 23% higher than the Recommended Dose of Fertilizers (RDF) and 39% higher than the farmers’ practice (FP) (Table 5).

Table 5: Yield of wheat (t/ha) as influenced by site-specific nutrient management (SSNM) in different sites of Southern India.

Treatments	Site 1	Site 2	Site 3	Site 4	Site 5	Mean
SSNM	3.70	3.80	3.50	3.60	3.72	3.66
RDF	3.20 (16)*	2.84 (34)	2.96 (18)	3.00 (20)	2.90 (28)	2.98 (23)
FP	2.70 (37)*	2.60 (46)	2.70 (30)	2.64 (36)	2.56 (45)	2.64 (39)

*Numbers in brackets reflect SSNM yield increase (%) over RDF or FP.

3.2.4. GreenSeeker helps in timely application of site specific N-fertilizer in wheat

Blanket fertilizer nitrogen (N) recommendations for wheat production lead to low N-use efficiency due to field-to-field variability in soil N supply and seasonal variability in wheat yield. To achieve high N-use efficiency, a site-specific N management strategy using GreenSeeker™ optical sensor is the best option. High N-use efficiency in irrigated wheat can be achieved by replacing blanket fertilizer recommendations by GreenSeeker optical sensor-based N management strategies consisting of applying moderate amounts of fertilizer N at planting and crown root initiation stages and GreenSeeker optical sensor-guided fertilizer N dosages at Feekes 5–6 or 7–8 stages of wheat (Singh et al., 2011).

The utilization of information communication technologies (ICT), including computers, internet, geographical information systems, mobile phones, as well as traditional media such as radio or TV are playing important roles in large-scale deployment of site-specific recommendations to farmers and extension workers. Decision support systems (DSS) are now progressively used to facilitate application of improved nutrient management practices in farmers' fields. A recently developed DSS, Nutrient Expert for Wheat, synthesized the wheat on-farm research data into a simple delivery system that enables wheat farmers to rapidly implement SSNM for their individual fields.

3.3. Effect of conservation agriculture

Conservation agriculture (CA), which has its roots in universal principles of providing permanent soil cover, minimum soil disturbance and crop rotation, is now considered the principal road to sustainable agriculture and is among pertinent agricultural technologies, which enable increased farm productivity, while conserving the natural resource base.

3.3.1. Improves soil moisture

The decreased soil disturbance with ground cover keeps biological activity and organic matter decomposition near the surface and helps maintain a soil structure that allows greater infiltration of water associated with reduced soil water evaporation rates. Residue retention can also improve the water-holding capacity and long-term nutrient cycling. Moussadek (2012) found relatively lower hydraulic conductivity and absorptivity values under no-tillage compared to conventional tillage systems in the Zaers region of Morocco.

3.3.2. Increases soil organic matter

CA practices enhance soil organic matter levels and nutrient availability by growing green manure/cover crops and returning their residues back to the soil. Thus, arable land under CA is more productive and for much longer periods of time. Increasing soil organic carbon (SOC) content showed positive impacts on soil physical properties, including increased stable aggregates (Mrabet et al., 2012). Moussadek et al. (2014) indicated that after five years of continuous no-tillage, the topsoil (0–30 cm) SOC values increased by 10% in the Vertisol, 8% in the Cambisol, and 2% in Luvisol, compared to conventional tillage.

3.3.3. Reduces erosion and runoff

CA improves soil structure and protects the soil against erosion and nutrient losses by maintaining a permanent soil cover and minimizing soil disturbance. In central Morocco, a reduction of 50% in soil losses was observed with no-till, having less than 2 Mg ha⁻¹ of residue mulch compared to conventional till on a Vertisol (Moussadek et al., 2011). On a Mollisol, no-till reduced the runoff volume by 30-50% and sediment loss by 50-70% compared with disk ploughing. In comparison with chisel ploughing, no-till reduced runoff volume and sediment loss by respectively 24-53% and 43-65%. This will increase water holding capacity and crop productivity particularly in drier seasons.

3.3.4. Improves climate change adaptability and mitigation

CA represents an environmentally-friendly set of technologies. Because it uses resources more efficiently than conventional agriculture, these resources become available for future generations. The significant reduction in fossil fuel use under no-till agriculture results in fewer greenhouse gases being emitted into the atmosphere. Reduced applications of agrochemicals

under CA also significantly lower pollution levels in the air, soil and water. No-till systems reduce the unnecessarily-rapid oxidation of organic matter to CO₂, which is induced by tillage (Mrabet et al., 2012). Soil moisture conservation through zero-tillage and stubble retention improve adaptation to certain climate change implications namely drought and high temperature.

3.3.5. Improves output, factor productivity (efficiency) and resilience

The sustainable use of natural resources through adoption and diffusion of no-tillage systems improves soil quality and enhances crop productivity vis-a-vis climate variability and drought. In Morocco, much of the CA work that has been done in various field situations has shown that yields and factor productivities can be improved with no-till systems (Moussadek, 2012). CA can be used for winter crops and for rotations with food legumes and oil-seed crops, and in field crops under irrigation, where CA can help optimize irrigation system management to conserve water, energy and soil quality and to increase fertiliser use efficiency.

3.3.6. Enables timely operation; use of reduced inputs of energy, labour, water, nutrients, pesticides, machinery and capital

Farmers using CA technologies typically report higher wheat yields (up to 45-48% higher) with less water, fertilizer, pesticides, capital and labour inputs, thereby resulting in higher overall farm profits. Studies of no-tillage systems in Brazil and Paraguay indicated 10–70% saving of the conventional labour input depending on farming system and conventional tillage practice. Other benefits include a more even distribution of labour across the year, more timely operations, a reduction in drudgery, and opportunities for livelihoods diversification (Pieri et al., 2002). Reducing the time draft animals spend in one farmer's field means there is more time available for tilling additional land (if available) or hiring out their services to others. CA has proved particularly beneficial for many small holder farmers who do not have access to animal or mechanical tillage, since it enables them to carry out all their operations on time and precisely, increasing productivity and yield potential.

4. Crops and varieties

4.1. General principles and strategies of variety development

The wheat breeding program at the CGIAR centres (CIMMYT & ICARDA) apply both conventional and molecular breeding approaches and techniques to develop high-yielding and widely adapted germplasm with resistance/tolerance to the major biotic and abiotic

constraints prevailing at global levels in general and in developing countries in particular. Some of these strategies and techniques include classification of Mega-Environments (ME), assembling targeted crossing blocks, shuttle breeding, utilization of doubled haploids (DH), marker-assisted selection (MAS), key location yield trials, distribution of germplasm to NARS through international nurseries, and partnership and capacity building of NARS. As water is becoming ever scarcer, even in irrigated areas, wheat germplasm development at the CGIAR Centers is based on identification of genotypes with disease resistance, high-yield potential and water-use efficiency, so that wheat genotypes targeted for irrigated areas can cope with temporary drought periods. Similarly, this approach minimizes yield losses and maximizes yield gains during drought as well as good seasons, for rain-fed production systems.

4.2. Development and deployment of high-yielding and semi-dwarf input responsive wheat varieties- experiences from the Green Revolution

The continuous supply of improved germplasm from the International Wheat Improvement Network (IWIN), an alliance of national agricultural research systems (NARS), CIMMYT, ICARDA, and advanced research institutes (ARIs) for nearly half a century has made major contributions leading to major gains during and after the Green Revolution, and also enabled developing countries to have a sustained increase of wheat production and productivity, and thereby improving food security and farmers' livelihoods (Payne, 2004; Reynold and Borlaug, 2006, Trethowan et al. 2007; Baum et al, 2013). At the global level, wheat production has increased from 235 million tons in 1961 to 732 million tons in 2013. The success of wheat improvement within the CGIAR has been remarkable. It has been estimated that more than 70% of all spring wheat cultivars grown in developing countries are CGIAR-derived, reaching up to 90% in South Asia (Lantican et al., 2005) as indicated in Figure 4.

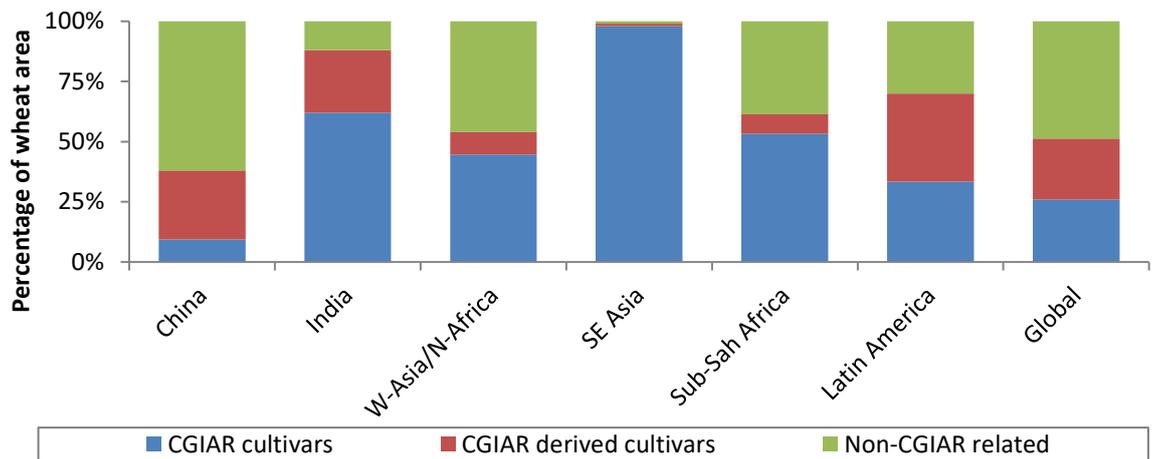


Fig. 4 Proportion of CGIAR and CGIAR-derived wheat varieties in farmers' fields. Source: Lantican et al., 2005.

The impact of wheat research has been witnessed not only by farmers, governments, policy makers and professionals but also by donors. According to World Bank (2008), for no other major crop is the percentage of improved cultivars in farmers' fields in developing countries higher than for wheat.

4.3. Breeding for drought tolerance

Identification and development of wheat varieties combining high-yield potential with water use efficiency can help stabilize yield gains in the face of climate change. The development of wheat varieties with early vigour and cold tolerance has been a major target of wheat breeders in dry land areas, as early and complete canopy establishment shades the soil and reduces evaporative loss from the soil surface, thereby significantly improving water productivity of wheat. High yielding and drought tolerant spring wheat genotypes have been identified from ICARDA's breeding program and their agronomic performance at the Sids Research Station in Egypt for yield potential, at the Wadmedani Station in Sudan for heat tolerance and at the Marchouch station in Morocco, as indicated in Table 6.

Table 6: Performance of elite bread wheat genotypes across key locations in Egypt, Sudan and Morocco, 2013/14

Variety	Marchouch	Sids	Wad Medani	Average	% of the check (Attila-7)
	(t/ha)	(t/ha)	(t/ha)	(t/ha)	
IBW-IMAR	7.11	11.62	3.23	7.32	119%
IBW-AMAL	6.49	12.72	2.50	7.24	118%
IBW-HAMID	7.13	9.56	3.77	6.82	111%
IBW-WAHID	7.31	10.16	2.92	6.80	111%
IBW-BRIVAN	8.98	7.81	3.05	6.61	108%
IBW-FARID	6.39	10.23	3.03	6.55	106%
IBW-OMAR	6.96	9.72	2.65	6.45	105%
IBW-AKID	6.50	9.87	2.94	6.44	105%
IBW-WIDAD	6.51	8.46	3.87	6.28	102%
IBW-TARTUS	5.89	9.39	3.40	6.23	101%
Sids-1 (Check)	5.36	10.88	2.35	6.20	101%
Attila-7 (Check)	6.19	8.40	3.86	6.15	100%
Pastor-2 (Check)	6.24	7.49	3.42	5.72	93%

4.4. Development and deployment of high yielding and disease resistant wheat varieties

Of all the major diseases known in wheat, stem/black rust and stripe/yellow rust are the most damaging and can cause very significant wheat yield losses. Developing and deploying genetically disease resistant varieties adapted to target growing environments is the most economical and environmentally friendly strategy for controlling rust diseases of wheat, particularly for resource-poor farmers. However, because of the co-evolution of the host and pathogen, the deployment of individual resistance genes often leads to the emergence of new virulent pathogen mutants, and hence the ‘boom and bust cycle’ of varieties performance continues. A new race of stem rust first identified in 1999 in Uganda (Ug99) became a threat to the global wheat industry as it overcomes many of the known and most commonly used stem rust resistance genes, such as Sr31, Sr24 and Sr36. Similarly, the breakdown of stripe rust resistance gene Yr9 in varieties derived from “Veery” lineage in the 1980’s, and Yr27 in 2000’s in major mega-cultivars derived from the “Attila” cross, such as MH97 (Pakistan), Kubsa (Ethiopia), PBW343 (India), and others such as Achar in Morocco, Hidab in Algeria and many

other cultivars in the CWANA region has caused significant wheat production losses of up to 70% (Solh et al., 2012).

The CGIAR centres (CIMMYT & ICARDA) have carried out intensive screening and germplasm evaluation activities against the Ug99 race of stem rust at Njoro, Kenya and at Debre Zeit, Ethiopia through the Borlaug Global Rust Initiative (BGRI). High yielding varieties of CGIAR origin with resistance to Ug99 and other diseases such as stripe rust and septoria have been released recently and deployed in many countries (Table 7).

Table 7: Recently released Ug99 stem rust resistant wheat varieties of CGIAR-origin.

Variety Name	Type	Cross/Pedigree	Selection History	Year of Release	Country
KINGBIRD	SBW	TAM-200/TUI/6/PAVON-76//CAR-422/ANAHUAC-75/5/BOBWHITE/CROW//BUCKBUCK/PAVON-76/3/YECORA-70/4/TRAP-1	CMSS99M00216-S-040M-030Y-0030M-16Y-2M-0Y	2007	Kenya
DANPHE	SBW	KIRITATI//2*PBW-65/2*SERI.1-B	CGSS02B00119T-099B-099Y-099M-099Y-099M-24WGY-0B	2008	Ethiopia
HOGGANA	SBW	PYN/BAU//MILAN (= ETBW 5780)	CMSW94WM00188S-0300M-0100Y-0100M-15Y-8M-0Y-0IAP-0QTAP-0YT	2011	Ethiopia
SHORIMA	SBW	UTQE96/3/PYN/BAU//MILAN	ICW02-00330-4AP/0TS-0AP-030AP-10KUL-030KUL-0AP/0KUL-0DZ/0AP	2011	Ethiopia
KARIM	SBW	T.AEST/SPRW//CA8055/3/BACANORA86	ICW92-0477-1AP-1AP-4AP-1AP-0AP	2011	Iran
GOUMRIA-3	SBW	VEE#7/KAUZ	ICW94-0029-0L-1AP-1AP-7AP-0APS-0AP-0SD	2013	Sudan
NORMAN	FWW	OR F1.158/FDL//BLO/3/SHI4414/CROW	ICWH860291-3AP-1AP-0AP-1AP-0AP	2007	Tajikistan
GIZIL BUGDA	FWW	SAULESKU41/SADOVO1	TCI950295-3AP-0AP-0E-1YE-0YE-1YM-0YM	2009	Azerbaijan
NARC-2011	SBW	OASIS/SKAUZ//4*BACANORA-88/3/2*PASTOR[3811];	CMSS00Y01881T-050M-030Y-030M-030WGY-33M-0Y-0S	2011	Pakistan
MUQAWIM 09	SBW	OASIS/SUPER-KAUZ//4*BACANORA-88/3/2*PASTOR	CMSS00Y01881T-050M-030Y-030M-030WGY-33M-0Y-0S	2009	Afghanistan
SUPER 152	SBW	PFAU/SERI.1B//AMAD/3/WAXWING	CGSS02Y00153S-099M-099Y-099M-46Y-0B	2011	India
MISR 1	SBW	OASIS/SKAUZ//4*BCN/3/2*PASTOR	CMSS00Y01881T-050M-030Y-030M-030WGY-33M-0Y-0S	2010	Egypt

4.5. **Breeding for quality**

In most developing countries, apart from grain yield, disease resistance and drought/heat tolerance, grain quality has not been a strong criterion in variety selection. However, some NARS are critically looking for high-quality varieties suited for the preparation of a range of end products. Varieties such as Anza, Bezostaya, HD1220 and Pavon-76 are known for their excellent bread-making quality. These varieties are still dominantly grown in some countries not only because of their wide adaptation, high yield potential and stability, but also because of their high protein content and bread-making quality. With this understanding, the wheat breeding programs at ICARDA and CIMMYT routinely undertake evaluation of germplasm for quality traits following international standard grain quality procedures. Most of the currently available elite genotypes for both irrigated and rain-fed environments are acceptable to excellent in quality, with protein levels of 12 to 16%. Most of these genotypes have the 5+10 (Glu-D1), 7+8 (Glu-B1) and 2* (Glu-A1) glutenin subunit alleles, which are known to be highly correlated with desired protein quality. Recently through the Harvest Plus (H+) Challenge program, progress has been made in the development of bio-fortified wheat with improved zinc (Zn) and iron (Fe) content in wheat grains in addition to protein content and quality. However, because of the negative correlation of yield and these quality traits, it may be difficult to combine high yield potential with high micronutrient grain content.

4.6. **Conservation and utilization of wheat genetic resources**

It is estimated that there are more than 800,000 accessions of wheat genetic resources (land races, wild relatives, elite breeding lines and genetic stocks) held in gene banks around the world. The CGIAR centers, CIMMYT and ICARDA alone, possess more than 150,000 and 41,000 accessions of wheat, respectively. Chapman (1986) determined that genetic resources (landraces and wild relatives) are used in about 10% of crosses at the global level. Landraces have contributed some of the most important genes such as Rht1 and Rht2 for semi-dwarf stature, disease and insect resistant genes and many other important adaptive traits (Kihara, 1983, Roelfs 1988). Synthetic hexaploid wheat is now being used to transfer genes from wild relatives to cultivated wheat for resistance to biotic and abiotic stresses and yield potential per se. (Ma et al., 1995; van Ginkel and Ogbonnaya, 2007; Ogbonnaya et al., 2013). According to Ogbonnaya et al. (2013), synthetic wheats are being utilized as parents both at ICARDA and CIMMYT breeding programs extensively. It is anticipated that the development of the Focused

Identification of Germplasm Strategy (FIGS) and the availability of new molecular tools such as genotyping-by-sequencing (GBS) would hasten and facilitate the characterization and mining of novel genes and alleles effectively and rapidly from such gene bank accessions (Ogbonnaya et al., 2013) and enhance their utilization in the wheat improvement programs at global level.

4.7. Seed production and distribution

Modern varieties and seed technology play a significant role in increasing agricultural production and productivity, ensuring food and nutritional security and improving livelihoods of farming communities. A robust seed system provides farmers with sufficient quantity seed of appropriate quality at the right place and time, and at reasonable cost. There are relatively well functioning wheat seed sectors across most developing countries, although it is dominated by the public sector, both in terms of agricultural research (varietal releases) and seed delivery (quantity supplied). The diversification of the national seed sector led to the emergence of a private sector in wheat seed delivery in countries like Egypt, India, Morocco, Pakistan and Turkey (Bishaw, 2004). However, wheat being a self-pollinated crop, farm saved seed continues to dominate the landscape. As a result, the varietal replacement rate measured by the average age of varieties in farmers' fields and average annual seed renewal rate measured by farmers regular purchase of certified seed remain low, with over 10 years and less than 20%, respectively. These figures are still worse in less favourable rain-fed areas and less accessible remote regions. ICARDA's two approaches to wheat seed delivery are described below.

4.7.1. Seed production and delivery in the formal sector: Cases in Egypt, Ethiopia and Pakistan

In recent years, the emergence of rust threats and food price spikes triggered renewed interest in food security in general and wheat seed supply in particular. For rapid deployment of stem rust resistant wheat varieties in Egypt, Ethiopia and Pakistan, ICARDA, supported by a USAID project from 2009-2012, developed a strategy to fast-track testing and release of rust resistant wheat varieties; massive popularization-and-demonstration and accelerated seed multiplication of early generations (breeder, pre-basic and basic seed) by NARS; and large-scale certified seed production by linking to existing public and/or private seed enterprises

and on-farm seed production with farmer groups. In total, two varieties in Egypt, eight varieties in Ethiopia and five varieties in Pakistan were released and substantial quantities of seed were produced and distributed under an accelerated scheme within the shortest possible period of time. In Egypt, 10,760 t certified seed were produced, which was sufficient to plant 7% of the total wheat area in Egypt; in Ethiopia, 27,000 t were produced sufficient to plant 10% of Ethiopia's total wheat area; and in Pakistan, 42,750 t certified seed were produced, sufficient to plant 5% of the total wheat area in Pakistan in 2011/13. Popularization and promotion of rust resistant varieties was reaching over 5,000 farmers every year in each of the three target countries.

4.7.2. Seed production and delivery in the informal sector: A case in Ethiopia

In Ethiopia, a similar approach was used for the deployment of stripe/yellow rust resistant varieties from 2011 to 2014 with USAID support. Apart from direct support to formal sector operations with NARS and commercial seed enterprises, the project brought seed directly to 45 target districts, working with farmers and district agricultural offices. In each district, 100 farmers were identified, clustered, provided with seed of rust resistant varieties sufficient to plant 0.25 ha and trained along with development agents on technical aspects of seed production. These were linked to regional seed inspection services to ensure seed quality. During the last three seasons, the project distributed directly 815 tons of stripe/yellow rust resistant varieties seed through on-farm seed production and technology scaling-out, planted on 5,6, 000 ha and producing 18,718 tons seed/grain potentially sufficient to plant 127,377 ha. The project directly reached 19,877 farmers (7.3% of whom are women farmers) benefiting 119,262 household members in four major wheat producing regions. In some target districts, a substantial wheat area is planted with stripe/yellow rust resistant varieties. The multiplier effect will be considerably higher as parts of the produce continue to be used as seed for planting purposes in subsequent years, leading to substantial area coverage with Ug99 and stripe/yellow rust resistant varieties.

5. Wheat water management

5.1. Wheat crop water needs

Bread and durum wheat water requirements vary depending on the environment and the variety used. Generally, the range of wheat's seasonal water needs is between 450mm and 650mm. Wheat can tolerate lower water supplies, but usually yields are lower when exposed to water stress. Generally, spring wheat is more sensitive to stress than winter wheat and flowering stage of growth for both types is the most sensitive to water shortage. The upper limit of wheat yields is 10-12 t/ha and wheat water productivity is about 2 kg/m³ of net water use, which is only attainable under favourable conditions and good management (Passioura and Angus, 2010). In developing countries, wheat yields are still low compared to developed countries and the wheat productivity per unit of water can be as low as 0.5 kg/m³ (Periera et al., 2002). Wheat yields drop with water stress and good water management is critical to enhancing wheat productivity especially in water scarce regions. Most of the produced wheat is from rainfed areas with green water use dominating, as is the case in the temperate and subtropics with winter rainfall. Supplemental irrigation is applied to rainfed wheat in areas where water resources are available. However, irrigated wheat is also important especially in dry areas where rainfall is limited in winter and in tropics and subtropics where the main rainfall is in the summer (Rockstrom et al., 2010).

As water scarcity is increasing in many parts of the world, the need to increase wheat water productivity/water use efficiency is crucial, especially in developing countries where there is still great potential for improvement (Figure 5). As this is also associated with food security, increasing wheat production per unit of water is a top priority policy concern for countries who are net importers of wheat and who depend on wheat as a staple food crop. This section focuses on the means of improving wheat productivity through better water management both of rainfed and irrigated systems.

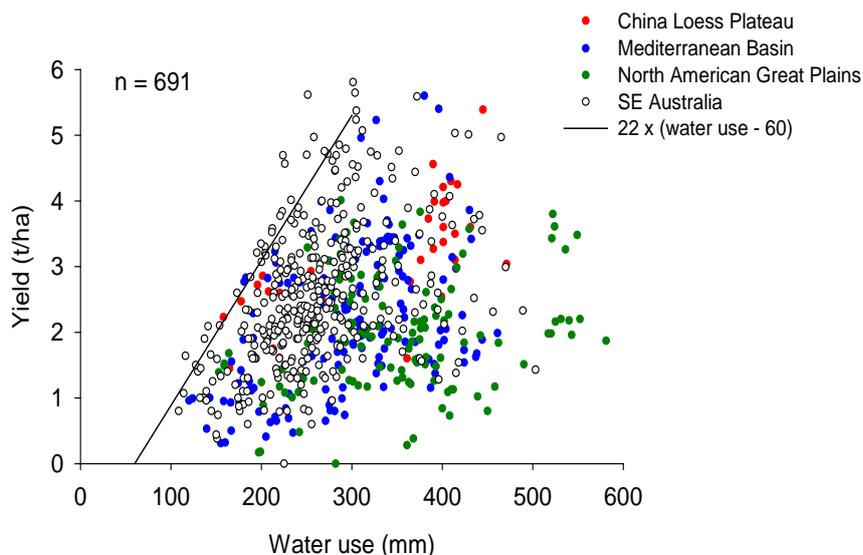


Figure 5. Wheat water use efficiency in different regions of the world. (Sadras and Angus, 2006)

5.2. Water management of rainfed wheat

5.2.1. Dryland wheat

5.2.1.1. Soil-water management

Soil characteristics play a vital role in dryland wheat production. As rainfall is variable and its timing unpredictable, soil water storage provides water reserves during drought spells. The soil depth and its water holding capacity determine how much water can be stored in the wheat root zone. Heavier and deeper clay/loamy soils store more water than lighter and shallower sandy soils. It is not easy or economic to increase the soil's water holding capacity, but small long term improvements can be achieved with proper soil-crop management. Soil surface preparations should allow maximum infiltration of rainwater into the soil. Often there are some problems in areas with low annual rainfall, but losses below the root zone or in runoff occur in areas with high rainfall, especially when it is intensive. Climate change is expected to cause an increase in rainfall intensity in some areas, which is likely to increase runoff and reduce infiltration into the soil. This will negatively impact rain-fed wheat soil water availability. Micro catchment water harvesting approaches, such as contour ridges and small pits, can help overcome this problem (Oweis et al., 2012). Other aspects of soil management include nutrient management and controlling soil compaction, both of which affect soil water use by wheat.

5.2.1.2. **Water use-efficient practices**

Two main strategies are available to increase water use efficiency in rain-fed wheat production systems. The first is to suppress evaporation losses that are usually unproductive. Evaporation from soil surface is the main loss of rainwater that otherwise would support crop growth. In a Mediterranean environment, this loss can be as high as 30% of annual rainfall (Zhang and Oweis, 1999). Practices that reduce soil evaporation include zero or minimum tillage, early and vigorous crop cover and keeping crop residues on the soil surface.

The second strategy is to select the appropriate wheat variety for the conditions in the field and associated good cultural practices. Varieties that can extract deeper soil water, tolerate some soil water stress and have higher harvest index are usually more water use efficient. Other agronomic practices such as fertility and weed, pest and disease control are necessary to achieve higher water use efficiency in rainfed wheat production systems (Molden et al., 2010).

5.2.1.3. **Supplemental irrigated rain-fed wheat**

Rainwater is often not enough to satisfy wheat crop water requirements as is the case in the dry and sub humid areas and/or non-uniform and variable rainfall regions, where even if the total amount is enough, the timing and the storage capacity of the soil do not meet the needs of the crop. In such conditions, water stress often occurs causing low yields and poor water use efficiency. In many countries, wheat yields are as low as 0.5-2.0 t/ha, where the potential can be 4-5 t/ha. This is mainly due to the occurrence of a drought spell during the growing season affecting crop growth and yield. Supplemental irrigation (SI) is the addition of limited amounts of water to essentially rain-fed crops, in order to improve and stabilize yields during times when rainfall fails to provide sufficient moisture for normal plant growth. SI is an effective response to alleviating the adverse effects of soil moisture stress on the yield of rainfed crops, including wheat during dry spells. Unlike full irrigation, the timing and amount of SI cannot be determined in advance given rainfall variability. SI in rain-fed areas is based on the following three basic aspects (Oweis, 1997):

1. Water is applied to a rain-fed crop that would normally produce some yield without irrigation.
2. Since rainfall is the principal source of water for rain-fed crops, SI is only applied when the rainfall fails to provide essential moisture for improved and stable production.

3. The amount and timing of SI are optimally scheduled not to provide moisture stress-free conditions throughout the growing season, but rather to ensure that a minimum amount of water is available during the critical stages of crop growth that would permit optimal yield.

5.2.1.4. Full and deficit supplemental irrigation

Full supplemental irrigation is meant to provide wheat with an amount of water equal to the difference between crop water requirement and effective rainfall. In other words, to provide stress free soil water for the crop that may produce, if other inputs are optimal, maximum yield. This can be attained by monitoring soil water and irrigating just before crop soil water stress begins. This strategy can bring maximum benefits to the farmer when water resources are available and can be delivered at low cost. However, in water scarce regions SI is not recommended as this is not sustainable. Instead deficit supplemental irrigation is more appropriate to save water resources for longer farmers' use.

Deficit supplemental irrigation is a strategy based on applying amounts of irrigation that are less than full crop water requirements. This means exposing the wheat to some moisture stress. Research by ICARDA and others have shown that cutting supplemental irrigation by 50% reduced wheat yield by only 10-15%. This is below maximum yield but would maximise the water productivity (water use efficiency). The saved water if applied to another area grown with a rainfed crop would result in higher total farm productivity. Maximizing water productivity of wheat with reasonable land productivity is a more sound strategy for areas with more limiting water than land.

5.2.1.5. Water resources for supplemental irrigation

Most of the rainfed areas lack water resources for SI, and dryland farming is a must. However, when small amounts of water can be secured, SI will bring substantial increases of wheat productivity. In northern Syria, applying SI once to three times (100-300 mm) in the spring increased wheat yields from 2 to 6 t/ha and water productivity from 0.5 to 2.0 kg/m³ of water. This is a huge return for a small amount of water. Many fully irrigated schemes can provide water in the rainy season for wheat SI such as the Tadla irrigation scheme in Morocco and the Euphrates schemes in Syria. In other areas, ground water is available and is being used for SI.

This should be dealt with carefully as to not allow mining of the aquifer, which is already happening in many regions. Policies to discourage over-pumping of ground water should be implemented in these areas. Surface streams and runoff water can also be used through water harvesting. Generally, water used in SI of wheat has very high returns, and when possible water resources may be reallocated to this highly water use efficient practice (Oweis and Hachum, 2012).

Most of the farmers in developing countries use SI methods such as furrows or small basins to supplement wheat water needs. Sprinkler irrigation is also common in many areas but requires more investment in equipment and energy. As water is applied occasionally, smaller systems are required to cut on cost. The best option, however, is to use existing irrigation systems in fully irrigated areas.

SI can also be used to adjust crop calendar by planting early before rainfall starts. This can be used to avoid drought and/or frost, and match crop growth stages with more favourable conditions. Research in the central Anatolian highlands of Turkey and western Iran has shown that early wheat sowing by applying 50-70 mm of SI increases wheat yields by over 2 t/ha. Finally, more inputs such as fertilizers can be applied and high yielding varieties can be used, when favourable soil moisture is secured with SI (Ilbeyi et al., 2006).

5.2.1.6. Supplemental irrigation and climate change

Climate change will have negative impacts on water resources and agriculture in the dry areas. Rain-fed agro-ecosystems, especially, will be further stressed as a result of increasing temperature, reduced precipitation, and prolonged droughts. Climate change effects are expected on crop productivity, water resources, and ecosystem services (Oweis and Hachum, 2012).

Higher temperatures and CO₂ levels will likely change the wheat growth patterns and duration by shortening the growth cycle and altering the phenological stages. However, higher early spring temperatures and fewer frost days may improve the early growth and vigor of the plants. With higher CO₂ levels, plants may transpire less. A combination of increased temperature with increased atmospheric levels of CO₂ will modify crop water use patterns, affecting the soil water status and the moisture uptake by the crops.

It is, therefore, necessary that adaptation measures be developed in advance to overcome climate change impacts of wheat production. For rain-fed wheat, the strategies may need to encompass improved water management, crop improvement, cultural practices, policies, and socioeconomic and other issues. SI, however, can play an important role in the adaptation efforts to climate change for rain-fed wheat.

SI can be used to overcome the changes in soil-water-plant relations, especially in alleviating soil water stress resulting from changes in crop water use and crop patterns. As rainfall is unpredictable, SI becomes the most viable practice to alleviate moisture stress caused by increased temperature. Another mitigation option is the possibility of changing planting dates. With SI, this can also help adaptation to global warming. With the help of SI, early planting is possible and the growing season can start relatively early.

Less and more erratic precipitation is expected in many wheat areas as a result of global warming. Lower precipitation will cause a further moisture stress on already stressed rain-fed crops. More erratic and intensive rainfall and prolonged drought spells are expected to make the crop situation even worse, and further drops in yields are expected as a result. SI provides some water to compensate for lower rainfall and less moisture storage, and it alleviates soil water stress during dry spells. It is however, important to quantify the changes in rainfall characteristics and the duration of potential drought spells in order to design SI schedules to adapt the system to climate change.

Higher intensity rainstorms are also predicted. This naturally will cause more runoff and soil erosion in rain-fed areas, especially on sloping lands. The proportion of the precipitation that normally infiltrates the soil to support plants growth will be less as more runoff will head downstream. SI combined with water harvesting can provide workable solutions to this problem. Macro- and micro-catchment water harvesting are effective strategies for intercepting runoff and storing water either in the soil profile or in surface and groundwater aquifers. Water stored in the soil may support plants directly or it can be used for SI during dry spells, if stored in small reservoirs or ground water aquifers. This model is being researched and tested in many places and should provide a good platform for overcoming the effects of climate change on runoff (Oweis et al., 2012).

5.2.2. Water management of irrigated wheat

Wheat is fully irrigated in areas where seasonal rainfall/soil water is not sufficient to practice dry farming continuously and economically. In areas with winter rainfall, if total seasonal rainfall is less than 250-300 mm, then wheat needs to be fully irrigated. Generally, when more than half of wheat water requirements is provided by irrigation it is considered irrigated wheat. Rainfall, however, contributes to irrigated wheat water needs either directly during the growing season or as soil water residual from the previous season. In major wheat irrigation schemes like those in the dry areas of Egypt and Iraq, little rainfall may contribute, but in other areas with higher winter rainfall more contribution may be guaranteed.

As rainfall is unpredictable, it is difficult to schedule irrigation based on expected rainfall events. This is why irrigation is scheduled at the beginning of the season with the assumption of no rainfall. Schedules then are adjusted, when rainfall occurs. Residual soil moisture, however, can contribute in the early stages of wheat growth. Farmers schedule irrigation of wheat based on water delivery pattern. Applying 500-600 mm seasonal irrigation may be done in 5-10 irrigations depending on water supply, soil type, weather and irrigation system. It is important, however, that minimum stress is ensued during flowering/grain filling growth stages (FAO 2006).

5.2.2.1. Irrigation systems

Most of the farmers use surface irrigation systems to irrigate wheat such as furrows, border strips and basins. The advantages of those systems are that they are low in cost, easier to the farmers to construct, operate and maintain. Irrigation efficiency of surface irrigation, however, is lower and in some cases farmers may lose up to 50% of farm water delivery in deep percolation and runoff. These losses at the farm level can be recovered at the scheme or basin level, but at cost to the farmer and other users. Losses in wheat surface irrigation systems can be substantially reduced through improving the systems by providing gated pipes and surge flow practice for furrow irrigation and land grading for borders and basin systems. One of the improved surface irrigation packages is the raised bed package described below (Periera et al., 2002).

The modern irrigation system suitable for wheat growing is mainly sprinklers. Those range from simple line source sprinklers to the more sophisticated centre pivot systems. Those systems are widely used for wheat production, especially in dry areas. Irrigation efficiency is

usually high at 65%-75%, and water can be provided at closer intervals with fertigation. These advantages improve productivity and reduce water losses at the farm level. However, capital needs and skills to operate the system by the farmer is often a problem. Energy cost in addition limits the use in many areas. Drip irrigation is too costly to be used for wheat and most of the farmers are not skilled or equipped to operate the system and maintain it. Many farmers were attracted to drip irrigation, but because it was costly and maintenance was a serious problem, since there are no services provided, many farmers converted back to surface irrigation.

5.2.2.2. **Raised bed planting**

In raised bed planting, wheat is grown in elevated strips of 1-1.25 m width between large furrows. In Egypt, since water is provided free of charge, ICARDA and the national research institutes failed to convince the farmers not to over-irrigate wheat. They started a program to adapt the raised bed practice within an integrated package at farmers' fields in the Delta. The setup of the furrows at wide spaces encouraged the farmers to reduce water application as furrows cannot take more water, as is the case with close spacing in the traditional practice. The result of several years of research was that farmers automatically cut on water application by over 30% without any loss in yield. Additional improvement in the package included better fertility, weed control and landscape of the crop. The overall package increased yield by 25% and water use efficiency by over 50%. Furthermore, an innovative adaptation of an implement to construct the furrows and the beds with a seed drill to sow wheat and other crops at the same time revolutionized water savings and yields for smallholder farmers in Egypt's Nile Delta (Figure 6). Over the last three years, nearly 42,000 hectares are now planted by the machines using the developed package. The machine and the package are now being out-scaled to irrigated wheat areas in Eritria, Ethiopia, Iraq, Morocco Nigeria, and Sudan (ICARDA, 2013).

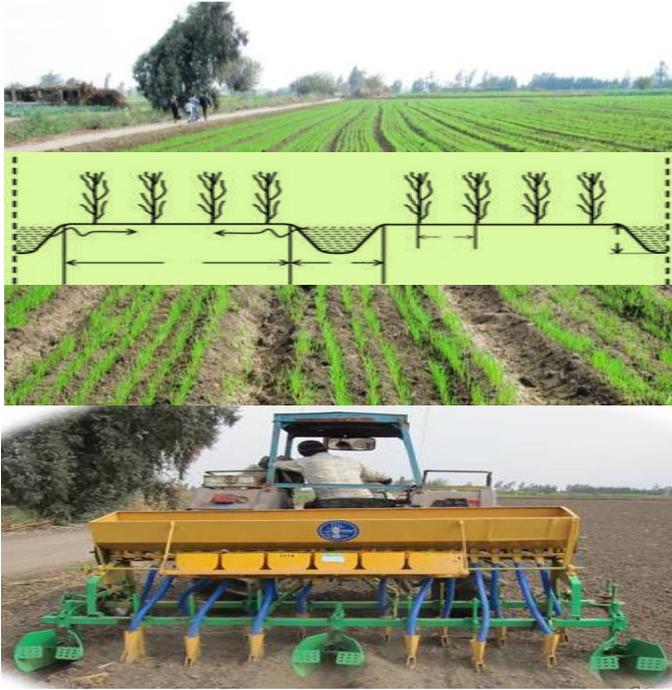


Figure 6. Mechanized raised bed wheat plantation in the Delta of Egypt. (ICARDA, 2013)

Irrigation to maximize water productivity

With water scarcity increasing, it is vital that water be more wisely used in irrigating wheat. In many wheat growing areas water became the most limiting input to production. Maximizing wheat water productivity aims at improving production, and achieves higher food security. Research at ICARDA shows that deficit irrigation of wheat can save 20-30% of the water, with only 5-10% reduction in yield. As land is not the most limiting natural resource, the saved water can be applied to new land with much higher production than the reduced yield associated with deficit irrigation. This is maximizing water productivity instead of land productivity (Figure 7). More gains can be achieved with deficit supplemental irrigation of rainfed wheat as indicated earlier. Other ways to improve water productivity is to suppress evaporation from soil surface by minimizing soil wetting and fast crop cover. Providing balanced nutrition and control of pests and diseases improves water productivity (Periera et al., 2002).

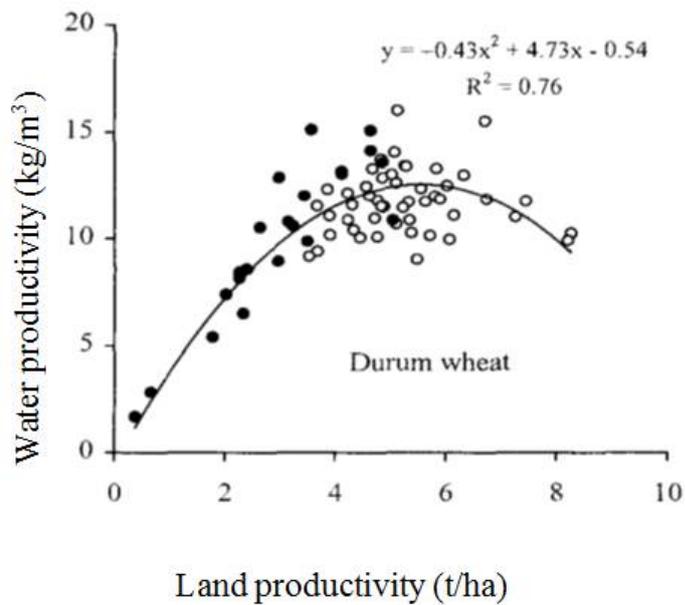


Fig. 7 .Relationship between water productivity and land productivity for durum wheat in a Mediterranean environment (Zhang and Oweis, 1999).

6. Plant protection

6.1. Major wheat pests

6.1.1. Wheat diseases and their economic importance

Wheat is affected by many diseases such as rusts, septoria, tan spot, fusarium, powdery mildew, the bunts and smuts, take-all, and root rots. Yield loss estimates for each disease vary from country to country and season to season. At the global level, the three rusts (stem/black, stripe/yellow and brown/leaf), septoria, fusarium head scab, and powdery mildew are significant diseases causing considerable yield losses. Epidemics of stem rust and stripe/yellow rust have been reported in many countries. Recently, in 2010, yellow rust epidemics were reported in the CWANA region causing yield losses of up to 80% (Solh et al., 2012). Stem rust epidemics can cause up to 100% yield loss as witnessed recently in the Bale region of Ethiopia. Yield losses by *Septoria tritici* can range from 3-35%, although in some cases it can easily exceed 50% (Duveiller et al., 2007). Fusarium head blight, also called head scab, is considered a potentially increasing problem in several countries mainly due to problems of mycotoxins in the grain. Powdery mildew is mostly common in winter wheat and yield losses can range from 5% to 45% (Conner et al., 2003). Powdery mildew also affects grain quality and therefore wheat selling price.

6.1.2. Major insects (major insects and losses estimated)

Of all the insects attacking wheat crop, Hessian fly, Sunn pest, wheat stem sawfly and Russian wheat aphids cause significant economic losses. Hessian fly, *Mayetiola destructor*, damage can result in total loss of the crop if high infestations occur in the early stages of crop development. In Morocco, bread wheat and durum wheat yield losses due to Hessian fly have been estimated annually at 36% and 32%, respectively, amounting to about US\$200 million/annum (Lhaloui et al. 1992). Sunn pest, *Eurygaster integriceps* Puton, affects some 15 million ha of wheat in West and Central Asia.

6.1.3. Weeds

6.2.

Both grass and broadleaved weed species are common in wheat and can cause 10-65% yield reduction due to competition, allelopathy, by providing habitats for pathogens as well as serving as alternate host for various insects and fungi, and by increasing harvest costs. Besides, weed seeds harvested and stored together with wheat can contribute to the proliferation of insect pests and microbes during storage, during milling can reduce flour quality, and therefore the revenues for millers and farmers by threatening the marketability of their products.

6.3. Control measures/strategies of wheat pests

6.3.1. Use of resistant varieties

6.3.1.1. Wheat rust resistant varieties: example resistance to Ug99 stem rust and Yr27

The use of rust resistant varieties is the most economical and environmentally friendly solution to combat rusts. However, accelerated replacement of susceptible cultivars requires close collaboration among research, seed production and dissemination, extension services and farming communities. A prime example of such coordinated efforts was witnessed recently in Ethiopia to combat the Ug99 stem rust and stripe/yellow rust problems. CGIAR origin (CIMMYT and ICARDA) wheat genotypes were tested and released by the Ethiopian Institute for Agricultural Research. This was followed by formal and informal seed multiplication systems and rapid diffusion of the varieties through the extension system of the Ministry of Agriculture, which resulted in covering an estimated 80% of wheat area by yellow rust or Ug-99 stem rust resistant wheat varieties. Such a strong collaboration and coordination

among the different stakeholders enabled the increase of wheat production from 1.61 Mt in 2003/04 to more than 4 Mt in 2014 – the highest ever and more than doubling in a decade. Development and deployment of resistant varieties against the Ug-99 race of stem rust and the Yr-27 virulent race of yellow rust have been carried out by many countries including Egypt, Iran, India, Pakistan, Nepal and Bangladesh.



Fig 8. Response bread wheat genotypes to stem and yellow rust at Kulumsa, Ethiopia, 2013

6.3.1.2. Reducing susceptibility to insects – the example of Hessian fly resistant wheat varieties in Morocco

Through joint efforts between the National Institute of Agricultural Research (INRA), Morocco, and ICARDA, and in collaboration with Kansas State University, ten resistance genes to Hessian fly have been identified in bread wheat. In addition, over a hundred other sources of resistance have been identified in wild relatives of wheat (El Bouhssini et al. 2012). Three bread wheat varieties ('Massira' in 1996, 'Arrihane' and 'Aguilal' in 1998) have been released in Morocco. Despite similar efforts on durum wheat, only a single source of resistance has been identified to Hessian fly in Morocco. However, resistant lines were developed through the introgression of genes from bread wheat and wild relatives (*T. araraticum*) into durum wheat. Six resistant cultivars ('Irden', 'Chaoui', 'Marwane', 'Amria', 'Nassira' and 'Faraj') of durum wheat, with good grain quality and adaptation to Mediterranean dry lands were released in Morocco in 2003 and 2010.



Fig 9. Response of resistant and susceptible bread wheat varieties to Hessian fly in Morocco

6.3.2. Chemical control (fungicides, insecticides, herbicides)

The use of chemicals to control pests is widespread around the globe although their use differs according to the type of cropping system and the availability, purchase capacity and knowledge of farmers.

Fungicides

In most developing countries, fungicides are applied when disease resistance of the wheat cultivars is broken. Sometimes, major losses are encountered due to the unavailability of chemicals, or unpreparedness and poor scouting and surveillance programs. In developed countries, fungicides are part of the wheat production package. Even the most resistant cultivars often gave profitable yield responses to fungicide treatment, indicating that disease resistance rarely covered all diseases and that fungicide treatment may have positive physiological effects on the crop (Barlett et al., 2002).

Insecticides

Sunn pest is the only insect pest where insecticides have been used for large scale control in wheat production. This task was usually performed by governments in Central & West Asia and Eastern Europe using areal sprays, since 15 million hectares of wheat are affected by Sunn pest. However, this approach has been replaced with ground applications and in some of the countries this operation is implemented by farmers after the introduction of integrated pest management packages. This has resulted in large savings of chemical use, as only fields infested by Sunn pest, and where the economic threshold of the insect population is reached, are sprayed.

Herbicides

Herbicides vary in their effectiveness and the time of safe window of application in wheat. Commonly used herbicides include 2,4-D ester and glyphosate. Application of a single chemical frequently at higher doses might result in the development of herbicide-resistant weeds. The best way to avoid or slow the build-up of herbicide resistance is to use a rotation of herbicides with different modes of action, so that resistant weeds do not build up in the population. The use of a good crop rotation will help make alternative herbicide selection easier. Cultural control methods such as the use of weed-free seed and tillage may be utilized to combat herbicide resistance.

6.3.3. Use of cultural practices to control of diseases, weeds and insects

Several cultural measures are known to reduce wheat diseases and pests. These include delayed sowing, ploughing rather than non-inversion tillage, crop rotations avoiding wheat and maize as preceding crops, reducing nitrogen input and lowering seed rates.

Sowing date: Early sowing favors many diseases such as take-all, eyespot, rust and septoria tritici blotch. On the other hand, planting early reduces the risk of Hessian fly and terminal drought. Late sowing increases the risk of powdery mildew and yellow rust in spring; increases Hessian fly damage, exposes the crop to terminal drought and heat stress, and thereby reduces yield.

Low and high crop densities: Seed rate recommendations vary, depending on whether wheat is irrigated or rain-fed. Seed rates also depend on planting dates. Low seed rates can help in reducing the risk of lodging as low seed rates strengthen both the stem and the coronal roots responsible for anchorage. Low seed rates also help in increasing water use efficiency especially in dry areas. However, low seed rates may increase weed population.

High input of nitrogen: Application of high dosages of nitrogen fertilizer increases development of foliar diseases such as septoria tritici blotch, rusts, powdery mildew and increases lodging. It may help to reduce weed populations and increase yield.

Crop rotations and tillage: Minimum or no tillage may increase diseases by conserving fungal propagules on crop residues left on the soil surface. It also increases the weed population.

Minimal tillage combined with pre-crop wheat or pre-crop maize has been seen to clearly increase Fusarium head blight and associated mycotoxins in the grain. Crop rotation is known to have significant impact on reducing diseases, and weeds. Similarly optimum tillage helps to reduce weeds.

6.3.4. Biological control

Biological control is the use of natural enemies to control pests. Effective use of biological control requires a good understanding of the biology of the pest and its natural enemies, as well as the ability to identify their life stages in the field. Frequent field scouting is necessary to monitor natural enemies and evaluate their impact on pest populations. In the case of wheat, Trichoderma species have been reported to be effective in controlling wheat diseases such as fusarium head blight, septoria and tan spot. Yeasts and bacteria have also shown positive effects in controlling septoria and tan spot diseases. Insect predators and parasites have been used as biological control agents against Green bug, Hessian fly and Russian wheat aphid.

6.3.5. Use of integrated pest management (IPM) approaches

IPM uses a combination of cultural, physical, chemical and biological control methods to control wheat pests by minimizing economic, health and environmental risks. The use of resistant varieties, crop rotations and one time application of fungicides have been found to control most wheat diseases. IPM is recommended in controlling the most important insect pests of wheat, such as Hessian fly, Sunn pest, Sawfly and Russian wheat aphid. Early planting and use of resistant wheat varieties are effective in controlling Hessian fly. The IPM package for the control of Sunn pest has multiple components: changing spraying policy from indiscriminate aerial spraying to localized ground sprays based on economic insect population thresholds, devolution of control to farmers, enhancement/conservation of egg parasitoids through the use of flowering medicinal plants alongside wheat fields, and entomopathogenic fungi in overwintering sites. Farmers' field schools have been used to disseminate IPM options for both Hessian fly and Sunn pest. Some elements of the Sunn pest package are being used by farmers on over 3 million hectares in several countries in West Asia. Use of insect resistant wheat varieties (e.g. with solid-stem), swathing, tillage, delayed planting, crop rotation and the use of parasitoids have been recommended as effective IPM options in controlling wheat stem sawfly.

7. The way forward

7.1. Exploring Hybrid wheat

In the past, hybrid wheat production was discouraged for its poor economic return, and limited heterotic advantage (10%); lack of clear advantage in terms of agronomic, disease and quality traits; expensive seed production costs; and due to the argument that yield increment can be obtained using conventional varieties and consequently hybrids would have no biological advantage over inbred lines (Picket and Galwey, 1997). Hybrid wheats can provide higher grain yield, higher thousand grain weight, more tillers, higher biomass, deeper roots and better resistance to both biotic and abiotic stresses as compared to their parents. Currently, hybrid wheat is predominantly produced in Europe using the chemical hybridization agent (CHA) CROISOR® 100. Other countries such as the USA, China, India and Australia use the Cytoplasmic Male Sterility (CMS) method. It is anticipated that the application of biotechnological methods will help capture increased heterosis by direct selection of favourable alleles and the development of new genetically based systems to control male sterility.

7.2. Use and application of biotechnology and genomic tools

Biotechnology and modern genomic tools have lots of promises in improving the efficiency of conventional breeding and development of improved wheat varieties with high level of yield potential, quality, and resilient to climate change. Unlike many other major crops (notably maize, soybean, cotton, and canola) that now account for more than 180 million ha of commercial transgenic crop production across many countries, there is no GM wheat production in any country. The GM approach would be particularly valuable for traits for which there is limited or no genetic variation within the *Triticum* species. This would include herbicide resistance, Fusarium resistance, novel quality traits and technologies for creating hybrid cultivars. In addition, GM technologies hold promise for enhancing drought and heat tolerance, as well as disease and pest resistance. Major efforts are needed to break yield barriers in wheat to increase yield potential by 50% to cope with growing demand. Increasing the radiation use efficiency of wheat through modification of key enzymes (e.g. Rubisco) and biochemical pathways to increase photosynthesis, ear size and lodging resistance are key areas for wheat research through the integration of physiological and molecular breeding methodologies to increase wheat yield potential. A further increase in yield potential could be

achieved through the development of hybrid wheat systems based on native and transgenic interventions collaboratively, leveraging private sector technologies for the benefit of stakeholders in the developing world. There have been substantial commercial concerns regarding the effect of consumer resistance to GM products in some countries. However, more recently, there has been a resurgence of interest in GM wheat, and it is very likely that GM wheat cultivars will be released within the next 10 years.

7.3. Adopting climate smart wheat technologies

Wheat is the most water use efficient amongst the three major cereals (i.e. wheat, rice, maize) as reflected by the fact that the major wheat exporting countries such as Australia, United States, Kazakhstan, and Russia produce wheat under rain-fed conditions. It is anticipated that because of climate change, water will be a major limitation for wheat production even in irrigated environments, in addition to increased heat stress. As a result, wheat is expected to be increasingly grown in rain-fed environments. It is therefore important to develop climate smart wheat varieties combining high yield potential with resistance/tolerance to drought and heat stresses, in order to cope with the increasing effect of climate change and thereby to produce more grains per drop of water. Furthermore, climate smart technologies such as improved water harvesting techniques, drip irrigation, conservation agriculture, fertigation, and site-specific nutrient management need to be implemented and promoted in order to enhance sustainable wheat production.

7.4. Using wild relatives and synthetics

Wheat genetic resources including land races, wild relatives and synthetic wheats have played and will play major roles as sources of resistance to biotic and abiotic stresses and yield potential. It is anticipated that the development of the Focused Identification of Germplasm Strategy (FIGS) and the availability of new molecular tools such as genotyping-by-sequencing (GBS) would hasten and facilitate the characterization and mining of novel genes and alleles effectively and rapidly from wild relatives, land races and synthetics in order to develop improved wheat germplasm with high yield potential, improved quality and resistance to drought, heat and major diseases and insects.

7.5. Improving Integrated pest management practices

Integrated Pest Management (IPM) is a sustainable approach to managing pests such as weeds, diseases and insects by combining cultural, physical, chemical and biological tools in a way that minimizes economic, health and environmental risks. This diverse approach has the potential to substantially reduce the use of chemicals, while providing a high level of effective pest management. However, IPM programs require a higher degree of commitment and awareness creation from policy makers and extension agents in order to implement and promote IPM packages at farm level.

7.6. Establishing stronger seed systems and scaling up methods

Despite progresses in wheat seed sector, there are remaining critical challenges. A time lag between variety release and availability of certified in farmers' fields due to low multiplication factor and large quantities of seed required for planting unless productivity increased and mechanisms for accelerated seed production introduced (pre-release and off-season seed multiplication of early generation where feasible). The low varietal replacement and seed renewal rates, the predominance of mega-varieties, and quick breakdown of rust resistance continue to be the main challenges of wheat seed sector. Efficient and effective seed delivery systems both through the public and private sector are critical for new crop varieties - including new wheat varieties - to reach farmers and bring meaningful impact. Many national seed systems in the developing countries are weak and operate under heterogeneous agro-ecological farming system, crop and market environments. They also face a broad range of constraints such as poor policy and regulatory frameworks; inadequate institutional and organizational arrangements; deficiencies in production, processing, and quality assurance infrastructure; poorly trained personnel, and limiting technical and managerial capacities, compounded by farmers' difficult socio-economic circumstances. It is therefore crucial to assist and strengthen NARS in managing a strong seed system through capacity development, establishing fast-track variety release systems, participatory demonstrations and accelerated seed multiplication of newly released wheat varieties to ensure fast replacement of existing vulnerable commercial varieties. Strengthening NARS capacity (supporting seed units) and diversification of the seed sector (encouraging private sector participation) and overall government policy in wheat sector would help to address some of these challenges.

7.7. Improving grain quality –segregation for added-value

With increasing incomes of many global consumers, the demand for specific wheat quality attributes and products is increasing. This creates a differentiation of wheat products in markets, based on visible or non-visible characteristics and opens the possibility of adding value to the wheat industry, creating extra employment along value chains, and increasing farm gate prices. The willingness to pay premium price for high quality wheat encourages farmers to grow wheat varieties with known quality profiles and reasonably good yield potential. In this regard, it is noteworthy that it is possible to improve the nutritional value of wheat by introgressing genes for high quality proteins and micronutrients such as iron and zinc. This effort, however, requires investment in research, institution capacity building for varietal classification and grading into different wheat classes, and raising public awareness.

7.8. Promoting enabling policies and working environments

For sustainable wheat production, favourable and conducive government policies play an important role. Government subsidies to agricultural inputs such as improved seed, irrigation water, and chemicals encourage farmers to adopt improved wheat technologies and increase wheat production. Furthermore, creation of adequate infrastructures and marketing systems is of paramount importance for having a successful and competent wheat industry at national and regional levels.

7.9. Strengthening regional and international networks

The International Wheat Improvement Network (IWIN) and currently the WHEAT CRP, an alliance of international Centers (CIMMYT and ICARDA), NARS, universities and regional institutions has been a successful and efficient network for making available and distributing widely new wheat genotypes globally (Payne, 2004; Dixon et al., 2009; Beyerlee and Dubin, 2010). Such a network could be strengthened by widening partnerships and collaboration, in order to develop, disseminate, and market more productive, stress tolerant, and nutritive wheat varieties, and to perfect and promote production practices based on the principles of conservation agriculture, which boost yields while conserving or enhancing critical resources like soil and water.

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