

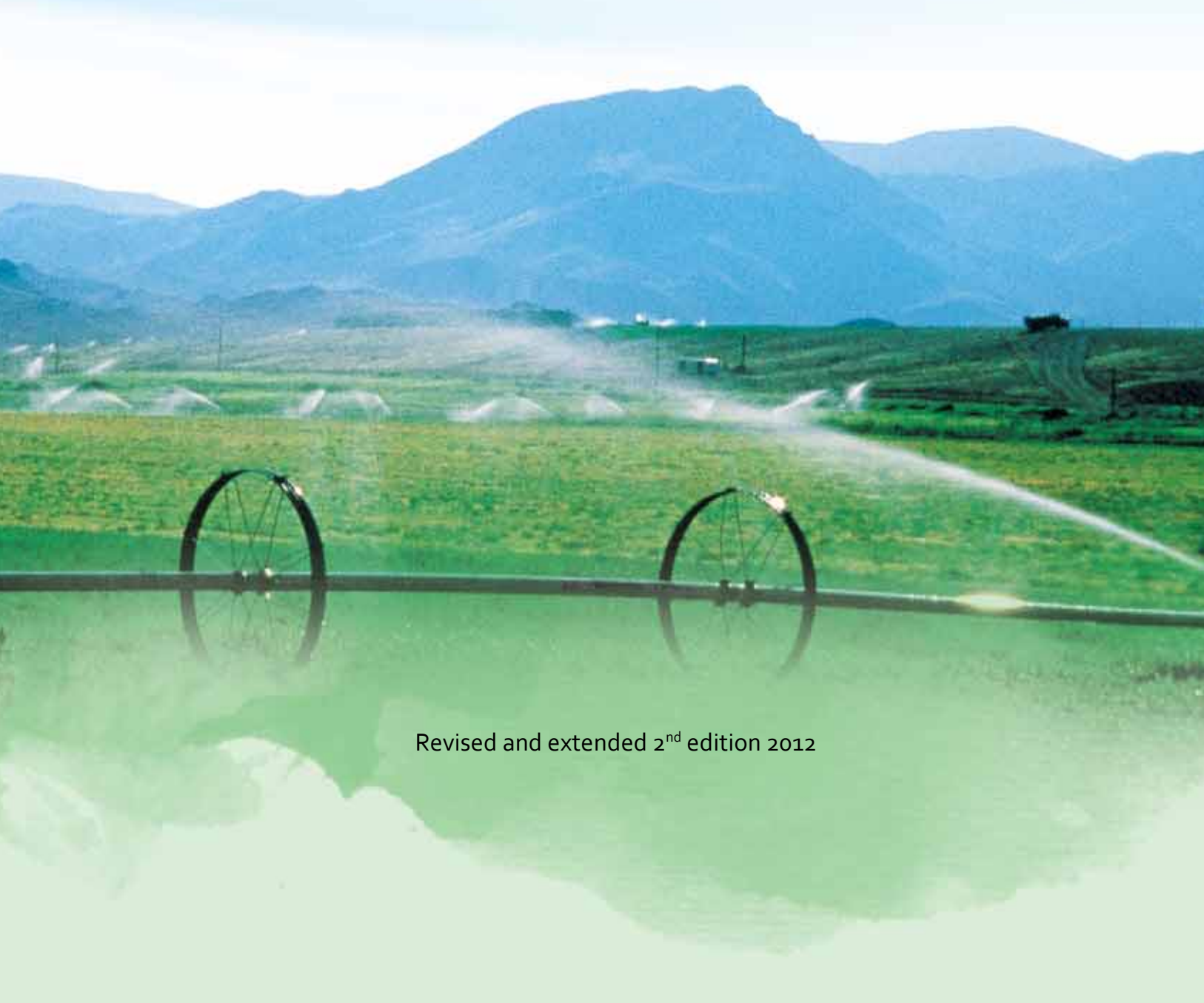


International Center
for Agricultural Research
in the Dry Areas

SUPPLEMENTAL IRRIGATION

A HIGHLY EFFICIENT WATER-USE PRACTICE

Theib Oweis and Ahmed Hachum



Revised and extended 2nd edition 2012

Water and land research at ICARDA

Dry areas cover 41% of the world's land surface. They are home to 2 billion people, and the majority of the world's poor. Agriculture in these areas is limited by a number of factors including water scarcity, drought and land degradation – which are all key areas of research focus at ICARDA.

ICARDA's Integrated Water and Land Management Program (IWLMP) aims to help improve water and land productivity, farm income and livelihoods in dry areas through research and capacity building. All work is implemented through partnerships with farming communities, national agricultural research systems, advanced research institutes, civil society and others.

IWLMP's mandate covers non-tropical dry areas worldwide, with a special focus on Central and West Asia and North Africa (the CWANA region). The program is structured under five research themes, each with a strong capacity-development component:

1. Assessment of water and land resources for agriculture

- Assessing the quantity and quality of available water resources (rainwater, surface water, groundwater and marginal-quality water) and projections for the future.
- Assessing water and land productivity at plant, field, farm and basin levels.
- Assessing the potential for using water-use efficient practices and the likely impacts on productivity and the environment.
- Assessing the availability and potential use of marginal quality water in agriculture, and the possible environmental consequences.
- Developing multi-scale tools and methods to assess land degradation (location, extent, causes, impacts).

2. Increasing water and land productivity

With few opportunities to expand cultivated land, increases in food production must come mainly from higher water and land productivity – more 'crop per drop'. Water

and land productivity can be increased in various ways: improved crop varieties and cropping patterns, precision agriculture, and most importantly, improved water management. Research is helping to develop technologies and management options to maximize water and land productivity at plot, field, farm and basin levels.

- Options and tools to improve productivity in dryland farming systems: soil fertility management, crop management, improved germplasm, and supplemental irrigation.
- Water harvesting techniques to rehabilitate and improve the productivity of crop-rangeland-livestock systems in marginal environments.
- Improved irrigation management, new cropping patterns, water use efficient germplasm.

3. Combating land degradation

Soil erosion, salinity and loss of vegetation cover are early warning signs of land degradation and desertification. The research program develops and disseminates practical, low-cost options to protect soil and water resources, using a community-led approach. Farmers are fully involved at every stage, from planning and implementation to dissemination of results.

4. Drought and climate change: preparedness, adaptation and mitigation

ICARDA's research aims to help farming communities prepare for, adapt to, and mitigate the effects of droughts and climate change through better management of water and land resources.

5. Integration of policies and institutional options.

Technologies are necessary but not sufficient – they must be supported by effective policies and institutions. Research aims to help develop a framework for this support, and inform the development of appropriate water and land policies. The approach is based on broad partnerships, linking local land users and other stakeholder groups with policy makers.



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Design: George Chouha



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PREFACE

Rain-fed agriculture accounts for about 80% of the world's farmland and two-thirds of global food production. Despite the higher risks and generally lower productivity compared to irrigated areas, rainfed agriculture will continue to play a dominant role in providing food and livelihoods for an increasing world population.

Yields of rainfed crops, particularly in developing countries, are low as a result of moisture deficits, inappropriate management of soil, water and nutrients, and lack of other production inputs. But rainfed systems have huge untapped potential, especially in Asia and Africa, where the bulk of the world's poor live. This potential can be realized through improved technologies, sound water policy and greater investment. This book describes one technology – supplemental irrigation (SI) – that has been extensively tested, widely adopted, and has generated substantial impacts in different countries.

In many rainfed environments, shortage of soil moisture often occurs during the most sensitive stages of crop growth, i.e. flowering and grain filling. This can severely affect plant growth and yield. Supplemental irrigation – the application of limited amounts of water during critical crop growth stages – can substantially increase yield and water productivity.

In 1997, ICARDA published *Supplemental irrigation: a highly efficient water-use practice*, an illustrated booklet describing the principles and practical application of SI. With continuing demand for copies, it was reprinted numerous times, and translated into Arabic, Russian, French, Persian and Pashto. During the 15 years since its publication, there have been significant advances in SI experiences. We have therefore extensively revised the booklet, to include recent developments on experimental research stations as well as farmers' fields.

The new edition emphasizes the need greater for a better balance of investments in rainfed versus irrigated agriculture. We need a new governance, investment and management paradigm in which all water options in the farming system are considered. The book highlights several other aspects including water productivity, integration, and participatory research and development. In rainfed dry areas, where water (not land) is the most limiting factor, the priority should be to maximize yield per unit of water, rather than yield per unit of land. SI can play a key role in increasing water productivity, and in ensuring more sustainable use of groundwater. For maximum benefit, SI must be part of an integrated package that includes non-water inputs, improved crop management methods and other components. Optimal SI regimes would be based on sound water management policies, economic evaluations (e.g. crop:water price ratios) and timely application. As past experience has shown, integrated, farmer-participatory research and development programs are the best way to introduce, test and scale out SI technology.

The information presented here is drawn largely from research projects, training programs, technical workshops and other initiatives by ICARDA and its partners. We hope this revised edition will be even more useful than the 1st edition, in learning from past experience and building on previous work to strengthen smallholder agriculture under ever more challenging conditions.

INTRODUCTION

Rain-fed (or dry farming) systems occupy about 80% of the world's agricultural lands and contribute to over two-thirds of the global food production. In sub-Saharan Africa, more than 95% of farmed land is rain-fed; in Latin America 90%; in South Asia 60%; in East Asia 65%; and in West Asia and North Africa 75% (Rockström et al. 2007). Dry farming systems depend on precipitation, specifically the component called green water, which is stored directly in the soil and used later as evapotranspiration. In water-scarce regions, green water resources make up between 85 and 90% of the precipitation, reflecting the significant proportion of the available freshwater that sustains rain-fed agriculture.

Agriculture is the principal user of water, with a global average of about 70% of all blue water withdrawals from rivers, lakes, and aquifers. This rises to over 80% in developing countries. As water resources become more limited, available water allocations for agriculture face increasing competition from other, higher utility uses – municipal and industrial – and calls for more water to be allocated for the environmental use. Therefore, agricultural policies and investments need to become more strategic to bring about higher returns from agricultural water.

Precipitation in rain-fed areas is characterized by a low annual amount, and for unfavorable distribution over the crop's growing season, with high year-

to-year fluctuations. Except in limited areas and seasons, rainfall amounts in the dry areas are short at economic production levels. Large annual (Figure 1) and seasonal (Figure 2) variations make predictions very difficult. Although explanatory examples are mostly selected from Syria, where ICARDA's headquarters and main research station (Tel Hadya)

are located, the conclusions stated apply to most of the dry areas of West Asia and North Africa (WANA) having a Mediterranean-type climate.

Historically, the focus of water resource planning and management has been on blue water resources for irrigation, industry, and domestic purposes.



ICARDA's main research station at Tel Hadya, near Aleppo, Syria.

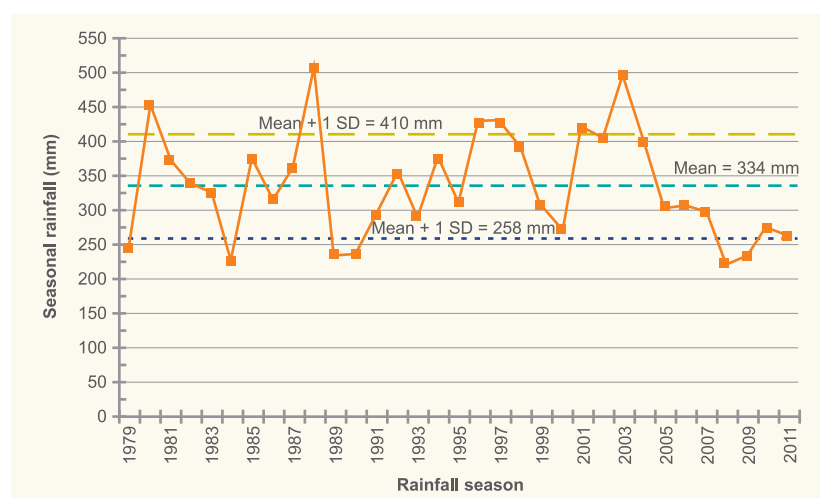


Figure 1. Annual precipitation amounts at Tel Hadya, northern Syria (1979-2011) with long-term annual mean of 334 mm and standard deviation of 76 mm.

Undoubtedly, irrigation plays an important role in food production, but potential increases in irrigation water are limited. Despite the higher risks in rain-fed agriculture, it is widely accepted that the bulk of the world's food will continue to come from rain-fed systems. Investments in rain-fed agriculture are insufficient to

realize its potential. Green water use, monitoring, and management have received little attention by engineers, planners and policy makers.

Given the importance of cereal and legume production as much as trees for food security, potential rain-fed production can play a

significant role in meeting future food demand. This potential could be realized by adopting improved management options on a large scale. The low and variable yields obtained by farmers in rain-fed regions in the developing countries are largely a result of low rainwater productivity caused by inappropriate soil, water, nutrient, and pest management options as well as a shortage of the seeds of improved varieties (Figure 3). This variation in yield leads to instability in farmers' incomes. In the semi-arid, tropics, the yield of rain-fed agriculture is often low – around 1 t/ha – (Rockström et al. 2001). For cereal, it is only 0.85 t/ha in sub-Saharan Africa (SSA) and around 1.40 t/ha in the WANA region. These numbers are below the potential rain-fed productivity. Therefore, with modest inputs and efforts, there is great potential to increase the rain-fed yield and boost rainwater productivity in developing countries.

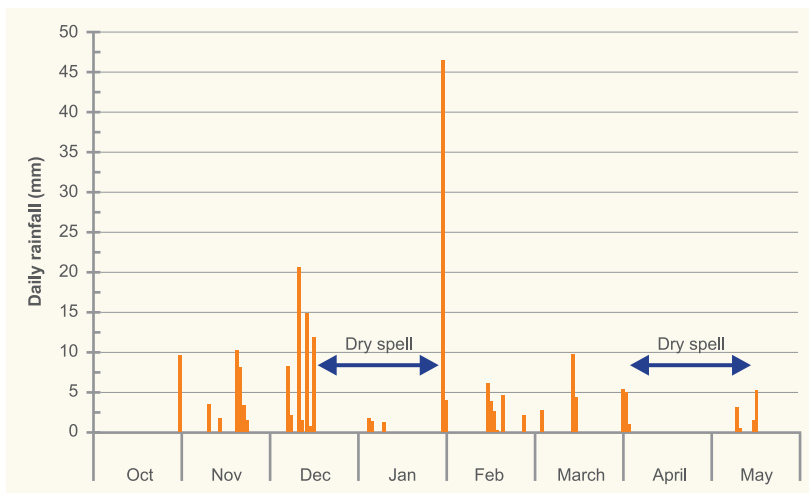


Figure 2. Daily rainfall-distribution showing a critical dry spell (from 2 April to 7 May and mid-December to end of January) in the 2007/08 winter crop season at the ICARDA research station, Tel Hadya, northern Syria.

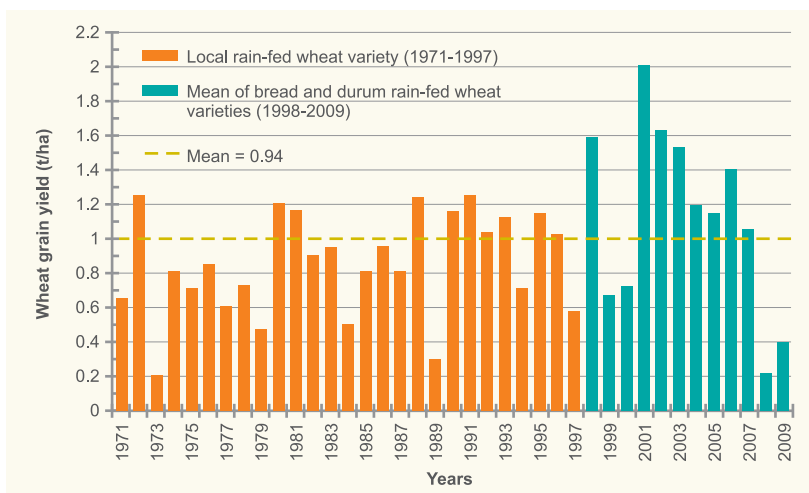


Figure 3. Average grain yield of rain-fed local wheat and the mean yield of bread and durum wheat in Syria.

There is a large untapped potential for rain-fed agriculture, especially in Asia and Africa, where the bulk of the world's poor people live. The lack of clear and sound water policies for rain-fed agriculture is one of the reasons for the low yield and water productivity (WP) in these areas.

The WANA region covers about 125 million ha of rain-fed agricultural land with an annual precipitation varying between 200 and 600 mm. The onset of rain that can be considered safe and dependable for sowing a rain-fed crop occurs over a long time interval (November to January).

Moreover, rain-fed crops always suffer terminal droughts to varying degrees in April and May. Wheat and legumes, are usually grown in rotation in the 300 to 600 mm rainfall belt throughout the region, while barley is grown in drier zones

(200 to 300 mm annual rainfall). The yields of these crops are low, ranging from 0.5 to 2.5 t/ha. While irrigated areas produce higher yields, the overall value of the rain-fed production, which amounts to around half of the total wheat

production of the region, is greater than its market value because of the social and other indirect benefits associated with these systems.

DRY FARMING: HIGH UNCERTAINTIES

Rain-fed agriculture in the water-scarce tropics and large parts of the dry areas is not only related to the total amount of rainfall, but also to its spatial and temporal variability. The key challenges lie in mitigating the risk of the intra-seasonal dry spells in order to improve and stabilize rain-fed crop yields.

Rainfall characteristics results in that soil moisture in the crop root zone does not satisfy the crop needs over the whole season. For wheat in northern Syria, as an example, in the wet months (December to February) stored rain is ample, crops sown at the beginning of the season (November) are in their early growth stages, and the water extraction rate from the root zone by evapotranspiration is very low (Figure 4). Usually little or no moisture stress occurs during this period. Generally, rain-fed crops do not undergo moisture stress before the month of March in the Mediterranean region. However, in early spring (March-April) rainfall rate drops, crops grow faster with a high rate of evapotranspiration

(ET) which results in faster soil moisture depletion and soil moisture in the crop root zone drops below critical levels. A stage of increasing moisture stress starts and continues until the end of the growing season. Such a stress occurs in all Mediterranean-type rain-fed areas with no exception, but varies in its timing and severity. As a result, rain-fed yields are very low relative to the potential achieved with no moisture stress. Even in relatively high rainfall Mediterranean areas,

or in wet seasons, the distribution of the rainfall exposes the crops to terminal moisture stress during sensitive stages of growth and reduce production.

In addition to water stress in rainfed systems, several other sectors widen the gap between the potential yields in rain-fed areas and the actual yields achieved by farmers (Figure 5). Proper agronomic policies, inputs such as fertility and the use of improved varieties are among the most important. Investment in rain-fed areas, policy reform, and transfer of technology, such as supplemental irrigation and water harvesting, require a coordination of efforts among all players

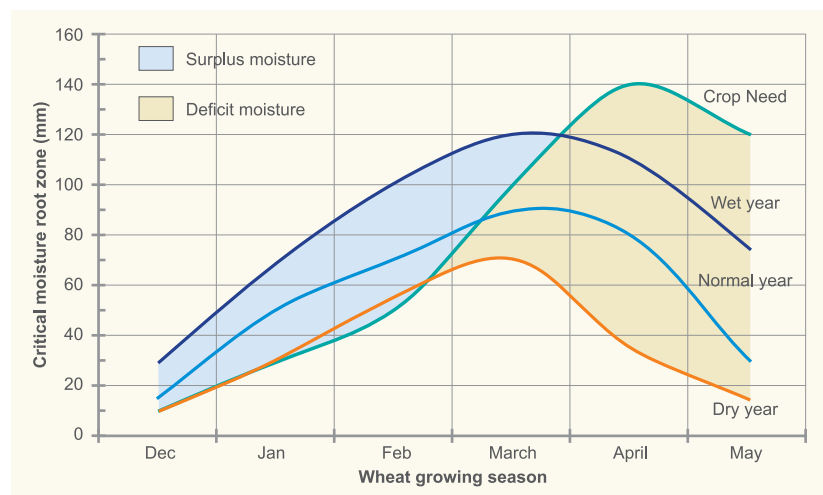


Figure 4. Typical soil moisture patterns for a rain-fed wheat growing season in the eastern Mediterranean for wet, normal, and dry years.

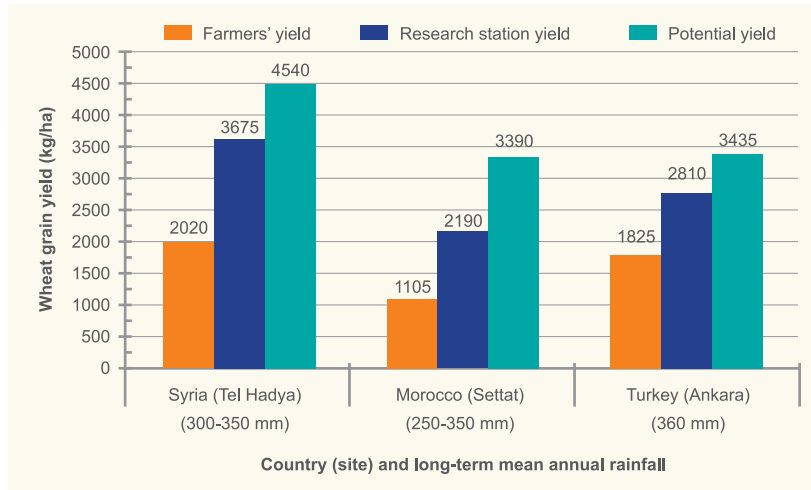


Figure 5. Yield gap for wheat at selected areas in the WANA region. Data periods are: Syria (1986–2000), Morocco (1990–2000), and Turkey (1990–2001). (After Singh et al. 2009).

including agricultural researchers, local organizations, farmers, community leaders, NGOs, national policymakers, and donors.

There are three primary ways to enhance rain-fed agricultural production:

1. Increase rainwater productivity through improved water management
2. Improved agronomic practices and inputs (varieties, fertility, disease and insect control, etc.)
3. Expand supplemental irrigation as a highly efficient and yield stabilizing practice.

SUPPLEMENTAL IRRIGATION: A HIGHLY EFFICIENT RESPONSE

Definition and concept

Supplemental irrigation (SI) may be defined as *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*. Supplemental irrigation is an effective response to alleviating the adverse effects of soil moisture stress on the yield of rain-fed crops during dry spells.

A shortage of soil moisture in the dry rain-fed areas often occurs during the most sensitive stages of crop growth (flowering and grain

filling). As a result, rain-fed crop growth is poor and consequently the yield is low. Supplemental irrigation, with a limited amount of water applied, especially during the critical crop growth stages, results in a substantial improvement in yield and water productivity (WP). Research results



Yields are much higher with SI, rainfed wheat supplemental irrigated in northern Syria.

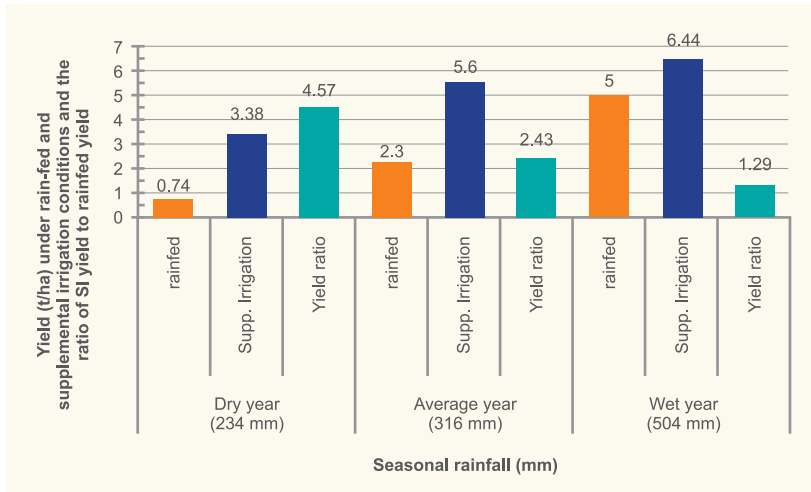


Figure 6. Wheat grain yields for rain-fed and supplemental irrigation (t/ha) and the ratio of SI yield to rain-fed yield for dry, average, and wet years in northern Syria. (After Oweis, 1997).

show substantial increases in rain-fed crop yields in response to the application of relatively small amounts of water. When rainfall is low, more water is needed, but the response is greater, and the increases in yield are remarkable even when rainfall is as high as 500 mm (Figure 6).

Unlike full irrigation, the timing and amount of SI cannot be determined in advance given the rainfall variability. Supplemental irrigation 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.

Supplemental irrigation of field crops

Besides wheat, other field crops in the WANA region also respond positively to SI. Several barley genotypes were irrigated at different levels to replenish 33, 66, and 100% of the soil moisture deficit in the crop root zone in an area under a Mediterranean climate with total rainfall of 186 mm. The mean grain yield (in t/ha) for the barley genotypes was 0.26 t/ha (rain-fed), 1.89 t/ha (33% SI), 4.25 t/ha (66% SI), and 5.17 t/ha (100% SI). The highest yields of one genotype, Rihane-3, were 0.22, 2.7, 4.75, and 6.72 t/ha for these four SI treatments, respectively. These dramatic results under SI were obtained partly because of the drought during this season (Oweis and Hachum 2006).

Northern Iraq is a typical rain-fed area where most of the grains of the country are produced. In a rainfall zone (receiving from 300 to 500 mm of rain with non-uniform temporal and spatial distributions),



Supplemental irrigation substantially improves wheat growth.



Lentil



Chickpeas



Faba bean

Lentil, Chickpeas and faba beans grown under supplemental irrigation produce high yields and provide low cost protein in dry areas.

huge investments in SI systems were made to overcome the 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), rain-fed wheat yield increased from 2.16 t/ha to 4.61 t/ha by applying only 68 mm of irrigation water in the spring. Applying 100 to 150 mm of SI in April and May achieved the maximum results.

Food legumes are important crops in WANA, particularly for providing low cost protein for resource-poor farmers. Rain-fed yields are low for the same reasons outlined earlier for cereals. Data was accumulated over four years (1996–2000) for the SI of winter-sown food legumes at ICARDA's fields, northern Syria, under different water management options. Analysis of the data has identified significant improvements in the yields and WPs for chickpeas, lentil, and faba beans (Oweis and Hachum 2003). However, lentil and faba bean are more responsive to supplemental irrigation than chickpea.

Supplemental irrigation of fruit trees

By definition, supplemental irrigation in rainfed areas implies that rainfall is the principal source of water for plant growth, survival, and production, which is the usual case for all field crops and growing trees during the rainfall season in all of the Mediterranean countries. During the dry rainless months, field crops are only grown with full irrigation. However, fruit trees can use the water stored in the soil profile during the dry months of the year. The amounts

of water that can be stored in the soil profile depend on the annual precipitation amounts and the depth and capacity of the soil profile in addition to the extent of the tree root system. It is common that trees are exposed to soil water stress when the available water in the soil is not enough to provide water requirements during the long summer and autumn before the rain of the following winter. Supplemental irrigation to alleviate severe moisture stress can improve trees growth, yield and fruits quality. Farmers in the Mediterranean region irrigate



Peaches are successfully grown under rainfed conditions with minimal supplemental irrigation during rainless months.

their orchards in the summer (June through September) when water resources are available. Amounts to apply and time depends on crop water requirements and the water available in the root zone after the rainy season. However, 100-200 mm of supplemental irrigation

may be enough in most of the areas and years.

Water sources for supplemental irrigation may include groundwater and surface streams but water harvesting in small farm reservoirs is also common. Usually

surface irrigation is used to irrigate fruit trees, but more frequent drip and bubbler irrigation is practices (Tubieleh et al. 2004).

IMPROVED LAND AND WATER PRODUCTIVITY

Water productivity and water-use efficiency (WUE) are indicators of the return on the water consumed by the crop. In areas with limited water resources, where water is the greatest limitation to production, WUE is the main criterion for evaluating the performance of agricultural production systems. No longer is productivity per unit area is the only objective, since land

in most of the dry areas is not as limiting to production as is water. The effect of SI goes beyond yield increases to substantially improving WP. Both the productivity of irrigation water and that of rainwater are improved when they are used conjunctively (Oweis et al. 1998, 2000).

The average rainwater productivity for wheat in the dry

areas of WANA is about 0.35 kg/m³. With improved management and favorable rainfall, water productivity can be increased up to 1 kg/m³. However, the water used in SI can be much more efficient. Research at ICARDA has shown that a cubic meter of water applied at the right time (when the crop is suffering from moisture stress), combined with good management, could produce more than 2.5 kg of grain above that of rain-fed production (Figure 7). This extremely high WP is mainly attributed to the effectiveness of a small amount of water in alleviating severe moisture stress during the most sensitive stages of crop growth and seed-filling. When SI water is applied before such conditions occur, the plant may reach its high yield potential.

In comparison to the productivity of water in fully irrigated areas (when the rainfall effect is negligible), the productivity is higher with SI. When irrigated wheat produces a grain yields of about 6 t/ha it uses about 800 mm of water with WP of about 0.75 kg/m³, one-third of that under SI with similar management. This suggests that water resources may be better allocated to SI when other physical and economic conditions are favorable.

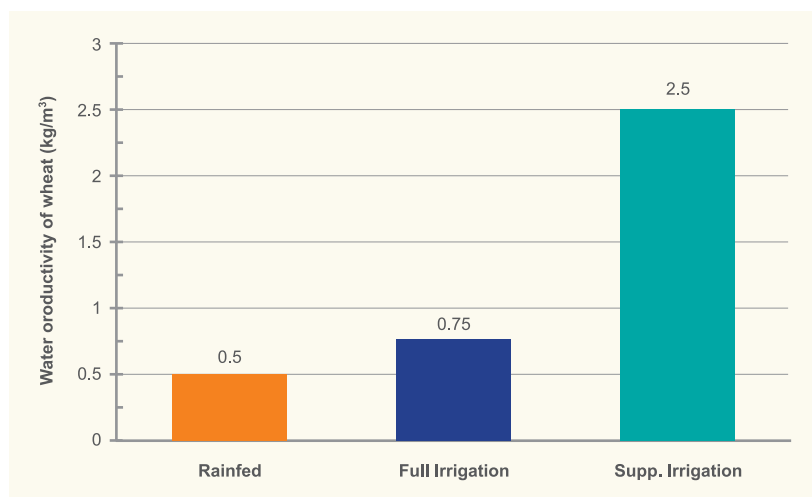


Figure 7. Average water productivity of green water (purely rain-fed), of blue water (full irrigation with little or no rain), and of SI water for wheat in Syria (After Oweis, 1997).

WHEN SHOULD FARMERS APPLY SUPPLEMENTAL IRRIGATION?

The most difficult decisions in SI management are to determine when to irrigate and how much water to apply. Many, perhaps most, farmers apply too much water if they can get it at low cost. Evidence of the overuse of irrigation water is clear in many dry area situations, and SI is no exception. Farmers tend to overuse water in SI when water and irrigation costs are low because of the large benefits obtained. The objective of any SI management program should be to provide sufficient water to the crops at the right time; farmers should also be discouraged from over-irrigating.

Supplemental irrigation for early sowing

In the lowlands, farmers usually sow/seed their land only when a sufficient amount of rain has fallen. The date by which this amount of rain has fallen is usually called the 'onset rainfall', meaning the beginning of the rainy season. It is implicitly assumed that there will be little risk of an early dry spell for the crop. Nevertheless, there is always a risk of having a false start to the rainy season or a late start. It is in these situations that SI has a role to play. Farmers can decide on the beginning of the growing season and help a crop combat terminal drought during its later stages (Figure 8).

Early November is the optimal sowing date for wheat in the eastern Mediterranean. Every week's delay in sowing may result in a grain yield loss of up to 0.2 t/ha for purely rain-fed wheat and up to 0.5 t/ha of wheat under supplemental irrigation. In the winter rainfall environment of the WANA region, delaying the sowing date retards 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 prevails as pure cereal or cereal-legume rotations, mid-November was found to be an optimum sowing time for cereals. Every week's delay after this time results in a yield decrease of between

200 and 250 kg/ha. If the onset of the seasonal rain is delayed, early sowing can be realized with the help of a SI system. With SI it is possible to decide on the sowing date of the basically rain-fed crops without needing to wait for the onset of the seasonal rain. This results in a longer growing season, better yield, and an earlier maturity that helps crops to escape terminal drought.

In the highlands, frost conditions occur between December and March and field crops remain dormant. Usually, the first rainfall, sufficient to germinate the seeds (the onset rain), comes late (November) and results in a small crop stand when the frost occurs in December. As a result, rain-fed yields are much lower than when the crop stand, pre-frost, is good. Ensuring a good crop stand before frost can be achieved by early sowing and applying from 50 to 70 mm of SI. Supplemental irrigation, given at early sowing, dramatically increases wheat

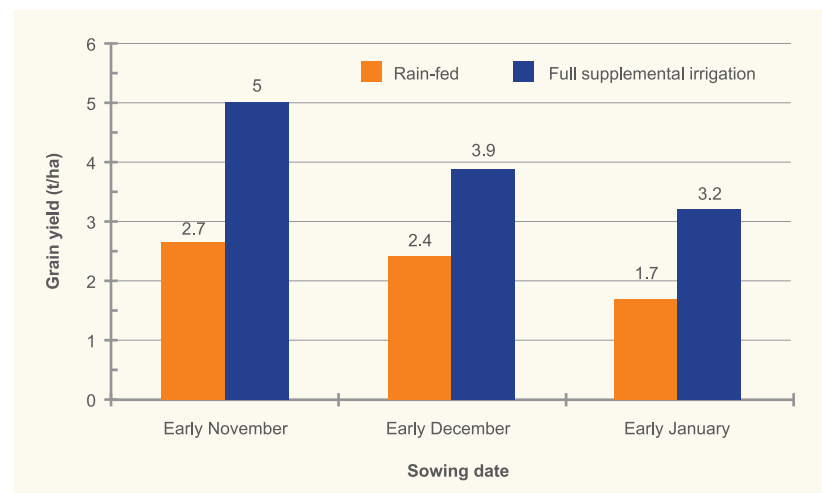


Figure 8. Effect of sowing date on bread wheat grain yield at the ICARDA research station, Tel Hadya, northern Syria (1992–1996). (After Oweis, 1997).

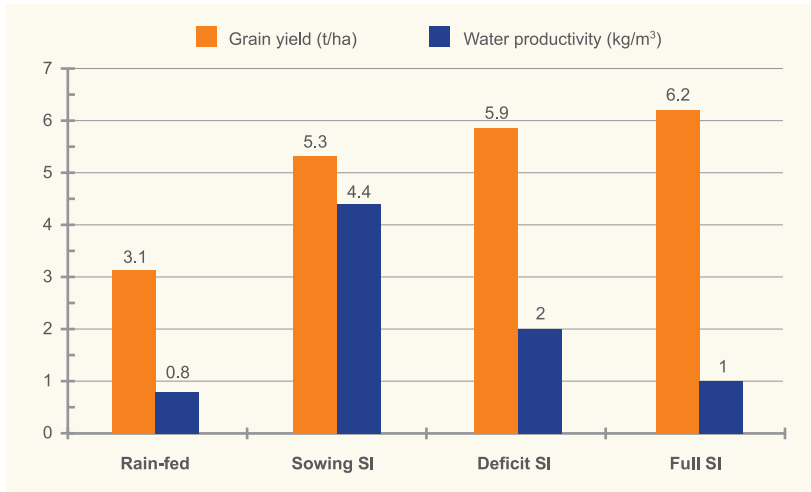


Figure 9. Effect of early sowing of wheat on yield and water productivity in the highlands of Turkey (After Ilbeyi et al. 2006).

yield and water productivity. In the highlands of Turkey, applying 50 mm of SI to wheat sown early has increased grain yield by more than 60%, adding more than 2 t/ha to the average rain-fed yield of 3.2 t/ha (Ilbeyi et al. 2006). Water productivity reached 4.4 kg/m³ of consumed water compared to WP values for wheat from 1 to 2 kg/m³ under traditional practices (Figure

9). Similar results were found in the Iran highlands for wheat and barley (Tavakoli et al. 2010).

Supplemental irrigation to alleviate moisture stress

Unlike for full irrigation, the time for SI irrigation cannot be

determined in advance. This is because the basic source of water to rain-fed crops is rainfall which, being variable in amount and distribution, is difficult to predict. Since SI water is best given when the soil moisture drops to a critical level, the time for irrigation can be best determined by measuring the soil moisture on a regular basis. Unfortunately, there is no simple and low cost device that an average, uneducated farmer can use for this purpose. The well-known tensiometers are not suitable, since SI management allows a lower soil moisture potential than these instruments are able to read; other more sophisticated methods are either costly or complex for farmers to use.

Instead, most farmers in the region rely on personal experience related to the amount of rainfall received and the crop appearance. Generally, they tend to irrigate earlier and more frequent than necessary when they have water supply.



Tensiometers are not suitable for scheduling supplemental irrigation.



The neutron probe or TDR allows quick measurement of soil water status on research station fields.

ICARDA has developed a methodology, through modeling, for analyzing historic rainfall records in the area together with soil and crop parameters, to determine the most probable conditions occurring after knowing the rain amounts at any time during the season. Research in the eastern Mediterranean region has shown that the amount of rain falling before the end of February is a good indicator of what will later be the situation in the season. Usually, however, one to three supplemental irrigation applications of not more than 100 mm each annually appear sufficient, depending on the rainfall amount and distribution. In the WANA region, these irrigations may best be given between late March and early May.

HOW MUCH WATER SHOULD FARMERS APPLY?

In water-scarce areas, the optimal amount of irrigation water to apply may not satisfy the full crop water requirement or produce maximum yield per unit area. Rather for optimal operations it needs to satisfy several criteria, of which water productivity is the most important. Those include:

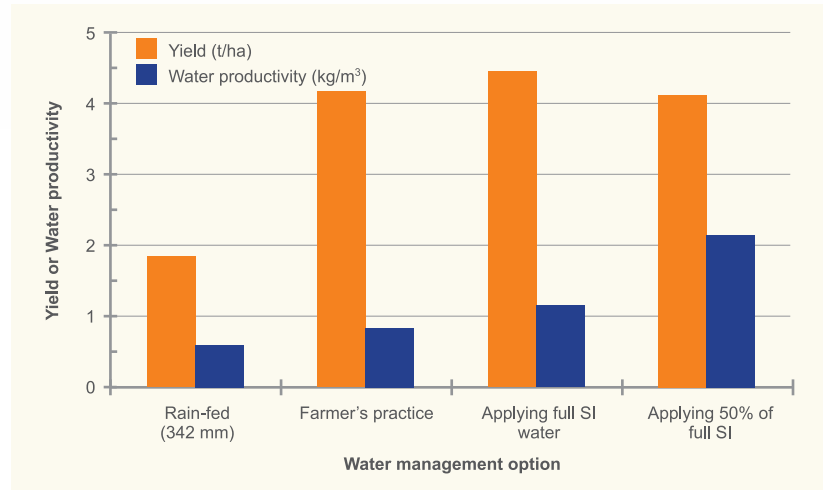


Figure 10: Yield and water productivity for wheat under different water management options for a 4 ha farm in northern Syria (After Oweis, 1997).

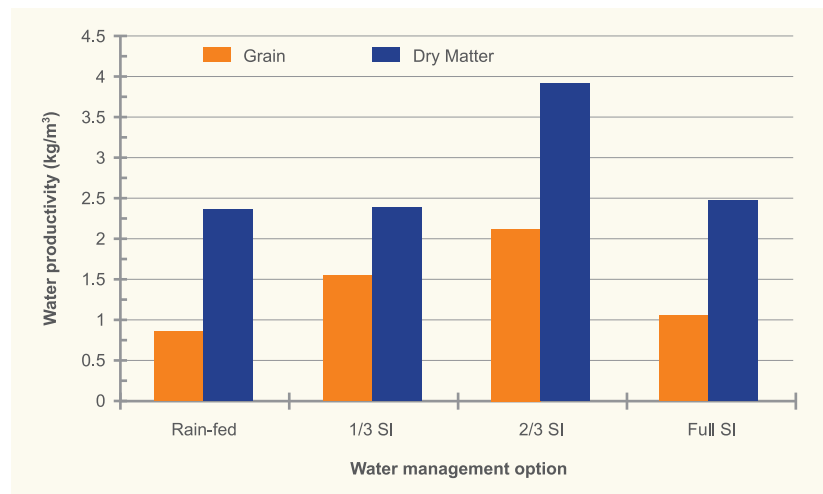


Figure 11. Water productivity of wheat as affected by the amount of supplemental irrigation in northern Syria (Oweis and Hachum 2003).

Water productivity/ water-use efficiency

Research in the WANA region has shown that applying just 50% of the full SI requirements causes a yield reduction of wheat of 10 to 15% relative to that obtained under full SI. Using the 50% water saved to irrigate an equal area gives a much greater return in

the total production. By so doing, the area under SI can be doubled using the same amount of water, and total farm production may substantially increase. When there is not enough water to provide full SI to the whole farm, the farmer has two options, to irrigate part of the farm with full SI leaving the other part purely rain-fed or to apply deficit supplemental

irrigation to the whole farm. Under limited availability of water resources, using 50% of the full SI requirements – deficit SI – has been shown to be a winning option by farmers. A farmer having a 4 ha farm would, on average, produce 33% more grain from his farm if he adopts deficit irrigation for the whole area, rather than applying full SI to half of the area (Figure 10).

In some areas, groundwater resources are being over-exploited for full irrigation and their quality is deteriorating. With such pressure on the existing water resources, sustainable use can be obtained only by producing more crops from less water, that is, by improving water productivity.

Water productivity in SI is a function of the amount of irrigation water applied. It was found that maximum WP is attained when from one- to two-thirds of the full irrigation water is applied (Figure 11). Given that many farmers over-irrigate, at least one-third of the full supplemental irrigation requirement can be saved without any losses in productivity.

Farmers' benefits

The farmer's objective is to maximize income from farming. ICARDA has developed methodologies to help farmers determine the amount of SI that the farmer should apply to maximize his economic return. Developing rain-fed and SI production functions is the basis for optimizing water-use strategy. Supplemental irrigation production



Transfer of supplemental irrigation technologies is an important objective of ICARDA.

functions are developed for each rainfall zone by subtracting the rainwater production function (Figure 12) from the total water (SI + rain) production function. Since the rainfall amount cannot be controlled, the objective here is to optimize the SI water amount. The seasonal depth of SI to maximize profit occurs when the marginal product of water equals the ratio of the unit water cost to the unit product sale price. Applying this analysis to wheat in northern Syria, the production functions of SI under different rainfall conditions are developed (Figure 12). Coupled with current and projected water costs and wheat sale prices, the functions are used to develop an easy-to-use chart for determining seasonal SI rates that maximize profit under a range of seasonal rainfall amounts. Profit maximization charts are developed as shown in Figure 13. However, the cost of irrigation, the price of production, and the annual rainfall have to be determined to use the chart. The latter can be

determined after most of the rain has fallen by the end of March.

The ultimate goal is to contribute to balancing profitability for the farmer and water resource sustainability. The approach is illustrated using data for rain-fed durum wheat in northern Syria. Results show that, for a given seasonal rainfall, there is a critical value for the ratio of water cost to product sale price beyond which SI becomes less profitable than rain-fed production. Higher product prices and lower irrigation costs encourage the use of more water. Policies supporting high wheat prices and low irrigation costs encourage maximizing yields, but with low water productivity. The resulting farmer practice threatens the sustainability of water resources. Balancing profitability with sustainability is a challenge for policy makers and helps determine the optimal production level for the prices offered. It can help national and local water authorities and policy makers

implement appropriate policies for water valuation and allocation. It can also help extension services and farmers plan irrigation infrastructure and farm water management.

Yield, water productivity/WUE and profit

Maximizing farmers' profits may not necessarily result in maximum WP/WUE – just as maximizing WP/WUE may not produce maximum profits. When the cost of irrigation is low, farmers do not have much incentive (in terms of profit) to try to maximize WUE; they tend to apply full crop water needs to achieve near-maximum yield. However, when transfer of SI technologies is important, the cost of water is high, or access to water is limited, maximum yield does not ensure maximum profit. The relation between wheat grain yield and total WUE under SI systems shows a non-linear increase in WUE with the increase in yield peaking at around 5 to 6 t/ha (Figure 14). However, the increase in WUE slows down after 50% of this yield is reached. The proper management under these circumstances should take into consideration (a) the interests of the farmer together with the long-term sustainability of the resource, and (b) the value of water at the national and farmer levels.

Trade off between profitability and sustainability

In the dry areas, groundwater is heavily used as a source for

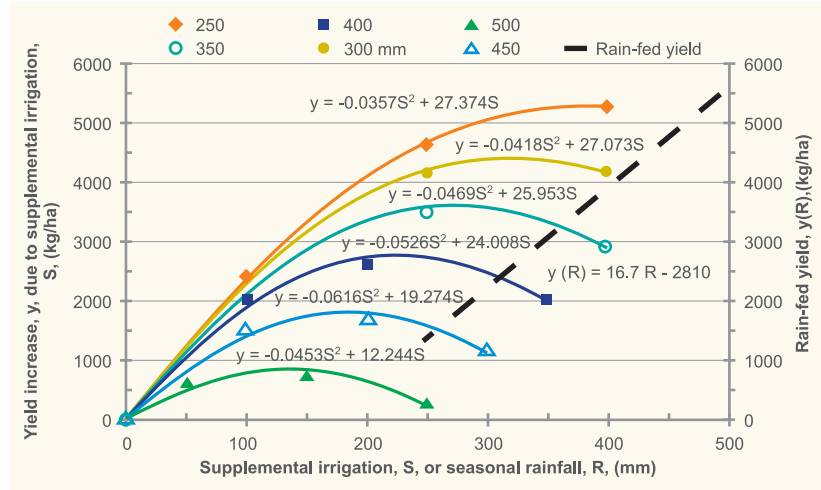


Figure 12. Supplemental irrigation production functions for different probable seasonal rainfalls together with the rain-fed production functions, at ICARDA experiment station. 'S' denotes the seasonal depth of supplemental irrigation and 'R' is the seasonal probable rainfall (Oweis and Hachum 2009).

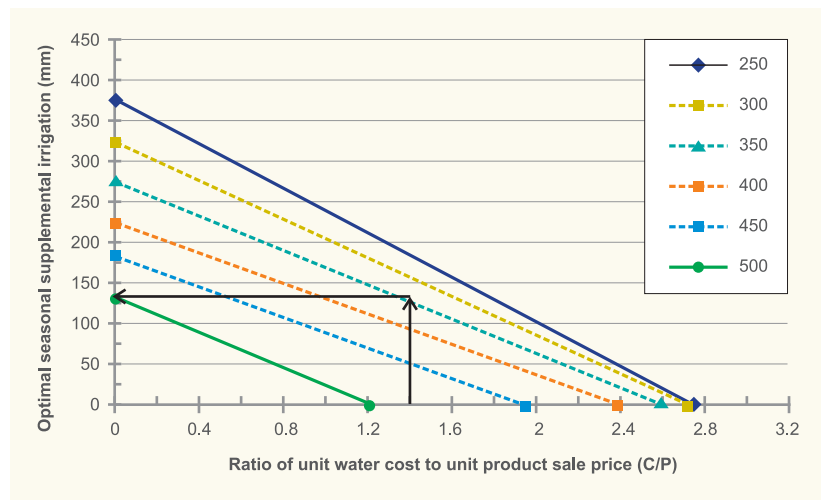


Figure 13. Optimal amount of net seasonal SI for a ratio of unit water cost to the unit product sales price for different rainfall zones at Aleppo, Syria (Oweis and Hachum, 2009).

supplemental irrigation. In Syria, for example, about 60% of irrigation uses groundwater resources. This resource is being increasingly overused as farmers are encouraged by free water and high profits (Somme and Al-Qaise 2000). Sustainability is a crucial

issue under such circumstances. Liberalizing energy prices may discourage farmers from over-exploiting groundwater aquifers and depleting their precious natural resources. Naturally, and as shown in Figure 13, for a given cost of irrigation, increasing

wheat prices encourages the use of more water, while increasing the cost of irrigation water, for a given wheat price, forces farmers to use less water. Unfortunately, farmers, though generally aware of the consequences to the environment and the natural resource base, continue to ignore the issue of sustainability. Policies must be developed to ensure that maximizing farmers' profits does not adversely affect resource sustainability.

In countries, such as many in the WANA region, where water pricing is not socio-politically feasible, a monetary value could be added to the cost of water to discourage overuse. Increasing the cost of water will certainly result in reduced SI amounts. The question is how high irrigation costs should be to ensure sustainability of both the resource and the farmers'

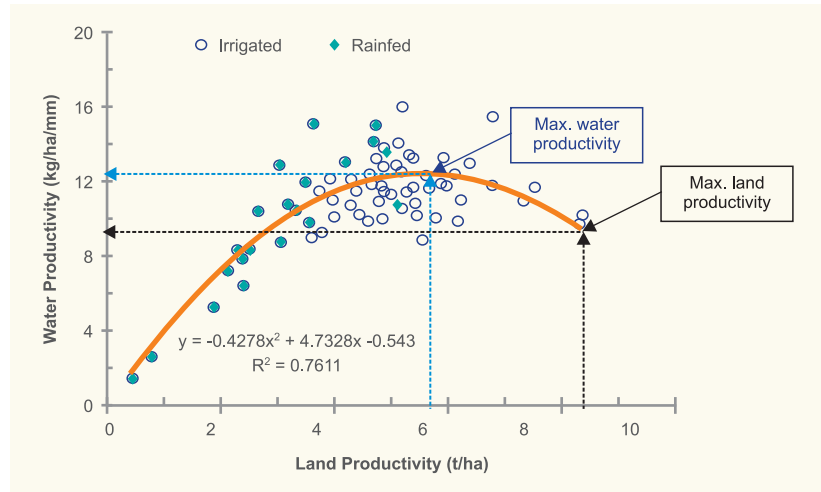


Figure 14. Relationship between WP and land productivity for durum wheat under SI in northern Syria (Zhang and Oweis 1999).

livelihoods. Water authorities and policy makers should develop policies and regulations for determining appropriate allocations and requiring the rational and sustainable use of limited water resources.

Figure 13 illustrates that, for the 300 mm rainfall zone, 150 mm is the optimal amount of SI for a ratio of the cost of 1 m³ of irrigation water to the sale price of 1 kg of durum wheat grains of 1.5 (Oweis and Hachum 2009).

OPTIMIZING SUPPLEMENTAL IRRIGATION

Supplemental irrigation alone, although it alleviates moisture stress, cannot ensure the best performance of the rain-fed agricultural system. It has to be combined with other farm management practices and inputs. The following are among these:

Fertility

Mediterranean soils are generally deficient in nitrogen. Improving fertility greatly improves yield and WUE. Under rain-fed conditions, the rate of application of nitrogen fertilizer need not be high, and with some water stress, high rates may actually be harmful. Under Syrian

rain-fed conditions, 50 kg N/ha may be sufficient (Figure 15). However, with more water being applied, the crop responds to nitrogen up to 100 kg N/ha, after which no benefit is obtained. This rate of N application greatly improves WUE (Figures 15, 16). It is also important that there is an adequate amount of phosphorus available in the soil so that the response to the N and applied irrigation is not constrained. Other areas may have deficiencies in other elements. It is always important to eliminate these deficiencies in order to increase yield and WUE.

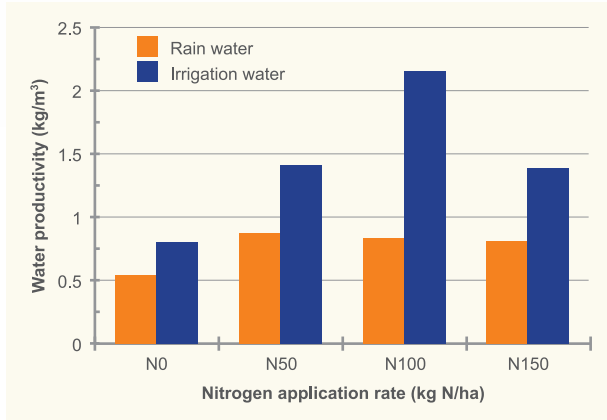


Figure 15. Water productivity of bread wheat under rain-fed and SI conditions as influenced by nitrogen at ICARDA's research station, Syria. November sowing with 66% SI. (Oweis and Hachum 2003).



Nitrogen deficiency affects both yield and water-use efficiency

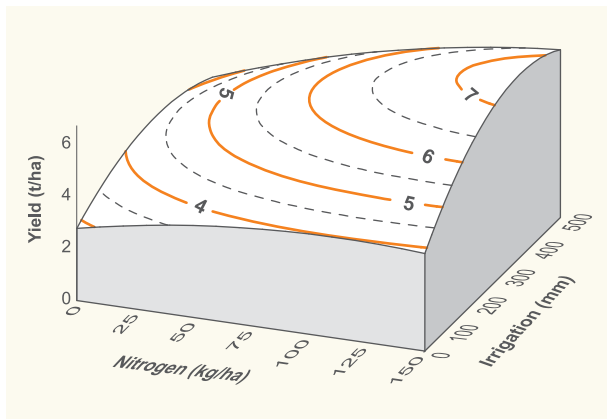


Figure 16. Response surfaces of durum wheat (Cham 3) grain yield in relation to SI and nitrogen at ICARDA's research station. Early sowing + 350 mm rainfall. (After Oweis et al. 1999).

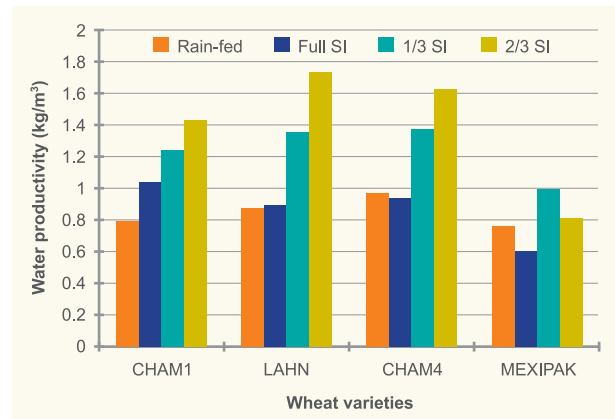


Figure 17. Average rainwater and SI productivity for durum and bread wheat varieties grown in northern Syria. (Cham1 and Lahn are durum wheat varieties while Mexipak and Cham4 are bread wheat varieties). (Oweis and Hachum 2003).

Crop varieties

The selection of the appropriate crop variety makes a difference under both rain-fed and SI. In rain-fed areas, breeders produce drought-tolerant varieties. These

perform well under rain-fed conditions, but because they were not developed for SI conditions their response to more reliable water supplies may not be highest (Figure. 17). A suitable variety for

SI is one with a good response to limited water application while maintaining some drought tolerance.

ADAPTATION TO CLIMATE CHANGE

Climate change will have negative effects 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. Effects are expected on crop productivity, water resources, and ecosystem services.

Higher temperatures and CO₂ levels will likely change the growth patterns and durations of crops. Higher temperature will shorten the growth cycle of field crops and alter the phenological stages. However, higher early spring temperatures and fewer frost days may improve the early growth and vigor of the plants. Stomatal opening and closing, and thus the loss of water by transpiration, depends, among others things, on the CO₂ concentration within the plant tissue. This means that with higher CO₂ levels plants may transpire less. This, however, is only the case if the temperature, and thus evaporative demand, does not increase and make it necessary for the crop to transpire more water to keep the canopy cool. The RuBisCO enzyme responsible for photosynthesis also responds positively to an increase in CO₂. Both processes (stomata

behavior and RuBisCO activity), however, are highly complex, and counterbalancing or saturation effects may play a further role. In any case, combining increased temperature with increased atmospheric levels of CO₂ will modify crop ET patterns. This will affect the soil water status and the moisture uptake by the crops.

It is, therefore, necessary that adaptation measures be developed in advance to overcome the consequences to agriculture and the livelihoods of people depending on farming. Climate change adaptation strategies can only be effective if done in an integrated manner. For rain-fed agriculture, the strategies may need to encompass water

management, crop improvement, cultural practices, policies, and socioeconomic and other issues. Supplemental irrigation, however, can play an important role in the adaptation efforts to climate change in rain-fed agro-ecosystems. Following are some of the potential responses that SI can make to adapt to climate change.

1. ICARDA is currently investigating climate change effects using biophysical crop models. First scenario simulation results highlight the positive effect of SI in alleviating the negative impact of climate change, especially on the year-to-year variability in crop yields which are predicted as consequences of climate change in the near future (2011–2050). Supplemental irrigation management resulted in an application of

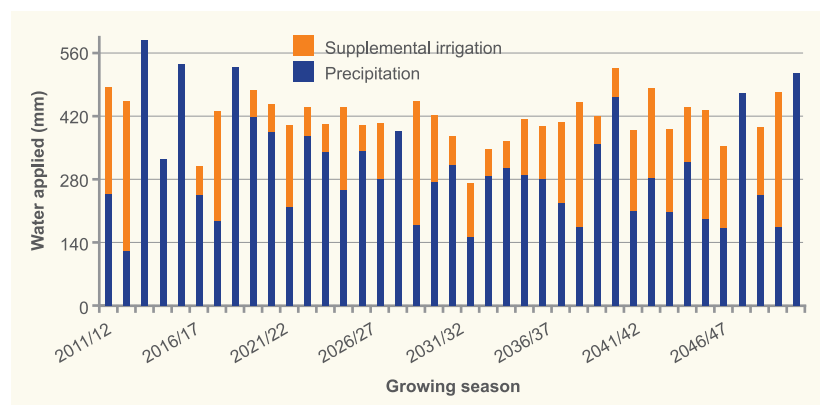


Figure 18: Simulations of future SI requirements of wheat under climate change expected for 2011/12–2049/50³. (Sommer, Oweis and Hussein, 2011).

³The following SI management decisions were realized in the simulations. SI was started upon crop emergence and continued until 15 days after the start of grain-filling. When the soil water content within the rooting zone dropped to below 15% plant available, not less than 15 mm and not more than 60 mm of water was applied, to fill up the plant available soil water store to 100%. Climate change weather predictions were provided by the (ENE) model PROTHEUS (see: <http://utmea.enea.it/research/PROTHEUS/>) under SRES-scenario A1B.

irrigation water of between 0 and 330 mm (average, 122 mm), usually, between one and three (maximum, six) irrigation events per season. No supplemental irrigation was necessary in six of the 49 years. See Figure 18.

Thus, on average, yields were 2.6 times higher with SI than without. The corresponding water-use efficiency (precipitation plus irrigation) increased from 0.50 kg/m³ under rain-fed-only conditions to 0.99 kg/m³ under full SI.

Therefore, in conclusion, it can be noted that SI can be used to overcome the changes in soil-water-plant relations, especially in alleviating soil water stress resulting from changes in crop ET and crop patterns. As rainfall is unpredictable, SI becomes the most viable practice to alleviate the 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.

2. Less and more erratic precipitation is expected in the dry areas as a result of global warming. Lower precipitation will cause a further moisture stress on already stressed rain-fed crops and some areas on the peripheries of the rain-fed

zones may drop out of dryland agriculture as a result. It is also expected that rainfall will be more erratic and intensive, and the season will have prolonged drought spells. Crop yields and WP losses are mainly associated with soil moisture stress during such drought spells. Prolonged drought spells during the rainy seasons resulting from global warming will make the crop situation even worse and further drops in yields are expected as a result.

Supplemental irrigation, by definition, deals with two situations. It adds 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 durations of potential drought

spells in order to design SI schedules to adapt the system to climate change. Figure 19 shows the alleviation potential of SI at various levels of rainfall on wheat grains in Aleppo area. It should be noted that with this, the demand for SI is increased but with enhanced productivity.

3. Higher intensity rainstorms are also predicted, not only in the dry area, but also in SSA and globally (Karrou and Oweis 2008). This naturally will cause more runoff and soil erosion in rain-fed areas, especially on sloping lands. The portion of the precipitation that normally infiltrates the soil to support plants growth will be less as more runoff will go downstream. In addition, it is predicted that the process of land degradation will be accelerated.

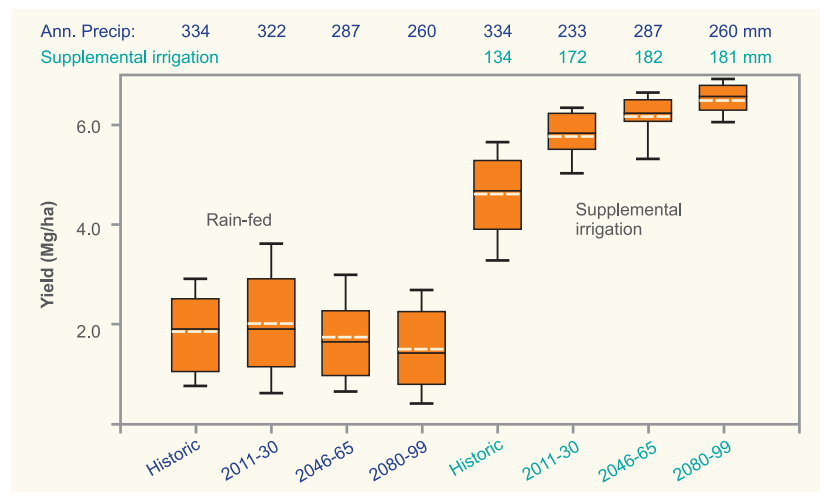


Figure 19: Potential of supplemental irrigation to alleviate climate change impacts in Aleppo region, northern Syria (yield based on GCM IPSL-CM4) (Sommer et al 2011).



Small farm water harvesting reservoirs used for supplemental irrigation in the Highlands of Ethiopia.

Supplemental irrigation 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.

IRRIGATION SYSTEMS

Irrigation systems that are suitable for full irrigation are also, technically, suitable for SI. The difference between SI and full irrigation is in the management, not in the irrigation system itself. There are also economic considerations. Supplemental irrigation systems are only occasionally used. In most of the rain-fed areas only one to three irrigations may be needed each year. Using a system occasionally rarely justifies large investment. This may be why most SI systems are of the surface type, although they have lower application efficiency and uniformity. More costly systems, such as sprinklers and trickle irrigation are mainly acquired for full irrigation in the summer, but can be utilized for

SI in the winter. When labor and water are costly and the field is not suitable for a surface system, or no full irrigation systems exist, then sprinkler systems are generally used. The objective then is to minimize the cost by an appropriate selection of the type and size of the system. Currently, farmers use three major irrigation methods in practice:

- Surface irrigation methods including basins, furrows, and border strips
- Sprinkler irrigation methods including set systems, travelling guns and continuously moving systems
- Trickle irrigation methods with drip, micro-sprinklers, and sub-surface systems.

These systems vary greatly in their application, distribution, and storage efficiencies. The major contribution of irrigation systems to improved SI performance is in making water more available in amount and timing for plant growth. The key factor in successful irrigation is the control of the water at all times and the levels of water conveyance, distribution, and field application. For crops grown in large fields, a high level of water control is inherently built-in in most of the sprinkler systems given the nature of these systems. Though the drip or micro-irrigation systems offer higher levels of water control than the sprinkler system, they are only recommended for trees and row crops. As such, there are great opportunities for investment in sprinkler irrigation (Box 1).

The sprinkler system can be more flexible and durable as:



Attempts to adapt furrow irrigation for supplemental irrigation of wheat may help in reducing irrigation costs while maintaining high efficiency.



Border strip irrigation is not very common for supplemental irrigation because of the costly land-leveling requirements.



Surface irrigation is very popular. It is labor-intensive, but requires little capital investment.

- There is no need for land grading or reshaping (which is a basic requirement for successful surface irrigation)
- The same system can fit different types of soil and crop
- Portability allows use of the system on many farms at different locations during the same season
- A higher degree of control over the water allows for shorter

irrigations which are suitable for SI

- Dual uses of the system, such as chemical application and crop cooling (during summer). A portable sprinkler system can be efficiently used for SI to serve a large cropped area during spring, when the rain is insufficient for the crop, by using a low flow rate water source, such as a well or a water harvesting pond. This is an

important factor in which sprinkler irrigation is superior to surface irrigation in water-short regions.

Although surface irrigation is relatively inexpensive and does not require high technical skill, it is recommended for SI when proper land grading is made to the field or small basins are used. Surface irrigation can be made suitable for SI by using the following techniques:

- **Surge flow irrigation:** by applying water intermittently, instead of continuously, to the furrow, a more uniform distribution of water along the run is achieved as a result of the reduced infiltration rate upstream
- **Raised bed furrows:** partially supplying the cropped land with irrigation water can be useful under deficit irrigation management
- **Alternate water application to furrows:** irrigating every other furrow in one irrigation cycle then irrigating the dry furrows of the previous cycle in the next



Drip irrigation systems are still very costly for field crops.



A hand-moved sprinkler irrigation system is low in cost, but labor intensive.

cycle, has shown some savings in the amount of water applied

- **Level basin:** a conventional surface irrigation method that can achieve very high application efficiency if properly implemented.

One aspect of SI is associated with the need to irrigate a larger area in a short time during a drought spell. A high rate of supply of the water and a large irrigation system are then needed. This conflicts with the objective of minimizing costs. To overcome this problem the following strategies may be adopted:

- The use of mobile sprinkler systems that can be moved easily within the field either mechanically, or by hand – hand-moved systems are suitable when labor is not very costly. However, side-roll and gun sprinklers also give good value for money
- Spreading the peak water requirements over a longer period in late spring by using different planting dates in



In northern Iraq, this linear-move system is used for full irrigation in summer and SI in winter.

different parts of the field (Oweis and Hachum 2001). Planting dates for wheat in the Mediterranean, for example, can range from early November to late January, which spreads the peak water requirements over a longer time. Also selecting different crops and varieties that require water at different times can help (Figure 20).

Although this may affect the yield and production a little, it will cut the cost of irrigation.

- Water can be stored in the soil profile before the beginning of the irrigation time. During the early spring, the crop consumption rate increases and some soil storage space is created before the critical level is reached. During this time farmers can start irrigating

early and fill part of this space, which in turn will delay the time by when the next irrigation will be needed. This will reduce the peak water need. In fact, some farmers who have small irrigation systems (one hand-moved system) already practice this

- When the farm has irrigated summer crops, the system must be designed to suit both full irrigation and SI
- When the system is used only for SI, the size and cost may be reduced by considering the optimal water-scheduling needs, not the crop's full water requirement. Providing 50% of the full irrigation requirement not only increases WUE and net return, it also cuts water need, irrigation system size, and cost
- There are three major problems associated with the use of sprinkler irrigation:
 - high cost, including the power requirements to pressurize the system; This problem can be alleviated by government support through subsidies and credits
 - technical skill and know-how for installation, operation, and maintenance. This problem can be solved by human capacity building through training and effective extension services
 - water sprinkling can significantly increase ET over surface systems especially in

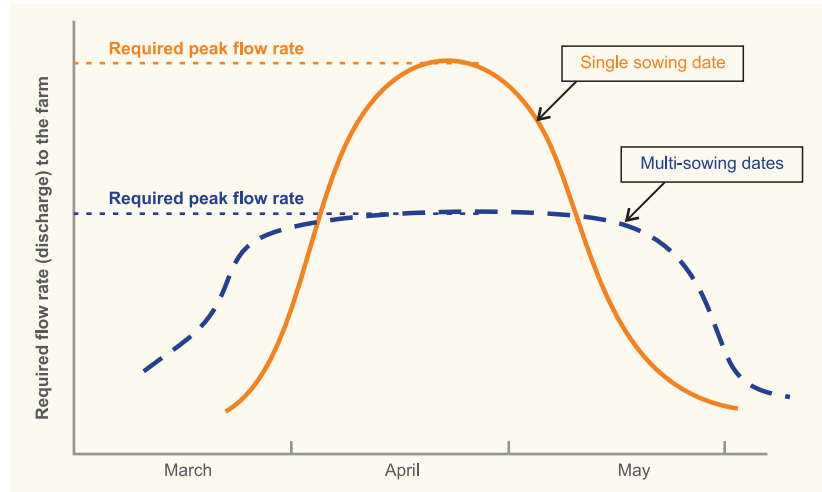


Figure 20. How spreading sowing dates across time reduces the required peak flow rate to a farm under SI. (The cropped area is the same in both cases).



Suitable planting dates can be used to reduce pressure on water resources and irrigation systems.

dry windy areas, because of aspiration and wind drift. This problem can be managed by not operating the sprinkler

irrigation system during the windy and dry hours of the day.

SOURCES OF IRRIGATION WATER

Surface water resources: When planning SI for rain-fed agriculture, the question of the source of water for irrigation is crucial. In a developed river basin with full irrigation for summer crops and rain-fed irrigation for winter crops (such as in the WANA countries characterized by a Mediterranean climate), the same water sources and irrigation facilities used for full irrigation during rainless dry seasons (summers in the WANA region) can be used for SI during the rainy season. One good example is the North Jazirah Irrigation Project in Nineveh Province, northern Iraq, in which 25% of the 60,000 ha project area is cultivated under full irrigation in summer and 75% of the area is under rain-fed wheat with SI in winter (Adary et al. 2002). The source of water for the project is the river Tigris.

Groundwater resources: These are the most common sources of water for SI. In Syria, for example, groundwater represents 60% of all the water used in irrigation. In many dry regions, more than 90% of the rain-fed areas with SI are fed from groundwater. However, the problem of using groundwater for irrigation in the dry areas is the overexploitation of this valuable natural resource. Pumping groundwater in excess of the natural recharge of the water to the aquifer endangers sustainability of the development which depends on this water.

Water harvesting: could be very useful in providing the water needed for SI to upgrade the productivity of rain-fed crops grown in marginal environments characterized by low and/or highly

variable rainfall and no other water resources. In this case, runoff water is collected in a surface or sub-surface storage facility for later use as a water supply source for SI. In SSA and other tropical, semi-arid areas, rainwater harvesting, which collects surface runoff, is used to provide most water for SI.



Surface irrigation sources are the cheapest supply for SI, but are often not available in rainfed areas.



In many areas, groundwater is being over-exploited and its sustainability threatened.



Water-harvesting in surface reservoirs is a good source for SI. This mountain lake in northern Tunisia supports wheat and vegetables downstream.



Water-harvesting in small reservoirs is a sustainable and low cost source for SI.



Farmers in Central Asia use wastewater for the SI of winter crops and full irrigation of summer crops. Precautions must be taken to prevent health and environmental hazards associated with using this source of water.

Water often flows in a temporary (ephemeral) stream called a 'wadi'. This could be captured and stored in surface or sub-surface reservoirs. Water storage is important when ephemeral flows are not available or run low at the time when SI water is most needed. Surface storage of ephemeral or intermittent flows in wadis or valleys could be in small dams, ponds, man-made tanks,

or small-scale reservoirs (Oweis et al. 1999). Several issues, both technical and socioeconomic, need to be considered for optimal implementation of such a water harvesting system. There are many scenarios for the management of the water harvesting reservoir for SI (Oweis and Taimeh 1996). One scenario is to empty the reservoir as soon as possible after it is filled, storing the water in the soil profile.

This saves the water that would otherwise be lost by evaporation and ensures reservoir space for the next runoff. More water can be stored and utilized, but the risk of not having additional runoff after emptying the reservoirs is real. Bridging dry spells through the SI of rain-fed crops using harvested rainwater can be an interesting option to increase the yield and WP (Oweis et al. 1999).

Marginal-quality water: In water-scarce areas, farmers use marginal-quality water resources for SI. Whether beneficially used or wasted, marginal-quality water needs appropriate treatment and disposal in an environmentally appropriate manner. The protection of public health and the environment are the main concerns associated with such wastewater reuse. The use of saline and/or sodic drainage and brackish groundwater resources is increasing and warrants attention in order to cope with the inevitable increases in salinity and sodicity that will occur.

Agricultural drainage water is becoming an appealing option in many countries, not only to protect natural resources from deterioration, but also to make a new water resource available for agriculture. In Egypt, the total

volume of re-used drainage water is now approximately 7.2 billion m³ per year, some 12% of the total water resources available to Egypt. Treating these drainage waters as a 'resource' rather than as a 'waste' contributes to the alleviation

of water scarcity, protection of the environment, and the sustainability of agricultural production systems.

POTENTIAL AREAS OF SUPPLEMENTAL IRRIGATION

At the country, the river basin levels, and at global levels it is important for planners to know the areas where SI can be implemented, how much water will be needed, and what consequences it may

have downstream. Those areas are primarily rainfed (Figure 21). A GIS-based methodology was developed using the combination of a simple model to calculate the additional rain-fed area that can be irrigated by the water

saving achieved by shifting from spring/summer fully irrigated crops to winter/spring crops with SI, through a water allocation procedure for the surrounding rain-fed areas based on suitability criteria. The criteria take into consideration the distance from the water source, the soil type, and the land slope. The methodology is based on mapping existing water resources within the rain-fed areas and the summer irrigated areas using remotely sensed data. As the amount of water used per hectare in full summer irrigation is four or five times the amount used in winter SI, the potential areas for SI are expanded around the summer cropped areas proportionally to this ratio. The land suitability and economics are also considered. Potential areas can be mapped and water needs determined. Details may be found elsewhere (see De Pauw et al. 2008). Figure 21 shows an example of one output.

In the Karkheh River Basin (Iran), with its semi-arid to arid climate, SI is strongly recommended in the upper part of the basin to increase crops yields and WP. However, development activities upstream will certainly affect the water quality and quantity flowing downstream. The potential hydro situation of the basin with SI is evaluated by assuming various scenarios at

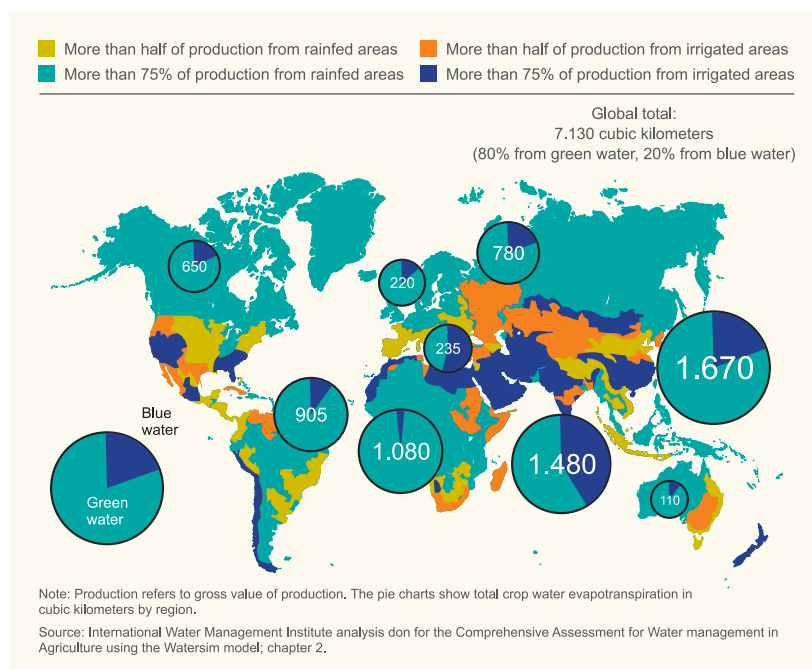


Figure 21. Areas depending mainly on rainfed (green water) for agricultural production and global rainfed areas times productivity.

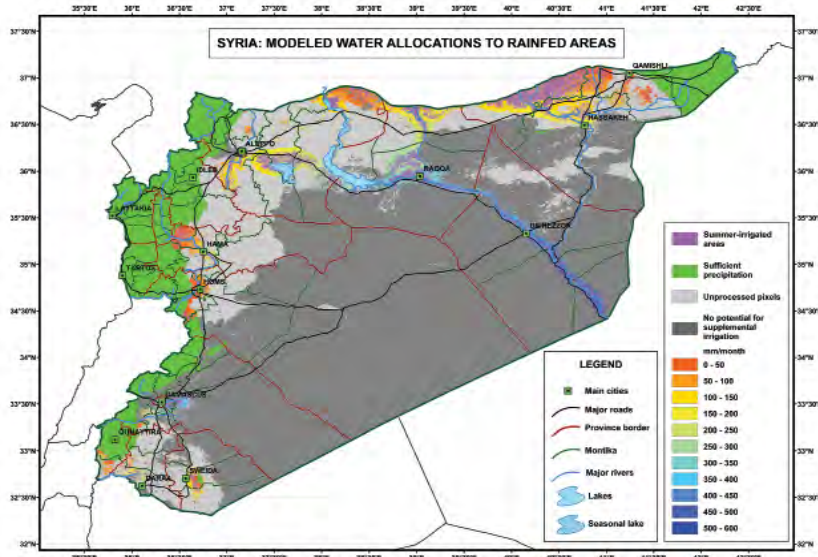


Figure 22. Potential areas for SI in Syria by allocating water from a fully irrigated summer crop (cotton) to a rain-fed winter crop (wheat). (De Pauw et al. 2008).

the upstream sub-basins. Current runoff in the upstream Karkheh River Basin is assessed using a surface water balance in a GIS framework. A map of potential areas for SI at the upstream sub-basins was prepared using the intersecting layers method within the GIS framework to investigate upstream-downstream interactions. The results indicate that if all potentially suitable areas (about 0.2 million ha) for SI are developed, water allocation to SI in normal seasons could decrease downstream flow by not more than 15% (Hessari et al. 2011).

In the event of water scarcity, some shift (reallocation) may be made from the normally less efficient full irrigation in summer to the highly efficient winter SI. The water savings may be calculated as the difference in total crop water need that could be achieved by shifting from a standard irrigated crop, planted in spring and grown during the summer and early

autumn months (cotton), to a standard crop, planted in autumn and grown using precipitation supplemented by irrigation during the late autumn, winter, and spring months (wheat). For example in a district in Syria with a mean long-term annual rainfall of 360 mm, the crop water requirement for cotton turns out to be 1056 mm (full irrigation), while that for wheat it is only 154 mm (as SI above the rainfall amounts). This simply means that in this locality, one can potentially grow 7 ha of wheat (under SI) using the same amount of water as needed for growing 1 ha of cotton (under full irrigation). Although, the last statement looks simple, a lot of technical and economic efforts and inputs are needed to justify its feasibility. It appears that in Syria, a large potential for SI exists by shifting from a fully irrigated summer crop to a partially irrigated winter-spring crop. Roughly this potential amounts to the area currently under SI (Figure 22) being doubled.

Potential water sources for developing SI may be identified by taking advantage of the available local experience in water harvesting. In Tunisia for example, small hill reservoirs are used to collect runoff water for SI purpose. Hill reservoirs or lakes have been constructed to collect surface runoff from catchment areas and store it in small surface reservoirs to give farmers in remote areas access to water. With watersheds of a few hundred hectares, excess, uncommitted rainwater runoff during the rainy season is diverted to storage ponds and apportioned for irrigation purposes. The average reservoir's capacity varies typically between 10,000 to 200,000 m³ and the runoff catchment's area from 40 to 700 ha (Ben Mechlia et al. 2006).

Unlike large reservoirs, hill lakes are not permanent sources of water and their management is very site specific. Farmers assure themselves of all their water needs and decide on the area that should be put under SI during the winter. By the end of the winter season, i.e., in March, the state of the reservoir is of particular interest if late spring or summer irrigation is planned for vegetable crops. During a wet year, the total amount of water used may be, on average, equivalent to 80% of the reservoirs' capacities. The rainfall amount, watershed area, and mean slope determine the amount of runoff water that can be stored in a hill reservoir. However, the determinants of the size of the reservoir and its location depend on technical, socioeconomic, and environmental factors and constraints.

MAXIMIZING PRODUCTIVITY WITH INTEGRATION

Considering the current situation and the potential of SI technology, it has been agreed that the most effective approach for introducing new technology and/or improving existing practice is through integrated and participatory research and development programs. Any development and/or applied research program overlooking or underestimating the role of the farmer is doomed to failure. One condition for the success of SI techniques is their acceptance by male and female farmers. A typical water basin may be chosen based on agreed criteria between all the involved stakeholders. An integrated research and development program will be designed and implemented involving local communities, institutions, and decision makers, taking into consideration the following issues (Box 2).

- a. The introduction of SI techniques should, as far as possible, build on existing water conservation measures.
- b. The benefits of the project should be apparent to farmers as early as possible. Motivation and promotion of awareness among the people with regard to the project objectives and the ways to achieve them are essential. Implementation typically requires the commitment and

cooperation of neighboring farmers (or the community) in the coordination and management of their limited water resource. Today, local communities seldom initiate group action and depend considerably on assistance from external agents, such as non-governmental organizations. The lack of developed local institutions is a critical constraint on exploiting the potential of improved water management technologies such as SI.

- c. Understanding the specific needs of a local community or a group of beneficiaries is critical in designing and implementing an appropriate
- d. To prevent greater inequality at the village level as a result of introducing SI, special care should be taken to make sure that both poor male and female farmers have equal access to the technique. Generally, it is important to know more about the

system. Farmers' acceptance of a new technology depends on their attitudes to production risk and their perceptions of the risk. It is often important to know whether differences in adoption behavior among farmers are caused by differences in their perception of the risks or by differences in the constraints they face in accessing credit and other inputs. Risk-averse farmers can be expected to accept a new technology if they perceive that the increased risk is compensated for by the increased returns.

Box 1 Investment opportunities in SI

Among the recommended investment opportunities are:

1. Reform policies and regulations to govern groundwater development and operation
2. Strengthen/create water users organizations to manage water at the scheme-level
3. Develop systems for monitoring groundwater quality and preventing overexploitation
4. Finance water resources development for supplemental irrigation through the source, conveyance system, and field irrigation systems
5. Develop low cost low energy precision irrigation systems, such as drip or sprinkler, including a pumping set
6. Build the capacity of extension workers and farmers to install, operate, and maintain their systems
7. Support the development of simple and practical tools for SI scheduling which is a key for improving water use efficiency.

- reasons for adoption or refusal of SI techniques by local communities.
- e. Dry area ecosystems are generally fragile and have a limited capacity to adjust to change. If the use of natural resources, especially land and water, is suddenly changed, for example, by the introduction of SI systems, the environmental consequences are often far greater than foreseen.
 - f. Quite often, the necessary conditions for the adoption of the new technologies are location-specific as they are influenced by cultural differences, level of education, and awareness of the need for change among the beneficiaries. It has been found that land and water resource users are usually aware of land degradation, but they may not have a choice when it is a question of survival. They are unlikely to adopt new practices quickly unless they are convinced that it is financially advantageous and that the new practices do not conflict with other activities they consider important, or demand too much of their time for maintenance.
 - g. Institutional capacity building, water resource management policies, and management and maintenance programs are the keys to success. The institutions could be at village, regional or national levels, depending on the size of the SI projects and the degree of decentralization in the country concerned. Multiple plantings to increase rainfall utilization should become a standard practice under SI; therefore, knowledge of the water-stress-sensitive growth stages in relation to the timing of water application is critical.

Box 2 Lessons learned in SI practice

Alleviation of the following constraints will help SI achieving its potential:

1. The best irrigation water delivery system that suits SI is the on-demand one, which is the case with small-scale farms using wells or nearby surface water sources
2. Supplemental irrigation must be properly integrated with other production inputs including crop and soil management options, improved germplasm, and others that are necessary to achieve the desired output
3. Poor farmers in rain-fed dry areas often cannot afford the costs given their limited resources. Carefully planned socioeconomic interventions through proper policies should be derived and implemented
4. Farmers need to understand the technology and how to operate/manage it properly. Extension and human capacity building should play major roles in this respect. Long-term training and advisory programs should be carefully designed and implemented
5. Natural resources, particularly land and water, are more efficiently utilized on a collective basis than individually. A water users association is a good example of an efficient approach to the collective use and management of water. Institutional constraints hindering the establishment and transparency of these associations must be seriously looked at.

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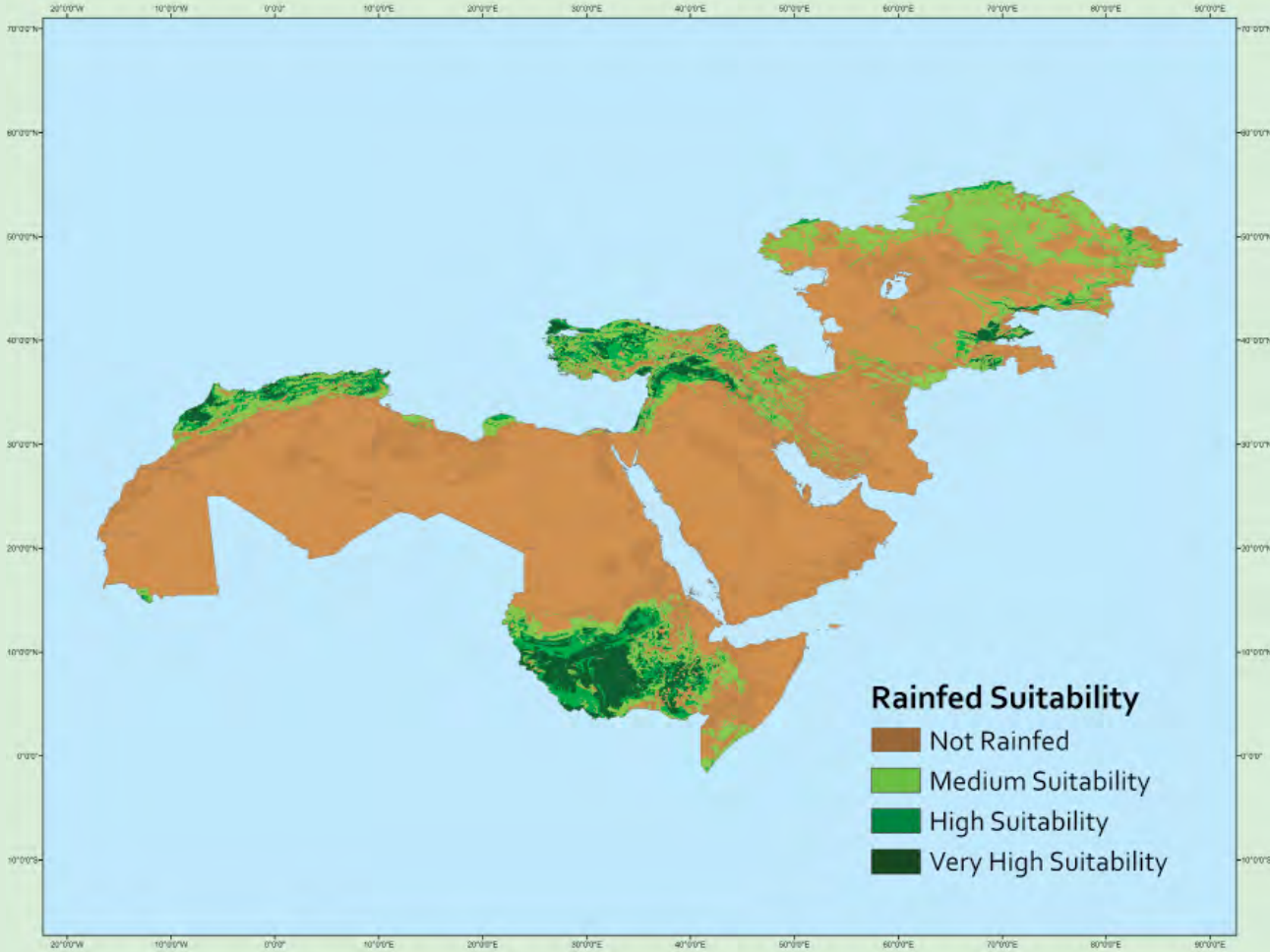
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Rainfed areas in CWANA where supplemental irrigation can be applied



Map by IWLMP, ICARDA.

