Water Harvesting and Supplemental Irrigation for Improved Water Productivity of Dry Farming Systems in West Asia and North Africa

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Abstract
In the dry areas, water, not land, is the most limiting resource for improved agricultural production. Maximizing water productivity, and not yield per unit of land, is therefore a better strategy for dry farming systems. Under such conditions, more efficient water management techniques must be adopted. Supplemental irrigation (SI) is a highly efficient practice with great potential for increasing agricultural production and improving livelihoods in the dry rainfed areas.

In the drier environments, most of the rainwater is lost by evaporation; therefore the rainwater productivity is extremely low. Water harvesting can improve agriculture by directing and concentrating rainwater through runoff to the plants and other beneficial uses. It was found that over 50% of lost water can be recovered at a very little cost. However, socioeconomic and environmental benefits of this practice are far more important than increasing agricultural water productivity.

This paper highlights the major research findings regarding improving water productivity in the dry rainfed region of West Asia and North Africa. It shows that substantial and sustainable improvements in water productivity can only be achieved through integrated farm resources management. On-farm water-productive techniques if coupled with improved irrigation management options, better crop selection and appropriate cultural practices, improved genetic make-up, and timely socioeconomic interventions will help to achieve this objective. Conventional water management guidelines should be revised to ensure maximum water productivity instead of land productivity.

Introduction

Water scarcity in West Asia and North Africa (WANA) is a well-known and alarming problem because water in this region is the scarcest in the world and water-related issues have become extremely acute and even critical. Today, this problem is of increasing concern to national governments and research institutions. In WANA countries, agriculture accounts for over 75% of the total consumption of water. With rapid industrialization, urbanization and high population rate increase (up to 3.6%), economic realities seem certain to reallocate water increasingly away from agriculture to other sectors though the demand for more food and fiber is steadly increasing.

The average annual per capita renewable supplies of water in WANA countries is now below 1500 m^3, well below the world average of about 7000 m^3. This level has fallen from 3500 m^3 in 1960 and is expected to fall to less than 700 m^3 by the year 2025. Most of WANA countries had per capita water availability of less than 1000 m^3, the threshold for water poverty. Some countries like Jordan, the annual per capita share has dropped to less than 200 m^3 (Margat and Vallae, 1999).

Despite its scarcity, water continues to be misused. Mining groundwater is now a common practice in the region risking both water reserves and quality. Land degradation is another challenge in the dry areas, closely related to water. Climatic variation and change, mainly as a result of human activities, is leading to depletion of the vegetative cover, loss of biophysical and economic productivity through exposure of the soil surface to wind and water erosion and shifting sands, salinization of land, and water logging. Although these are global problems, they are especially severe in the dry areas of WANA.

Two distinct environments may be identified along a transect within the dry areas of WANA. The first is the relatively wet zone where winter rainfall is enough to support purely dry farming systems. Because rainfall amounts and distribution in this zone are usually suboptimal, moisture stress periods often occur during one or more stages of crop growth causing very low crop yields. Variation in rainfall amounts and distribution from one year to the other causes substantial fluctuations in production that can range in the case of wheat from 0.3 to over 2.0 t/ha. This situation creates instability and negative socio-economic impacts.

The second zone in the WANA dry areas is the drier environment (steppe or *badia*), adjacent to the first zone. It is characterized by an annual rainfall of less than 250, too low to support economical dryland farming. Much of WANA lands lie in this zone. Small and scattered rainstorms in these regions fall on lands that are generally degraded with poor vegetative cover. These areas have been exposed to mismanagement, overgrazing, and removal of bushes for fuel wood, and are subject to desertification. Rainfall, although low in annual average, when multiplied by the vast areas results in a large volume of ephemeral water. Although this water forms a major resource, it is lost almost completely through direct evaporation or through uncontrolled runoff. Therefore, agricultural productivity of rainwater in these areas is extremely low.

Most of the agricultural area of WANA is rainfed and a large proportion of the region's agricultural livelihood is based on dryland farming systems. While irrigated areas may produce far higher yields and marketable surpluses, the overall value of dryland production is much greater than its market value due to social and other indirect benefits associated with these systems. In the dry areas, water, not land, is the most limiting resource for improved agricultural production. Therefore, maximizing yield per unit of water used (water productivity), and not yield per unit of land is a better strategy. Agricultural production and livelihoods in dry areas can be sustained, only if priority is given to improving water productivity and enhancing the efficiency of water procurement. In other words, more food, feed and fiber must be produced using less water.

Water resource management strategies have become more integrated and current policies look at the whole set of technical, institutional, managerial, legal, social, and operational aspects required for development at all scales. Sustainability is a major objective of national policies. A sound strategy of an integrated approach for natural resources management in the dryland areas deals with water as the central issue and using it efficiently is accorded highest priority.

Many technologies to improve water productivity and the management of scarce water resources are available. Among the most promising and efficient-proven technologies are: (i) supplemental irrigation (SI) for optimizing the use of the limited water available from renewable resources in rainfed areas, and (ii) water harvesting (WH) for improved farmer income in drier environment (Oweis and Hachum, 2003). Improving crop water productivity, however, requires exploiting not only water management but rather all other inputs such as improved germplasm, fertility and cultural practices.

This paper addresses the potential role and major research findings of supplemental irrigation and water harvesting for improved water productivity in the dry areas of WANA.

Supplemental Irrigation

Rainfall in WANA rainfed areas, especially in the dominant Mediterranean-type climate, is characterized by low annual amount, unfavorable distribution over the growing season and large year-to-year fluctuations. In Tel Hadya, a major dryland farming area in northern Syria, the annual rainfall ranges from 230 mm to 504 mm with an overall average of 343 mm. Rainfall occurs mainly during the winter months (December- February) and early spring (March), so that crops must often rely on stored soil moisture when they are growing most rapidly during April and May. In the wet months, stored water is ample, plants sown at the beginning of the season (November) are in their early growth stages, and water extraction rate from the root zone is limited. Usually little or no moisture stress occurs during this period (Fig. 1). However, during spring, plants grow faster with high evapotranspiration rate and rapid soil moisture depletion due to higher evaporative demand conditions. Thus, a stage of increasing moisture stress starts in the spring and continues until the end of the season.

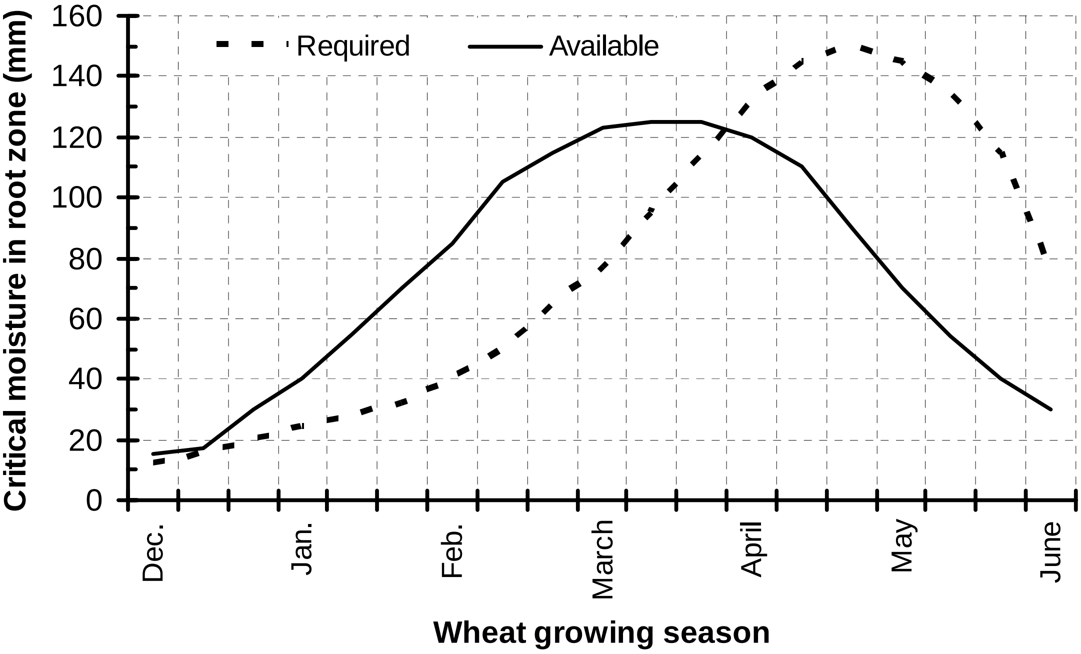

Figure 1. Typical soil moisture pattern over a Mediterranean-type wheat growing season

Shortage of soil moisture in the dry rainfed areas occurs during the most sensitive growth stages (flowering and grain filling) of cereal and legume crops. As a result, rainfed crop growth is poor and yield is consequently low. The mean grain yield of rainfed wheat in WANA is about one tonne per hectare, but ranges from 0.5 to 2.0 tonne/ha depending on the precipitation amount and distribution, and on agronomic factors such as soil fertility and crop variety. These yield levels are far below the yield potential of wheat (over 4 to 5 tonne/ha). Supplemental irrigation can, using a limited amount of water, if applied during critical crop growth stages, result in substantial improvement in yield and water productivity.

Research results from the International Center of Agricultural Research in the Dry Areas (ICARDA) and others, as well as harvest from farmer's fields, showed substantial increases in crop yield in response to the application of relatively small amounts of irrigation water. This increase covers areas with low as well as high annual rainfall. Table 1 shows increases in wheat grain yields under low, average, and high rainfall in northern Syria, with application of limited amounts of SI. Applying 212, 150, and 75 mm of additional water to rain-fed crop increased yields by 350, 140, and 30% over that of rain-fed receiving annual rainfall of 234, 316, and 504mm respectively. By definition, rainfall is the major water supply source for crop growth and production, thus the amount of water added by SI cannot by itself support economical crop production.

Table 1. Yield and water productivity for wheat grains under rain-fed and SI (SI) in dry, average and wet seasons at Tel Hadya, North Syria (Oweis, 1997)

Season/Annual Rainfall (mm)		Rain-fed yield (t/ha)	Rainfall WP (kg /m^3)	Irrigation amount (mm)	irrigated yield (t/ha)	Yield increase due to SI (t/ha)	GIWP* kg/m^3
Dry	(234mm)	0.74	0.32	212	3.38	2.64	1.25
Average	(316mm)	2.30	0.73	150	5.60	3.30	2.20
Wet	(504mm)	5.00	0.99	75	6.44	1.44	1.92

* GIWP* (irrigation water productivity) is taken as the ratio of increase in yield to the gross depth of SI applied.

In addition to yield increases, SI also stabilized wheat production from year to the other. The coefficient of variation was reduced from 100% to 20% in rainfed fields that adopted SI.

The impact of SI goes beyond yield increases to substantially improve water productivity. Both the productivity of irrigation water and that of rainwater are improved when both are used conjunctively (Oweis et al., 1998 and 2000). Average rainwater productivity of wheat grains in WANA is about 0.35 kg/m^3. However, it may increase to as high as 1.0 kg/m^3 with improved management and favorable rainfall distribution. It was found that one cubic meter of water applied as SI at the proper time might produce more than 2.0 kg of wheat grain over that of rainfed. Data from 5-year experiment (1991/92 – 1995/96) at ICARDA research station in northern Syria (Table 2) shows some of the results. The rainwater productivity (RWP) increases in most of the years, particularly in the driest year (1992/93) but on average it increased from 0.83 to 0.90 kg /m^3. Irrigation water productivity (GIWP) averaged more than 0.96 kg /m^3.

Table 2. Rainwater Productivity (RWP), total of rain and SI water productivity (TWP) and irrigation water productivity, GIWP, of fertilized (100 kg N /ha) bread wheat grains in northern Syria (Data from Zhang et al., 1998).

Year	Rain mm	Rainfed grain yield (kg/ha)	RWP[a] (kg/m^3)	SI (mm)	Rain+SI (mm)	Irrigated yield (kg/ha)	TWP[b] (kg/m^3)	GIWPc[b] (kg/m^3)
1991/92	351	3233	0.92	165	516	5221	1.01	1.20
1992/93	287	1646	0.57	203	490	4629	0.94	1.47
1993/94	358	3537	0.99	175	533	5350	1.00	1.04
1994/95	318	2823	0.89	238	556	4907	0.88	0.88
1995/96	395	3062	0.78	100	495	3275	0.66	0.21
Mean	342	2860	0.83	176	518	4676	0.90	0.96

[a] RWP is taken as the ratio of rainfed yield to rainwater
[b] TWP is taken as the ratio of irrigated yield to total water supply (rain + SI)
[c] GIWP is taken as the ratio of increase in yield to the gross depth of SI water applied.

Furthermore, using irrigation water conjunctively with rain was found to produce more wheat per unit of water than if used alone in fully irrigated areas, where rainfall is negligible. In fully irrigated areas water productivity in producing wheat ranges from 0.5 to about 0.75 kg/ m^3, one third of that achieved with SI. This difference suggests that allocation of limited water resources should be shifted to the more efficient practice (Oweis, 1997).

Other field crops also respond positively to SI. Several barley genotypes were supplementally irrigated to replenish 33, 66, and 100% of the deficit soil moisture in an area with total rainfall of 186 mm. The mean grain yield (in t/ha) for the barley genotypes tested was 0.26 t/ha (rainfed); 1.89 t/ha (33% SI); 4.25 t/ha (66% SI); and 5.17 t/ha (100% SI). The highest yield of one of the genotype (Rihane-3) was 0.22, 2.7, 4.75, and 6.72 t/ha for the four SI treatments, respectively. These dramatic results under SI were obtained partly because of the drought during this season (ICARDA, 1989).

Northern Iraq is a typical WANA's rainfed area where most of the grains of the country are produced. In a rainfall zone (from 300 mm to 500 mm with non-uniform temporal and spatial distribution), huge investments in SI systems were put to overcome rainfall shortages. The results of studies conducted by ICARDA and Iraq showed that substantial improvement can be made in yield and WP by using SI in conjunction with proper production inputs and system management (Adary et al., 2002). In the growing season of 1997-98 (annual rainfall 236 mm), rainfed wheat yield increased from 2.16 t/ha to 4.61 t/ha by applying only 68 mm of irrigation water at the critical time. Applying 100 to 150 mm of SI in April and May achieved maximum results. Early sowing (November) is the optimal sowing date for wheat in northern Iraq. Every week of delay in sowing may result in a grain yield loss of up to 0.5 t/ha of wheat. Yield, especially biological, significantly increased with the increase in nitrogen fertilizer, and farmers were strongly advised to continuously monitor the nitrogen level in the soil for economical and environmental reasons.

Food legumes are important crops in WANA, particularly for providing low cost protein for people with low incomes. Rainfed yields are low for the same reasons outlined earlier for cereals. Analysis of four-years' data (1996-2000) of SI on winter-sown food legumes at ICARDA's experimental fields, northern Syria, under different water management options has shown that in nearly all the cases GIWP is higher than RWP and TWP. Also, TWP is higher than RWP in most of the cases (Table 3) . It can be seen that lentil and faba bean are more responsive to irrigation than chickpea.

Table 3. Mean values of water productivity of 4 seasons (1996-2000) of lentil, chickpea, and faba bean under rainfed and SI at Tel Hadya, Aleppo, Syria. Data from Oweis et al., 2004a, 2004b, 2004c.

Water management option	Water Productivity (kg production /m^3 of water)					
	Grain			Biomass		
	RWP [a]	TWP [b]	GIWP [c]	RWP	TWP	GIWP
Lentil						
Rainfed	0.31			1.26		
1/3 SI		0.36	0.63		1.34	1.82
2/3 SI		0.37	0.55		1.31	1.45
Full SI		035	0.43		1.14	0.92
Chickpea						
Rainfed	0.36			0.92		
1/3 SI		0.36	0.4		0.94	1.00
2/3 SI		0.37	0.4		0.96	1.00
Full SI		0.35	0.32		0.90	0.85
Faba bean						
Rainfed	0.34			0.99		
1/3 SI		0.38	0.66		1.01	1.33
2/3 SI		0.39	0.59		1.00	1.11
Full SI		0.37	0.46		0.96	0.97

[a] RWP is taken as the ratio of rainfed yield to rainwater
[b] TWP is taken as the ratio of irrigated yield to total water supply (rain + SI)
[c] GIWP is taken as the ratio of increase in yield to the gross depth of SI water applied.

In the highlands of WANA region, frost conditions occur between December and March and put field crops in a dormant mode during this period. In most of the years, the first rainfall, sufficient to germinate seeds, comes later than October resulting in the crop stand being small when frost occurs in December and stops their growth. Rainfed yields as a result are much lower than when the crop stand is good when the crop takes off in early spring. Ensuring a good crop stand in December can be achieved by early sowing and applying small amount of SI in October. SI given at early sowing dramatically increases wheat yield because plants which emerge earlier in the autumn grow more vigorously and yield much more in the following spring than plants which germinate late. A four-year trial, conducted at the central Anatolia plateau of Turkey, showed that applying 50 mm of SI to wheat sown early increased grain yields by more than 60%, adding more than 2 t/ha to the average rainfed yield of 3.2 t/ha (ICARDA, 2003). Water productivity reached 5.25 kg grain/m^3 of consumed water, with an average of 4.4 kg /m^3. These are extraordinary values for WP with regard to the irrigation of wheat. The study also revealed that SI given later in the spring and early summer further increased yield, but resulted in lower water productivity. Similar results were obtained in the highlands of Iran at Maragheh (Tavakuli and Oweis, 2004).

Optimization of Supplemental Irrigation

Optimal SI in rainfed areas is based on the following three basic aspects (Oweis 1997):

- Water is applied to a rainfed crop that would normally produce some yield without irrigation.
- Since rainfall is the principal source of water for rainfed crops, SI is only applied when rainfall fails to provide essential moisture for improved and stable production.
- The amount and timing of SI are scheduled not to provide moisture-stress-free conditions throughout the growing season, but to ensure a minimum amount of water available during the critical stages of crop growth that would permit optimal instead of maximum yield.

Deficit supplemental irrigation

Deficit irrigation is a strategy for optimizing production. Crops are deliberately allowed to sustain some degree of water deficit and yield reduction (English *et al*., 1990). The adoption of deficit irrigation implies appropriate knowledge of crop water use and responses to water deficits, including the identification of critical crop growth periods, and of the economic impacts of yield reduction strategies.

For wheat in northern Syria, the results show significant improvement in SI water productivity at medium SI-application rates than at full irrigation. Highest TWP was achieved at rates between 1/3 and 2/3 of full SI.

Water productivity is an indicator of best irrigation scheduling with deficit SI of cereals (Zhang and Oweis, 1999), in analysing the water saving performance of irrigation systems and management practices, and to compare different irrigation systems, including deficit irrigation.

There are different ways to manage deficit-irrigation. The irrigator can reduce the irrigation depth, refilling only part of the soil water capacity of the root zone, or reduce the irrigation frequency by increasing the interval between successive irrigations. In surface irrigation, wetting furrows alternately or placing them further apart is one way to implement deficit irrigation.

Water vs. land productivity

Yield or net economical return per unit of water consumed (ETWP) is a good indicator for assessing the performance of SI. ETWP is the evapotranspiration water productivity defined as ratio of yield to the seasonal evapotranspiration. Higher ETWP is linked with higher yields. This parallel increase in yields and ETWP, however, does not continue all the way. At some high level of yield, incremental yield increase requires higher amounts of water to achieve. This means that ETWP starts to decline as yield per unit land increases above certain levels (Fig. 2).

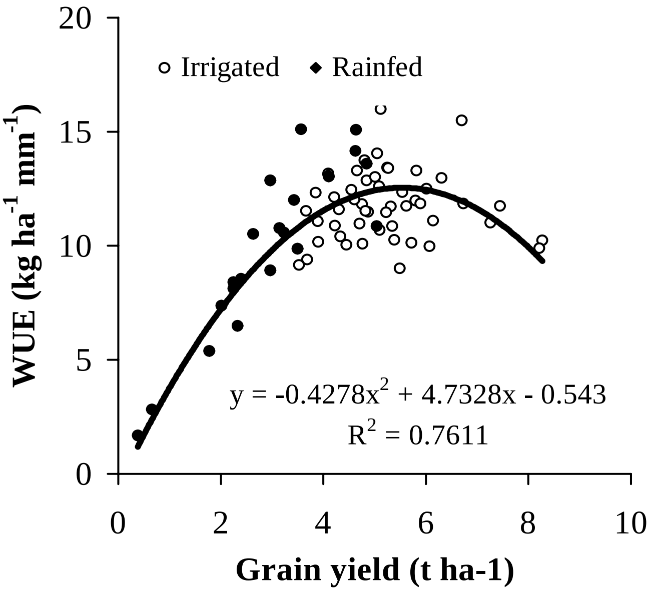

Figure 1. Relationship between crop water productivity and land productivity for durum wheat under supplemental irrigation in northern Syria (Zhang and Oweis, 1999).

It is clear in Fig. 2, that the amount of water required to produce the same amount of wheat at yield levels beyond 5 t/ha is much higher than the water requirement at lower levels. It would be more efficient to produce only 5 t/ha while the saved water may better be used to irrigate new land than to produce maximum yield with excessive amounts of water at low ETWP. This, of course, applies only when water not land is the limiting resource and without sufficient water to irrigate all the available land.

The association of high ETWP values with high yields has important implications for the crop management for achieving efficient use of water resources in water scarce areas (Oweis et al., 1998). Attaining higher yields with increased ETWP is only economical when the increased gains in crop yield are not offset by increased costs of other inputs. The curvilinear ETWP-yield relationship makes clear the importance of attaining relatively high yields for efficient use of water. Policies for maximizing yield should be considered carefully before they are applied under water-scarce conditions. Guidelines for recommending irrigation schedules under normal water availability (Allen et al., 1998) may need to be revised when applied in water-scarce areas.

Water productivity in farmers' fields

Research at ICARDA (Zhang and Oweis, 1999) has shown that applying only 50% of full SI requirements causes a yield reduction of only 10-15%. A farmer-managed field plots were established to demonstrate this finding, in collaboration with the Syrian NARS, over 6 years in the rainfed areas with annual rainfall ranging from 300 to 500 mm. It was observed that farmers tend to over irrigate their wheat fields. When there is not enough water to provide full irrigation to the whole farm, the farmer has two options: to irrigate part of the farm with full irrigation leaving the other part rainfed or to apply deficit SI to the whole farm. Assuming that under limited water resource only 50% of the full irrigation required by the farm would be available (i.e., 4440 m^3 for a 4 ha field), the option of deficit irrigation was compared with other options. The results are summarized in Table 4. They show that a farmer having a 4-hectare farm would on average produce 33% more grain from his farm if he adopted deficit irrigation for the whole area, than if full irrigation was applied to part of the area. The advantage of applying deficit irrigation increased the benefit by over 50% compared with that of the farmer's usual practice of over-irrigation.

Table 4. Wheat grain production scenarios for a 4-hectare farm with various strategies of SI in Syria.

Irrigation management strategy	Rainfed (342 mm)	Farmer's Practice	Applying full SI water	Applying 50% of full SI
SI water depth applied (m^3/ha)		2980	2220	1110
Grain yield (t/ha)	1.8	4.18	4.46	4.15
Rain or irrigation water productivity (kg/m^3)	0.53	0.80	1.20	2.11
Farm production (t), water is not limited [a]	7.2	16.7	17.8	16.6
Farm production (t) if only 50% of full irrigation requirements available	7.2	10.8 [b]	12.5 [c]	16.6 [d]
Per hectare average production (t) [e]	1.8	2.7	3.12	4.15

[a] Entries in this rows are obtained by multiplying the grain yield values by 4.
[b] Calculated as: (4440/2980) x 4.18 + [4- (4440/2980) x 1.8
[c] Calculated as: 2 x 4.46 + 2 x 1.8
[d] Calculated as: 4 x 4.15
[e] Calculated by dividing the entries of the preceding row by 4.

Maximizing net profits

Increase in crop production per unit land or per unit water doesn't necessarily increase farm profit because of the non-linearity of crop yield with production inputs, particularly with water and its interactions with other input factors. Following English et al. (1990) and English and Raja (1996) analysis, ten years of SI data (1985 to 1996) on bread and durum wheat were analyzed to evaluate water-yield relations and to develop optimal irrigation schedules for various rainfall conditions (Zhang and Oweis, 1999). Quadratic crop production functions with the total applied water (rain+SI) were developed and used to estimate the levels of SI water for maximizing yield, net profit and levels to which the crops could be under-irrigated without reducing income below that which would be earned for full SI under limited water resources. The results for both bread and durum wheat under different rainfall conditions are summarized and presented in Table 5. The study concluded that SI scenarios maximizing the profit under limited water resources conditions or for a targeted grain yield of 4 to 5 t/ha should be recommended for sustainable utilization of water resources and higher WP.

Table 5 Amount (mm) and timing of SI for maximizing yield, maximizing the net profit and a targeted yield under different rainfall conditions

Rainfall	W_m[a]	W_l[b]	W_w[c]	W_{ew}[d]	W_t[e]	Time of irrigation
Bread wheat						
250	430	336	260	161	158–254	Stem elongation, booting, flowering and grain filling
300	380	286	210	111	108–204	Stem elongation, flowering and/or grain filling
350	330	236	160	61	58–155	Flowering and/or grain filling
400	280	186	110	11	0–144	Grain filling
450	230	136	60	0	0–55	Grain filling
Durum wheat						
250	510	454	314	180	144–207	Stem elongation, booting, flowering and grain filling
300	460	404	294	130	94–157	Stem elongation, flowering and/or grain filling
350	410	354	244	80	44–107	Flowering and/or grain filling
400	360	304	194	30	0–57	Grain filling
450	310	254	144	0	0	–

[a]: amount of water required for maximizing grain yield,
[b]: amount of water required for maximizing the profit under limited land resource,
[c]: amount of water required for maximizing the profit under limited water resources,
[d]: amount of water required for deficit irrigation at which the net profit equals that at full irrigation under limited water resources,
[e]: amount of water required for targeted yield of 4–5 t/ha.

Unlike in full (or conventional) irrigation, the time of SI application cannot be determined in advance. When possible, and for rational allocation of limited water supplies, SI should be scheduled at the moisture sensitive stages of plant growth. For rainfed cereals in WANA, sensitive growth stages are: seedling, flowering and grain filling. Scheduling of SI should coincide with these sensitive periods to make certain that root zone moisture does not limit growth.

ICARDA has developed methodologies to help farmers determining the right SI management. Determining rainfed and SI production functions is the basis for optimal economical WP. SI production functions for wheat (Fig. 3) are developed for each rainfall zone by subtracting the rainwater production function from the total water (SI + rain) production function. Since rainfall amount cannot be controlled, the objective is to determine the optimtal amount of SI that results in maximum net benefit to the farmers. Knowing the cost of irrigation water and the expected price for a unit of the product, maximum profit occurs when the marginal product for water equals the price ratio of water to the product. Figure 4 shows the optimal amount of SI to be applied under different rainfall zones and various price ratios.

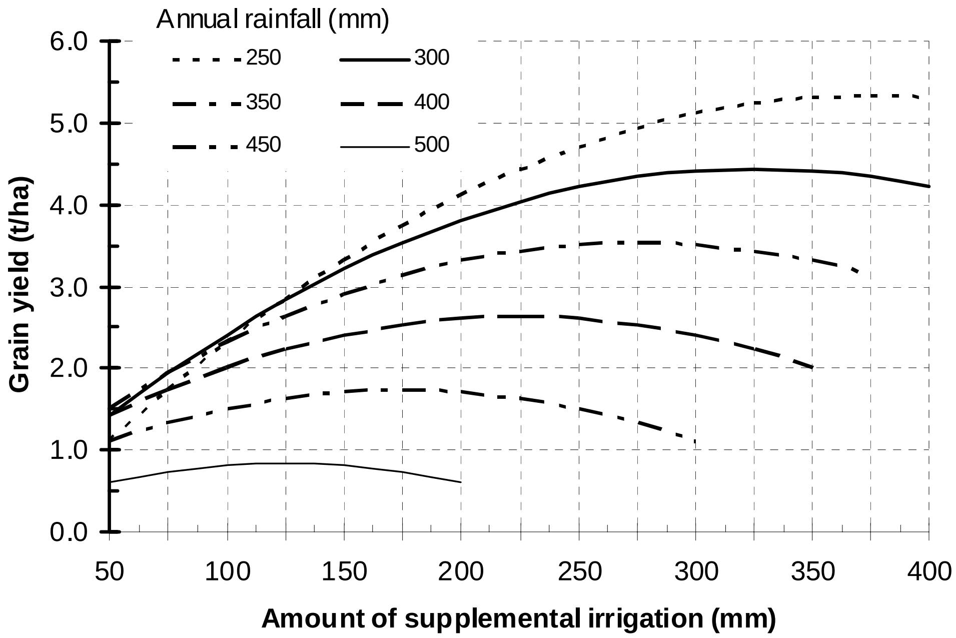

Figure 3. Supplemental irrigation production functions of wheat in Syria at different levels of rainfall. (Oweis, 1997)

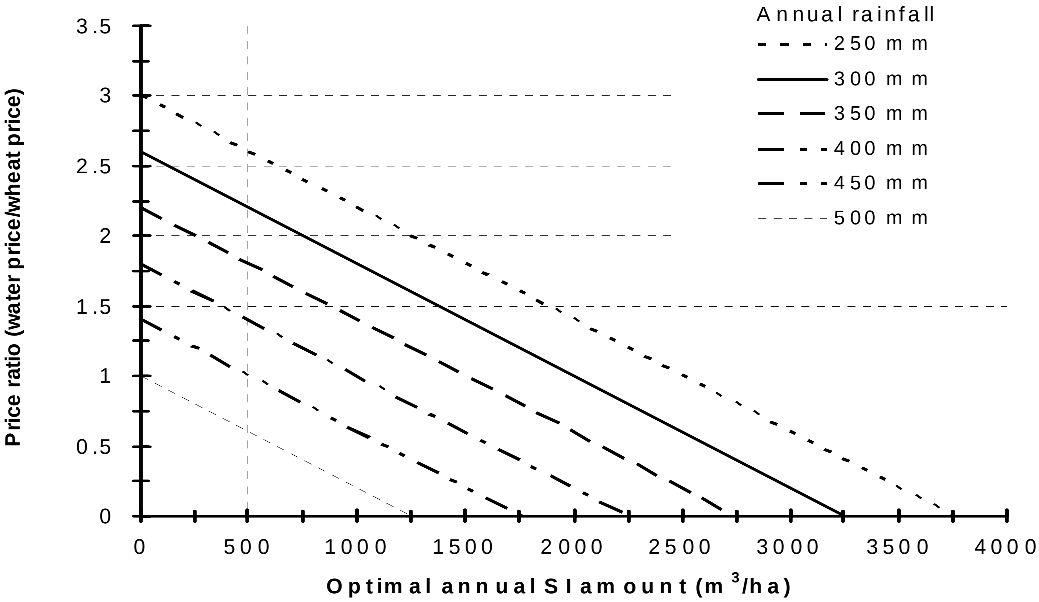

Figure 4. Supplemental irrigation optimization chart for wheat in Syria (Oweis, 1997)

One of the practical problems of SI is that all the fields may need irrigation at the same time in the spring. The result is a very high water supply and large irrigation system is required. A multi-sowing date strategy reduced the peak farm water demand rate by more than 20%, thus potentially allowing a reduction in the irrigation system size and cost (Oweis and Hachum, 2001). Also, the water demand of a larger area can be met with the same water supply. However, optimal sowing dates that minimize farm water demand do not always maximize total farm production and/or water productivity. The outcome depends on the crop water requirements and yield for each sowing date. Furthermore, selection of the optimal strategy is greatly influenced by the level of water scarcity.

Cropping pattern and cultural practices

Among the management factors for more productive farming systems are the use of suitable crop varieties, improved crop rotation, sowing dates, crop density, soil fertility management, weed control, pests and diseases control, water conservation measures (Pala and Studer, 1999). SI requires varieties that are adapted to or suitable for varying amount of water application. Appropriate varieties need first to manifest a strong response to limited water applications and they should maintain some degree of drought resistance. In addition, the varieties should respond to the higher fertilizer rates that are generally required under SI (Oweis, 1997), and resist lodging, which can occur in traditional varieties under irrigation and fertilization.

Delaying the sowing date prevents crop germination and seedling establishment because of the rapid drop in air temperature starting generally in November. In the lowlands of the Mediterranean region, where continuous cropping of pure cereal or cereal-legume rotations prevails, mid-November was found to be the optimum sowing time for cereals. Every week's delay after this time may result in an average yield decrease of about 250 kg/ha. If the onset seasonal rain is delayed, early sowing can be realized by SI.

Given the inherent low fertility of many dry-area soils, judicious use of fertilizer is particularly important. In northern Syria, 50 kg N per ha is sufficient under rainfed conditions. However, with water applied by SI, the crop responds to nitrogen up to 100 kg N per ha, after which no benefit is obtained. This rate of N greatly improves WP. It is also important that there is adequate available phosphorus in the soil so that response to N and applied irrigation is not constrained (Ryan, 2000).

To obtain the optimum output of crop production per unit input of water, the mono-crop WP should be extended to a multi-crop WP. Water productivity of a multi-crop system is usually expressed in economic terms such as farm profit or revenue per unit of water used. While economic considerations are important, they are not adaquate as indicators of sustainability, environmental degradation and natural resource conservation.

Water Harvesting
The drier environments, “the steppe”, or, as called in West Asia, “*Al Badia*”, occupy the vast majority of the dry areas of the world. The disadvantaged people generally live there. The natural resources of these areas are subject to degradation and the income of the people who depend mainly on grazing is continuously declining. Due to harsh conditions, people are increasingly migrating from these areas to the cities, with associated high social and environmental costs.

Precipitation in the drier environments is generally low compared to crop basic needs. It is unfavorably distributed over the crop-growing season and often comes with high intensity. As a result, rainfall in this environment cannot support economical dryland farming. In the Mediterranean areas, rain usually comes in sporadic, unpredictable storms and is mostly lost in evaporation and runoff, leaving frequent dry periods during the crop growing season. Part of the rain returns to the atmosphere, directly from the soil surface by evaporation after it falls, and part flows as surface runoff, usually joins streams and flows to swamps or to “salt sinks”, where it loses quality and evaporates; a small portion joins groundwater. The overall result is that most of the rainwater in the drier environments is lost with no benefits and/or productivity (Oweis et al., 1999).

Water harvesting in agriculture is based on the principle of depriving part of the land of its share of rainwater (which is usually small and non-productive) and adding it to the share of another part. This brings the amount of water available to the target area closer to the crop water requirements so that economical agricultural production can be achieved and thus improving the water productivity. Thus water harvesting may be defined as *"the process of concentrating precipitation through runoff and storing it for beneficial use"*.

Capturing rainwater and using it efficiently is crucial for any integrated development. Water harvesting is an ancient concept with a wealth of indigenous knowledge available. Indigenous systems such as *jessour* and *meskat* in Tunisia, *tabia* in Libya, *cisterns* in north Egypt, *hafaer* in Jordan, Syria and Sudan and many other techniques are still in use (Oweis et al., 1999 and 2001). Water harvesting may be developed to provide water for human and animal consumption, domestic and environmental purposes, as well as for plant production.

Water Harvesting Techniques
All water harvesting systems must have the following three components:

- **The catchment area** is the part of the land that contributes some or all its share of rainwater to another area outside its boundaries. The catchment area can be as small as a few square meters or as large as several square kilometers. It can be agricultural, rocky or marginal land, or even a rooftop or a paved road.
- **The storage facility** is a place where runoff water is held from the time it is collected until it is used. Storage can be in surface reservoirs, subsurface reservoirs such as cisterns, in the soil profile as soil moisture, and in groundwater aquifers.
- **The target area** is where the harvested water is used. In agricultural production, the target is the plant or the animal, while in domestic use, it is the human being or the enterprise and its needs.

Experience with rainwater harvesting in WANA includes Micro-catchments and Macro-catchments systems. Micro-catchments are those in which surface runoff is collected from a small catchment area and applied to an adjacent agricultural area, where it is stored in the root zone and used directly by plants. The target area may be planted with trees, bushes, or with annual crops. The farmer has control, within his farm, over both the catchments and the target areas. All the components of the system are constructed inside the farm boundaries. This is an advantage from the point of view of maintenance and management, but because of the loss of productive land it is only practiced in the drier environments, where cropping is most risky and farmers are willing to allocate part of their farm to be used as a catchment.

Macro-catchment systems are characterized by having runoff water collected from relatively large catchments. Often the catchments are natural rangeland or a mountainous area. Catchments for these systems are mostly located outside farm boundaries, where individual farmers have little or no control over them. Water often flows in temporary (ephemeral) streams called “*wadi*” and is stored in surface or subsurface reservoirs, but also can be stored in the soil profile for direct use by crops. Sometimes water is stored in aquifers as a recharge system.

Among the widely used microcatchment WH techniques are contour ridges, semi-circular and trapezoidal bunds, and small runoff basins. Two success stories for microcatchment WH will be reported.

Contour bunds and ridges in the Syrian badia
Mehasseh is a very dry area in southern Syria with a Mediterranean climate that receives only 150 mm of annual rainfall. Land is degraded with little vegetative cover. People are poor and depend on sheep production with grazing as the most important source of animal feed. Rainwater falls in a few sporadic and intensive storms on crusty soils causing runoff and soil erosion. Most of the rainwater flows to salt sinks where it evaporates. As a result rainwater productivity is extremely low. A water-harvesting project, based on contour bunds and ridges, was initiated in 1995 to improve the natural resources management and peoples' livelihood in this area.

Half a meter high *contour bunds or ridges* were constructed along the contour lines, spaced between 5 and 20 m apart. The first meter along the upper side of the ridge is allocated for cultivation, whereas the rest is the catchment. Ridges were usually formed manually, with an animal-driven implement, but then were mechanized to cut down labour costs. Contour ridges are one of the most important techniques for supporting the regeneration and new plantations of forages, grasses and hardy trees on gentle to steep slopes.

To overcome the contouring difficulties, semi-circular and trapezoidal bunds are usually used. Earthen bunds in the shape of a semi-circle, a crescent, or a trapezoid facing directly upslope are created at a spacing that allows sufficient catchments to provide the required runoff water, which accumulates in front of the bund, where plants are grown. Usually they are placed in staggered rows. The diameter or the distance between the two ends of each bund varies between 1 and 8 m and the bunds are 30–50 cm high. Cutting the soil to form the bund immediately upstream creates a slight depression. Runoff is intercepted here and stored in the plant root zone. These bunds are used mainly for the rehabilitation of rangeland or for fodder production, but also used for growing trees, shrubs and field crops.

The bunds were planted with Atriplex shrubs. An adjacent field was planted also with shrubs without constructing the water harvesting bunds. Rainfall in 1997 on the project area was 174 mm annual. Planted shrubs with no bunds had less than 10% survival rate, while those grew under micro-catchments had over 90% survival rate. The three following years were very dry with annual rainfall of less than 50 mm. Most of the surviving shrubs without bunds dried out during the 1st drought year. The shrubs supported with water harvesting bunds survived thee consecutive drought years and are still growing vigorously. Table 6 shows the rate of survival and volume of dry matter produced under the two water harvesting systems compared with the control where no water harvesting was applied.

Table 6. Atriplex (salt bush) survival rate (%) and dry matter production (1000 cm^3) under two water harvesting systems and a control in Mehasseh, Syria. (Somme et al., 2004)

Year	Annual rainfall	Survival rate (%)			Volume of dry matter (1000 cm^3/shrub)		
		No water harvesting	Contour ridges	Semicircular bunds	No water harvesting	Contour ridges	Semicircular bunds
1997/98	174	23	95	98	15	29	120
1998/99	36	12	91	95	15	74	164
1999/2000	42	5	90	93	23	79	167

Small runoff basins for fruit trees in Jordan
This technique is sometimes called *negarim* (Critchley and Siegret, 1991), and made of runoff basins of small diamond- or rectangular-shaped grid plots each surrounded by low earth bunds. They are oriented to have the maximum land slope parallel to the long diagonal of the diamond, so that runoff flows to the lowest corner, where the plant is placed. The usual grid size is 50 to 200 m^2. They can be constructed on any gradient. They are most suitable for growing trees but may also be used for other crops. When they are used for trees, the soil should be deep enough to hold sufficient water for the whole post-rainy season.

The arid lands of Jordan receives about 160 mm of rainfall annually and has a Mediterranean climate. No economic crop can be grown with this amount of rainfall. Farmers in the area depend on livestock and other forms of agriculture using limited groundwater. A project was launched in 1987 to diversify farmer's production by introducing trees in suitable areas. Lack of water resources limited this option. However, the introduction of the *negarim* to support fruit trees was a great success (Oweis and Taimeh 1996). Plots of 25 to 75 m^2 were constructed on deep soils and almonds and olives trees were planted in the winter season. Polymers were added to the tree pit in order to increase the water storage capacity of the soil so enough runoff is kept for the long dry summer. Table 7 shows the overall micro catchment system efficiency for three soil surface treatments of a catchment of 25 m^2 supporting the almond trees in Mouaqar Jordan. It indicates that 50 to 60 % of the rain in this environment can be captured and utilized by the plants.

Table 7. Microcatchment system efficiency of 25 m^2 area, supporting almond trees with three surface tratments in the Mouaqar area of eastern Jordan (Oweis and Taimeh, 1996)

Rain storm (mm)	**Overall water harvesting system efficiency[(1)] %**		
	Natural surface	**Compacted surface**	**Covered with plastic sheet**
16.0	60.2	54.9	83.0
65.0	61.0	58.4	80.6
8.5	44.3	46.9	81.7
5.5	32.0	34.4	73.2
5.0	60.8	49.2	78.4
15.0	42.7	51.2	82.3
230	38.8	51.5	25.3
10.5	69.6	60.1	32.0
Mean	**51.2**	**50.1**	**67.1**

(1) System efficiency is the product of runoff efficiency and storage efficiency. Runoff efficiency is the ratio of water collected from the catchment to the rainwater fell on the catcment. Storage efficiency is the ratio of water stored in the tree root zone to the water collected fom the catchment.

Planted trees survived the harsh climatic conditions and grew well only beasuse of providing the water harvesting system. The production was so good that farmers in the area started adopting the technology. Generally, it is important that the location, the design and the crop are properly selected for a successful development.

Water harvesting for supplemental irrigation

This rainwater harvesting system includes a surface storage facilities ranging from an on-farm pond or tank to a small dam constructed across the flow of a *wadi* with an ephemeral stream. It is highly recommended when inter-seasonal rainfall distribution, or variability, or both are such that crop water requirements cannot be reasonably met. In this case, the collected runoff is stored for later use as SI (Oweis et al. 1999). Important factors that should be considered in this system are storage capacity, location and safety of structure. Two major problems are usually associated with storing water for agriculture: evaporation and seepage losses.

Several issues both technical and socioeconomic need to be considered for optimal implementation of this water-harvesting system (Oweis and Taimeh, 2001). Among the important technical issues are:

- Harvested water should be transferred from the reservoir and be stored in the soil as soon as possible after collection. Storing water in the soil profile for direct use by crops in the winter season saves substantial evaporation losses that normally occur during the high evaporative demand period. Extending the use of the collected water to the summer reduces its productivity due to higher evaporation and seepage losses.
- Emptying the reservoir early in the winter provides more capacity for other runoff events, that is, it is beneficial to water store in the soil profile to allow more storage capacity in the reservoir. Large areas can be cultivated with reasonable risk.
- Sediment removal is worthwhile to extend the reservoir life and capacity.
- For safety reasons, a spillway with sufficient capacity and at the right location must be provided in case of a small dam constructed across the flow. Most of the small farm reservoirs built by farmers in WANA were washed away due to lack of or insufficient capacity of spillways.

Socioeconomic limitations

Constraints to the implementation and adoption of water-harvesting include:

- Difficulties due to farmers' unfamiliarity with the technology
- Conflicts and disputes on water rights, land ownership and use, and
- Lack of adequate characterization of rainfall, evapotranspiration and soil properties.

Micro-catchment systems are usually within individual farms. This is a simple and low-cost approach, although farmers may experience some difficulty with elements requiring precision, such as following the contour lines or determining maximum slope. The community may be involved in micro- and macro-catchment WH systems, typically through a careful locally- planned program.

In planning macro-catchment WH, it is important to consider any existing water rights to avoid upstream or downstream conflict of interests. Ideally these should be planned at the watershed level with farmers' participation in their planning. Community-based management, farmer participation in planning and cost sharing, or the establishment of a cooperative can be among alternatives recommended to manage these reservoirs and to overcome the problem of small holdings. Selection of the appropriate reservoir site to maximize storage and minimize sediments and nearness to the command areas is important.

These experiences and many others show that the productivity of rainwater in the drier environments can be substantially increased when a proper water harvesting technique is implemented.

Conclusions

In water-scarce areas, water, not land, is the primary limiting factor to improved agricultural production. Accordingly, maximizing yield per unit of water, and not yield per unit of land, is a more viable objective for on-farm water management in the dry farming systems. Improving water productivity in water-scarce areas requires a change in the way agriculture is practised. Conventional guidelines designed to maximize yield per unit area need to be revised with a view to achieving maximum water productivity. Appropriate policies related to farmer participation and water cost recovery are needed to prompt the adoption of improved management options.

More efficient irrigation practices must be adopted. Supplemental irrigation is an option with great potential for increasing water productivity in rainfed areas. Scarce water now used for full irrigation could be reallocated to supplement rainfed crops for improved water productivity. However, to maximize the benefits of SI other inputs and cultural practices must also be optimized.

Water harvesting is the only option for economic agriculture and environmental protection in the drier environments. Lack of wide adoption by farmers may be attributed to technical, socioeconomic and policy factors, but most importantly the lack of community participation in the development and implementation of improved technologies.

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