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Cropping systems and crop complementarity in dryland agriculture to increase soil water use efficiency: a review

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Abstract

Dryland agriculture under rainfed conditions is found mainly in Africa, the Middle East, Asia, and Latin America. In the harsh environments of Sub-Saharan Africa (SSA) and West Asia and North Africa (WANA), water is the principal factor limiting crop yield. A review has been carried out on soil and crop management research that can increase the water use efficiency.

The WANA production systems are dominated by cereals, primarily wheat in the wetter and barley in the drier areas, in rotation with mainly food legumes such as chickpea, lentil and forage legumes. The SSA production systems are generally characterized by cereal/legume mixed-cropping dominated by maize, millet, sorghum, and wheat. The major constraints in both regions to crop production are low soil fertility, insecure rainfall, low-productive genotypes, low adoption of improved soil and crop management practices, and lack of appropriate institutional support.

Different cropping systems and accompanying technologies are discussed as well as selected examples of impact of these technologies. Results indicate that there is an advantage to apply these technologies but being function of socio-economic and bio-physical conditions. It is recommended that future research focuses on integrated technology development while taking into account also different levels of scale such as field, village, and watershed.

Keywords: water use efficiency, impact, rainfed, technologies, West Asia, Africa

Introduction

Recent agricultural research has resulted in innovations which enable farmers to increase their yields. Mechanization of farm operations, proper and timely tillage and sowing, planting geometry, new crop varieties, use of fertilizers, pesticides, and herbicides in suitable crop rotations all contribute to the increase and stabilization of agricultural production. However, across wide tracts of Sub-Saharan Africa (SSA) and West Asia and North Africa (WANA), water scarcity is a major factor limiting agricultural production for millions of resource-poor dryland farmers. The small total amount of rain combined with its erratic and unreliable occurrence constrain the achievement of stable, sustainable production systems providing satisfactory, low-risk livelihoods. The occurrence of periods of water deficit for crop production, referred to as 'climatic drought', is commonly observed and leads to low water availability for crops. Besides climatic drought, crop water stress may also result from low levels of plant available water in the soil profile due either to the existence of physical barriers to water infiltration (e.g., surface sealing) or to soil chemical or physical limitations to plant root growth and root water uptake. Drought resulting from such factors will be referred to as 'edaphic drought' since it is caused by soil-specific conditions rather than by limited rainwater supply, and can occur even under conditions of sufficient and well-distributed rainfall. Finally, even where water is very scarce, particularly in the driest areas, a surprisingly small proportion of the available water is actually transpired by the crop. Non-productive losses include surface runoff, deep drainage, evaporation from the soil surface and deep cracks, and transpiration by weeds.

Within this context, innovations in soil and crop management are sought by agricultural scientists to make maximum use of the water available for crop growth. In general, in addition to soil fertility management, two main agronomic strategies have been identified to increase water use efficiency: soil and water management, and cropping system management. Figure 1 illustrates for representative countries of SSA and WANA the considerable variations in rainfall both within and between countries as well as the unequal distribution of rainfall throughout the year. This rainfall variability, combined with large variations in other climatic factors as well as large differences in soil types, makes it hard for scientists to develop general "blue print" solutions, but rather necessitates the development of site-specific technologies to help the resource-poor farmers of WANA and SSA.

This paper reviews the present status of research on cropping systems and crop complementarity in dryland agriculture in the light of increasing water-use efficiency (WUE). An example of a decision tree on how to optimize soil water use, and examples of impact of relevant techniques are presented. The paper focuses on representative countries of the WANA and SSA regions (i.e. Burkina Faso, Egypt, Iran, Jordan, Kenya, Mali, Morocco, Niger, South Africa, Syria, Turkey, and Zimbabwe) that are members of the Optimizing Soil Water Use (OSWU) Consortium. It is beyond the scope of the review to present all details, and if needed, the reader is requested to refer to Van Duivenbooden *et al.* (1999: e.g., chapters on each country) or the original articles.

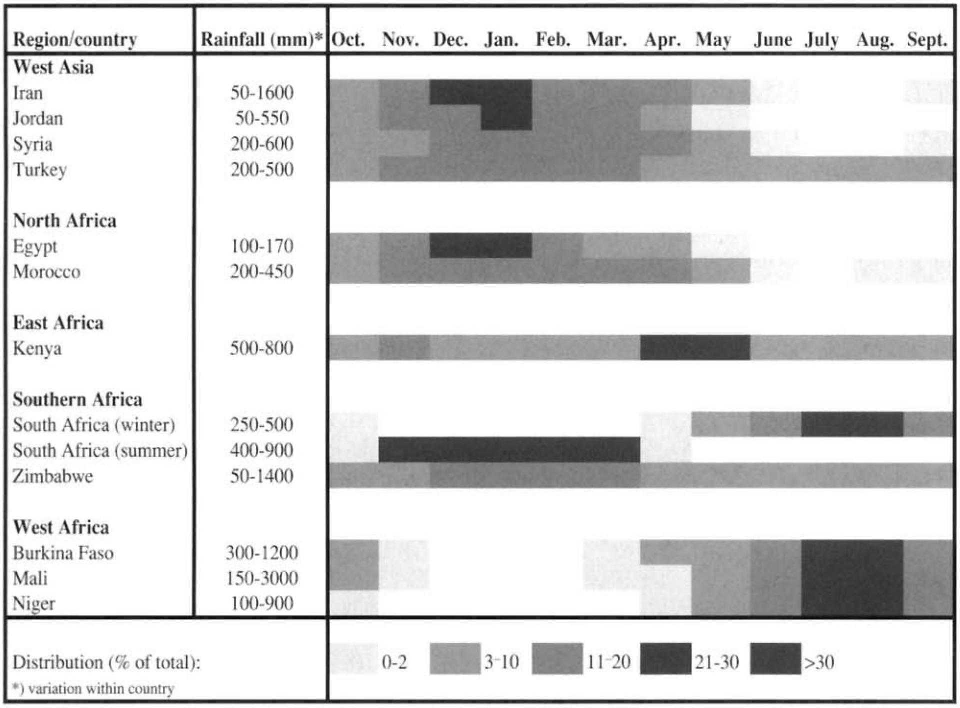

Figure 1. Long-term average rainfall and its monthly distribution in the course of the year in the crop production areas of the 12 member countries of the Optimizing Soil Water Use Consortium representing West Asia, North Africa (WANA) and Sub-Saharan Africa (SSA).

Definition of Water-Use Efficiency (WUE)

In it most general sense, WUE refers to the ratio of the amount of water used to achieve a given output. Both the 'type' of water whose use is being optimized – rainfall, (evapo-)transpired water, irrigation water, etc. – and the type of output vary according to the process that is being optimized and the objectives of the optimization process. WUE may therefore refer to crop yield per unit rainfall, total biomass per unit irrigation water, or mass of hydrocarbons stored per unit water transpired, to cite but a few definitions. In addition, WUE can be defined at different spatial and temporal (daily, weekly, seasonal, yearly) scales. Regarding spatial scales, it can be defined, for instance at: *(i)* the watershed scale, as the ratio of the amount of biomass produced to the amount of water flowing into this watershed (precipitation) minus the amount of water flowing out [kg biomass per m^3 water or kg per mm]; *(ii)* the farm scale, as the ratio of the economic value of the produce to the amount of water consumed by the crop (US$ per m^3 water); *(iii)* the field scale, as the ratio of the amount of biomass produced (total dry matter, grain yield, tuber yield, etc.) to the amount of water evapotranspired (i.e., transpiration by crop and evaporation from soil) [kg biomass per mm water evapotranspired]; *(iv)* the individual plant scale, as the ratio of the amount of biomass produced to the amount of water transpired by the plant (kg biomass per mm water transpired).

As a consequence, WUE should be replaced with more specific definitions such as precipitation-use efficiency (PUE), irrigation water-use efficiency (IWUE), transpiration efficiency (TE), etc., and the calculation procedures should be clearly explained. This is particularly important if WUE is not considered as yield over evapotranspiration.

In this paper, the meaning of WUE may vary from source to source according to the prevailing norms and procedures used in different countries and the origin of the data.

Dryland agriculture and its traditional crop production systems

In both WANA and SSA, the crop production systems are integrated closely with livestock production (e.g., stubble grazing, manure supply). Their main characteristics are listed in Table 1, showing the wide range of soil physical and chemical constraints for which solutions are required. Depending on the agro-ecological zone, crops are grown either as a mono-culture or as an intercrop with a legume at low planting density. Intercropping enables spreading of risks over two contrasting crops and of labour peaks, and allows exploitation of the long rainy season during good years. Planting densities depend on the expected rainfall and the soil type. Because of crop establishment problems – mainly due to prolonged dry spells – repeated sowing is common. Generally, weeding is done by hand, and external inputs such as fertilizers or pesticides are insufficiently applied or not at all.

For both regions, the importance of legumes for nutritious food and feed, their contribution to subsequent cereal productivity through biologically fixed N, for breaking disease and pest cycles, and conserving farming resources and promoting sustainable agriculture has been documented (Osman *et al.*, 1990; Bationo *et al.*, 1991; Harris *et al.*, 1991; Wiltshire & du Preez, 1993; Muehlbauer & Keiser, 1994). Soil degradation, in the form of soil erosion and loss of soil organic matter and essential nutrients, is an increasing problem in both regions. Legume cultivation to increase soil organic matter, to fix nitrogen and spare soil mineral N, to eliminate cereal diseases, and to provide more flexible weed-control options offers a means of alleviating soil degradation in the face of inevitable crop intensification in dry areas. The integration of legumes in the cropping systems can also reduce soil erosion substantially (Zougmoré *et al.*, 1998).

Strategies to optimize water-use efficiency

The basic principle of efficient water-use for plant production lies in optimizing each of the components of the soil water balance. There are two distinct management periods. The first is the period of rain storage lasting from harvesting of the previous crop till sowing of the next. Under semi-arid climatic conditions, the soil and water

Table 1. Selected main characteristics of traditional production systems in dry areas of WANA and SSA.

	West Asia	North Africa	West Africa	East Africa	Southern Africa
Cereal-based production system	<350 mm: barley in rotation with fallow, barley or forage legumes >350 mm; wheat in rotation with either fallow or barley, faba bean, chickpea, or lentil (winter or spring-sown), or melon, sunflower, or sesame (spring)	Same as West Asia	Driest part: millet, cowpea Wetter part: sorghum, groundnut, maize Transition: mix of above crops	Driest part: millet Wetter part: maize, sorghum, groundnut Transition: mix of above crops	SR: maize, wheat, sunflower, sorghum WR: wheat, barley
Livestock	Sheep and goats	Sheep and goats	Sheep, goats and cattle	Sheep, goats and cattle	Sheep, goats and cattle
Planting densities	15,000–50,000$^{(2)}$ (chickpea) 40–180$^{(3)}$ barley	Same as West Asia	5,000–10,000$^{(1)}$	70,000$^{(2)}$ favourable conditions < 20,000$^{(2)}$ unfavourable conditions	10,000–32,000$^{(2)}$ (maize) 30,000–40,000$^{(2)}$ (sunflower) 50,000–80,000$^{(2)}$ (sorghum) SR: 15–40$^{(3)}$ (wheat) WR: 100–130$^{(3)}$ (wheat)
Soil type	Xerosols, lithosols, cambisols	Xerosols, lithosols, cambisols	Arenosols, luvisols, regosols	Luvisols, acrisols, vertisols	Arenosols, acrisols, cambisols, ferralsols, luvisols, solonetz, vertisols, xerosols
Soil fertility	Low OM, low N and P, high $CaCO_3$	Low OM, low N, high $CaCO_3$	Low OM, N and P	Low OM, N and P	Low OM, N, P, K (locally)
Soil miscellaneous	Variable texture, depth, slope, and stoniness	variable texture, depth, slope, and stoniness	variable depth, and slope; texture: >65% sand and <18% clay	Shallow with petroplinthite horizons	Variable texture, depth and stoniness
Additional problems	High pH, water and wind erosion	High pH, water and wind erosion	Low pH (locally), soil compaction Driest part: water and wind erosion Wetter part: water erosion	Low pH, surface sealing, wind and water erosion	Low pH, soil compaction, crusting, wind and water erosion

OM = Organic Matter; N = Nitrogen; P = Phosphorus; K = Potassium; SR: Summer Rain; WR: Winter Rain.
Planting densities: $^{(1)}$: hills ha^{-1}; $^{(2)}$: plants ha^{-1}; $^{(3)}$: kg ha^{-1}

management strategies during this period should aim at maximizing soil water storage, i.e., at maximizing the gains and minimizing the losses in equation 1. The soil water balance during the period of rain storage can be written as follows:

$$\Delta S = P + I \pm D \pm R - E - T \qquad (1)$$

where, ΔS = change in the water content in the potential root zone; P = precipitation; I = irrigation; D = downward drainage out of the root zone (–) or upward capillary flow into the root zone (+); R = runoff (–) or runon (+); E = evaporation from the soil surface; and T = transpiration.

The growing season is the second management period, lasting from sowing till harvesting of the crop. The soil water balance can then be rearranged in the following form:

$$T = P + I \pm \Delta S \pm D \pm R - E \qquad (2)$$

To allow for the maximum amount of water to be available for transpiration (T), and thereby leading to maximum plant production, the parameters on the right hand side of equation 2 should be optimized.

Soil and water management

Efficient capture of rainwater by the soil requires that the infiltration rate equals the rainfall intensity for the entire duration of a storm. Otherwise, the excess water ponds on the soil, runs off, and is lost to the soil-crop water economy at that place. The severity of runoff is a function of rainfall quantity and intensity, land slope, soil and surface characteristics, and plant cover. Of these, only the last two are potentially subject to control on a routine basis, although land slopes can be modified by building terraces. Previous research has mainly concentrated on soil physical characteristics and how to ameliorate the limitations they impose on infiltration, either directly by surface sealing (or crusting) or indirectly by slow subsurface percolation. Surface crusting and restricted infiltration are also widespread problems in dry areas and may limit tillage opportunities. Technologies affecting soil physical characteristics in order to increase water availability comprise mainly tillage and anti-erosion measures.

Tillage

Tillage operations (with their form, depth, frequency, and timing) and the management of crop residues are important in water conservation, particularly in dry areas. In rainfed agriculture in semi-arid regions, conventional tillage has mainly four purposes: *(i)* to prepare a seedbed, *(ii)* to promote infiltration, *(iii)* to conserve water within the soil profile, and *(iv)* to prevent wind and water erosion. Where the land has been untilled since the previous harvest, in all but the lightest soils it is necessary to wait until the early rains have cumulatively wetted the soil sufficiently to permit the entry of an implement. A particularly vicious circle can arise where the crusted surface of 'hardsetting' soil resists infiltration and promotes the runoff of much of the heavy early-season rainfall. Research-derived recommendations to cultivate after harvest or before the next rains to assist infiltration are often inapplicable: one problem is the indigenous practice of *in situ* grazing of residues, another that the power available for tillage is inadequate to overcome the natural strength of the dry soil. For the driest environments, it may be advantageous to rethink the cropping pattern and its relation to the tillage requirements for water infiltration and weed control. Currently, most staple cereals continue extracting soil water beyond the end of the rainy season, so that after harvest many soils are unworkable until the next season. One solution is to give priority to the basic needs of the tillage operation (rather than those of a particular crop) and to increase the flexibility of the cropping system by introducing new varieties and species of shorter growth cycle (Jones, 1987). The underlying logic in all cases should be soil management to optimize the provision of water to crops most able to utilize it productively.

Increasing the surface area of soil exposed to radiation and wind by deep plowing increases the loss of water through evaporation. Maintenance of the soil structure is the basic requirement for any package aimed at recuperating and maintaining the productivity of soil. Conventional or clean tillage has a long traditional and historical basis in rainfed cropping areas of the world. However, conservation tillage, which requires that stubble residues remain on or near the soil surface, is becoming more widely used. The no-tillage system is a powerful point of entry to solve the problems of soil erosion, soil fertility, and soils with low water-holding capacity (Lal, 1976). Crop yields from no-tillage agriculture are usually as high as or higher than yields produced by conventional tillage (Campbell *et al.*, 1984). However, no-till systems create other challenges that need to be coped with, such as weed and pest infestations.

Tillage research in semi-arid Southern Africa has been related to compaction and water conservation. Controlled traffic and deep tillage resulted in higher maize yields and dry-matter production, improved WUE, and improved rooting (Bennie *et al.*, 1982). However, under higher rainfall and on more clayey soils, Berry & Mallett (1988) obtained better, or the same yields, with no tillage compared with conventional tillage, indicating the need for site-specific recommendations.

In West Africa, soils are characterized by low surface porosity, poor structure, susceptibility to crust formation, and low water-holding capacities. Tillage incorporates organic matter, improves weed control and water conservation, and enhances root proliferation, thus increasing both fertilizer- and water-use efficiency. Tillage, combined with other inputs such as fertilizer and improved cultivars, showed synergistic effects, which varied per year and cropping system. Nicou & Charreau (1985) reported an average yield increase of 22% with tillage from 38 experiments. In a millet-cowpea rotation, ridging and P fertilizer input increased biomass production by 10% for millet grain, 21% for millet straw, and 27% for cowpea fodder, but reduced cowpea grain yields by 8% (Klaij *et al.*, 1994). In another experiment, tillage resulted in a 76–167% millet yield increase (Klaij & Hoogmoed, 1993).

Except on sandy soils, ridging is traditionally practised in Nigeria, Mali, Senegal, and Niger, and hilling or mounding in the Seno plain in Mali. Ridging reduces bulk density, concentrates fertility and organic matter, stimulates seedling growth and establishment, and may help reduce wind erosion (Klaij & Hoogmoed, 1993). Where infiltration rates are low, tied ridging leads to higher infiltration by reducing runoff.

Large-scale adoption of primary and secondary tillage methods may only be realized through the acceptance of mechanization. In Southern Africa, the rapid mechanization of the commercial sector from the 1930s onward has meant that almost no research on tillage using animal draught has been carried out (Morse, 1996). Still, the use of animal traction seems a practical means to increase farmers' efficiency to produce food in many production systems in SSA, e.g., in Southern Africa, animal traction being particularly used to cultivate steep slopes. However, farmers' application of animal traction is often limited by the availability of the traction source, fodder availability, and equipment.

Within the WANA region, conventional tillage is a regular practice, i.e. plowing with a disc or moldboard to a depth of 20–30 cm each year, and preparing the seedbed with either a harrow or tine implement (Cooper *et al.*, 1987). Deep tillage with moldboard in the spring of a fallow year is recommended for control of grass weeds in cereal crops. This has an additional advantage of increasing surface roughness which enhances infiltration of rainfall late in the fallow season. When followed by a shallow secondary tillage at the end of the rains, the practice leads to greater storage of soil water and increased wheat yield through soil mulch serving as an isolation layer at 8–10 cm of the soil surface (Durutan *et al.*, 1991). However, in continuous cropping systems, this secondary tillage can not be applied because the soil is too dry. Thus, tillage operations under continuous cropping aim mainly at seedbed preparation and depend on the implements available to cultivate the dry and hard soil. Many farmers have to delay their planting until the first rains softened the soil allowing land preparation (Pala, 1991).

In the long term, tillage can be expected to cause breakdown of the surface structure and increased crusting. In soils where the surface structure is inherently weak, cultivation rapidly leads to surface degradation, reduced infiltration, and failure of crops to emerge through the solid crusts which form, particularly toward the drier margins of the cropped area in WANA (Cooper *et al.*, 1987). If these same soils are cultivated when they are dry, the lack of structure renders them very susceptible to wind erosion, but its severity is not quantified.

Although systems utilizing zero-tillage, reduced-tillage, and/or crop residue retention treatments have been credited with reducing evaporation, as well as improving infiltration and reducing erosion in the USA (e.g. Papendick *et al.*, 1991), these results have proved hard to reproduce in northern Syria (Jones, 1997). Over six years of continuous barley and vetch-barley rotations, any effect of zero tillage, with retention of stubble and straw, on the dry-season soil water economy was negligible. The small improvements in crop performance occasionally observed may reflect a marginal reduction in evaporation in young plant stands drilled directly into the standing stubble. Pala *et al.* (2000) reported that the general trends in soil water change were the same for all tillage practices (deep moldboard, deep chisel, shallow cultivator and zero-tillage), but that zero- and minimum-tillage treatments left more water at harvest for the following crop compared with deep-tillage practices. Furthermore, zero- and minimum-tillage is more energy-efficient with no reductions in yield observed.

Erosion control measures
In SSA, common water erosion control measures comprise stone bunds, stone lines, micro-catchments (locally called e.g. Zai and Teras), and rows of (leguminous) trees or perennial grasses (Roose, 1989; Manu *et al.*, 1994; Van Dijk, 1997; Ouattara *et al.*, 1999). Small-scale amendments, using hand labor or simple mechanization, are often proposed for such measures. Ways to manage the soil surface to collect and/or harvest water or to counter the effects of high-intensity rainfall on crust-prone surfaces and so prevent runoff include crust-breaking techniques (mainly employed soon after sowing to assist crop emergence) and, more widely, various systems of ridging. These are on or slightly off the contour, often with transverse 'ties' at intervals across the furrows that restrict flow and create a pattern of infiltration basins (Dagg & Macartney, 1968; Stroosnijder & Hoogmoed, 1984; Van Der Ploeg & Reddy, 1988).

Cropping systems also play a role in reducing soil erosion. For example, in Burkina Faso, a mixed crop of sorghum and cowpea reduced runoff by 20–30% compared to sorghum alone, and by 5–10% compared to cowpea alone, resulting in a reduction in soil erosion of 80 and 45–55%, respectively (Zougmoré *et al.*, 1998). In South Africa, Haylett (1960) found soil loss to be 44 times higher under continuous maize cropping compared with natural vegetation.

In addition, the strips between fields have positive effects on soil and water conservation, reduce soil erosion, and may contribute to the farmers' income (e.g. through selling of woven products, fodder for animals, traditional medicine, etc.). Examples are strips of Vetiver grass (*Vetiveria zizanioides* and *V. nigritana*) found in Burkina Faso, Kenya, Mali, Nigeria, Tanzania, Tunisia, and Zimbabwe (Vietmeyer & Ruskin, 1993), or *Andropogon spp.* or *Panicum maximum*. Hedgerows of shrubs or small trees are also being planted as observed in Kenya (Kiepe, 1995) and Senegal (Perez *et al.*, 1998). Similar systems are currently being tested in WANA, for instance in Egypt (Anonymous, 1999a), Morocco (Boutfirass *et al.*, 1999) and Syria (Somi & Abdul Aal, 1999). Larger-scale alternatives include contour strips (Carter *et al.*, 1988) and various bunding and terracing systems as part of an integrated soil and land management approach. Terracing may possibly be more appropriate in the wetter environments where soil and water conservation efforts focus more on prevention of massive soil erosion, as e.g. in the hilly areas of northern Syria, where olive plantations have substantially expanded recently (Anonymous, 1999b).

Evaporative losses from crops, weeds, and soil surface are partly a function of wind speed and, in dry conditions, appreciable savings of water may be achieved by reducing the wind flow through a crop. In Niger, windbreaks of neem trees increased millet yields by approximately 20% (Long & Persaud, 1988), while in Nigeria, *Eucalyptus* trees increased yields by 50% (Onyewotu *et al.*, 1998). In addition, windbreaks may have another beneficial effect through control of wind erosion. Nevertheless, windbreaks are rarely part of indigenous systems. If small farmers are to adopt them, they must be seen to have intrinsic economic value additional to any conservation role, as is the case for fodder shrubs and trees (*Acacia* and *Atriplex spp*) in WANA (Jones & Harris, 1993; Lamers *et al.*, 1994; Anonymous, 1999a).

Cropping system management

During the last decades, attention has been paid to the design of more productive and stable systems through improved cropping system management. This comprises various aspects, such as the use of appropriate crop varieties, improved cropping patterns, relay-cropping, and cultural techniques. The suggested technology packages vary with agro-ecological conditions and farmers' objectives.

Crop varieties

The identification of appropriate crops and cultivars with optimum physiology, morphology, and phenology to suit local environmental conditions, especially the pattern of water availability, is one of the important research areas within cropping systems management for improved WUE.

Short-duration varieties for SSA that mitigate the effects of drought periods (often occurring at the beginning and end of the growing season) are urgently needed and being developed. Such cultivars (preferably also with higher harvest indices) are considered a key component of management strategies in the drought-prone areas. However, many of the currently available cultivars are susceptible to insect pests and bird damage (i.e. picking of grains because other feed can not be found yet), and are more demanding in terms of soil and management conditions. In the WANA region, the varieties should be tolerant to cold, drought, and heat; resistant to diseases and insects; have vigorous early growth; and are of good quality and high-yielding. Early and complete canopy establishment to shade the soil and reduce evaporative loss from the soil surface can significantly improve the WUE of winter-rainfall crops in this region and also, apparently, of summer-rainfall crops over much of the semi-arid tropics (Gregory, 1991). For instance, Cham 1, an improved durum wheat variety, provided 3 to 86% grain-yield increase compared to Hourani, a local durum cultivar, under different water and nitrogen regimes in three distinct seasons (Pala *et al.*, 1996a). These results also show that improved cultivars may not render increased yields unless cultural practices are applied in an appropriate and timely manner.

Intercropping

Greater efficiency of resource utilization is expected from intercropping and mixed-cropping in a wide range of environments (Willey, 1979; Francis, 1989). However, these generalizations do not necessarily hold true in the more extreme environments. If rainfall is infrequent, evaporative losses from the usually dry soil surface may be relatively unimportant; and if water rather than radiation is limiting, intercrops grown under a cereal canopy (supposed to utilize low-intensity radiation that would otherwise be 'wasted') may in fact compete heavily with the cereal for the limited water available. This has been demonstrated in Botswana, where intercropped cow-pea had the same effect as weeds; in dry years, even at very low plant density cowpea was able to devastate the adjacent rows of sorghum (Rees, 1986a). In wet years, small grain-yield advantages from intercropping could be recorded, but over a run of years, intercropping greatly increased yield variation and the risk of total crop failure (Jones, 1987). Such results, however, although under different bio-physical conditions, contrast strongly with results from West Africa. Subsistence farmers practice forms of intercropping (e.g. millet with cowpea, sorghum, maize, or groundnut) that exhibit high complementarity between component crops and reduce the risk of crop failure (Swinton & Dueson, 1988) and these traditional production systems have a total yield advantage and are more stable than sole cropping (Fussell & Serafini, 1987; Shetty *et al.*, 1987). An additional benefit was the reduced *Striga* infestation in millet/groundnut systems (N'tare *et al.*, 1989). Replacement of cowpea by *Stylosanthes hamata* resulted in a higher WUE (Garba & Renard, 1991).

Relay cropping

Relay cropping, the practice of growing a short-duration, fast-growing secondary crop, usually a legume, after the principal cereal crop, is a well-known strategy. In the southern Sahel, favourable rainfall years do occur and these must be fully exploited, ensuring use of any stored soil water. The need for such a strategy is greatest on sandy soils with low water-holding capacities and subject to high rates of evaporative loss. It is, however, difficult to predict whether or not the coming rainy season is likely to be favourable. Hence, recent efforts have been made to predict the essential characteristics of the approaching rainy season and tailor crop management decisions to them (e.g., Sivakumar, 1988, 1993). Although the economic feasibility of relay-cropping systems, is still to be determined in the Sahel, in semi-arid Zimbabwe, relay cropping of maize and sunflower proved profitable (Nyakatawa & Nyati, 1998).

Cultural techniques

Timely cultural techniques, such as sowing with the first substantial rains, early weeding and thinning are important for increased use of soil water, and consequently, good yields. They also have synergistic effects with improved soil management practices, improved cultivars, and higher crop density (Fussell *et al.*, 1987). In the intercrop production system, adjusting cowpea sowing time to the millet's growth cycle and the probable length of the rainy season is a technique that might increase cowpea yields (N'tare *et al.*, 1989).

In WANA, any husbandry technique that facilitates rapid canopy development and enables the crop to cover the soil surface, to shade out weeds, and also to reduce wind speed through the crop may, in most circumstances, be expected to increase crop competitiveness and WUE (Cooper & Gregory, 1987). Practices that particularly contribute to this are: early sowing, selection of varieties with rapid early growth (under cool conditions), adequate fertilization, and adequate plant population and close spacing (Gregory, 1991).

Sowing date

Within the concept of improved WUE, water transpired by crops should be increased relative to evaporation from the soil surface. Since transpiration efficiency is a function of the atmospheric saturation deficit, i.e., relative dryness of the air, directing biomass production into periods of lowest atmospheric demand confers an advantage (Acevedo *et al.*, 1991; Gupta, 1995). This so-called "seasonal shifting" can improve the water-use efficiency of crops to a great extent, and allow for better use of limited (rain or irrigation)water and/or large water savings in crop production (Seckler, 1996). Timely sowing on the basis of a scientific method rather than a traditional method increased millet yields in Nigeria by 20–40% (Onyewotu *et al.*, 1998).

In WANA, despite temperature limitations to growth, it pays to sow early (late fall, early winter) so that as much as possible of the crop's growth cycle is completed within the cool, rainy winter/early spring period (Cooper & Gregory, 1987), while the earliness depends on the tillage/crop rotation system employed (Pala, 1991). Stapper & Harris (1989) simulated on the basis of field experiments that for northern Syria, each one-week delay in sowing after November 1st will reduce wheat yields by 4.2%. In the same region, Acevedo *et al.* (1991) observed a yield-decrease of 9 and 22 kg ha^{-1} day^{-1} in areas with 280 and 330 mm long-term average rainfall, respectively, if planting was delayed from late October to late January. Overall yield loss was about 50% in both areas. Mean rainfall-use efficiency of barley decreased from 12 kg ha^{-1} mm^{-1} at early planting to about 6 kg ha^{-1} mm^{-1} at late planting. Similar considerations lie behind the attempts to persuade farmers to move from spring to winter sowing of chickpea. Yield increases of 30–70% have been reported for winter-sown chickpea compared to spring-sown chickpea (Keatinge & Cooper, 1984; Pala & Mazid, 1992a), resulting in increased WUE by 78% (Brown *et al.*, 1989) and more than 100% (Keatinge & Cooper, 1983). Likewise, early sowing of lentil in mid November increased seed yield by 20-25% compared with late sowing in early January (Silim *et al.*, 1991; Pala & Mazid, 1992b).

Crop density improvement

Economic crop yields arise from plant densities that minimize inter- and intra-row competition, which widely depends on environmental conditions, while cereal grain yield is the product of heads per unit area, kernels per head, and kernel weight. The seeding density, plant distribution, and genotype in a given region have substantial effects on these components. Increasing the seeding density can increase the heads per unit area, but may reduce the other two components (Joseph *et al.*, 1985). Among yield components, there is compensation which tends to minimize yield loss when one component is reduced, but such compensation may not be complete. In the case of legumes, the optimum plant density depends upon environmental conditions and the genotype. A sowing density of 300–450 germinable lentil seed per m^2 generally resulted in the highest yield under Syrian conditions (Silim *et al.*, 1990). The effect of increased seeding density was more apparent at the earliest sowing date, which also resulted in a higher yield, decreasing when the sowing date was delayed. Tall and erect chickpea varieties respond better to increased plant population than the spreading types (Singh, 1981; Keatinge & Cooper, 1984). The yields of these genotypes at a density of 50 plants m^{-2} are increased significantly compared to 33 plants m^{-2} though the lower plant density appears to be optimum for a wide range of environments (Saxena, 1981). N'tare *et al.* (1989) concluded from their millet/cowpea intercrop experiments that millet yields were not greatly reduced by increasing cowpea densities when soil water and fertility were adequate. Bationo *et al.* (1990) observed that low plant density in farmers' fields is the primary reason for low crop response to applied fertilizer. Manu *et al.* (1994) demonstrated on-farm the yield-increasing effect of increased millet population under adequate nutrition. In addition, low plant densities can give rise to below-optimal crop WUE because the ratio of soil evaporation to crop transpiration may be increased. Wallace *et al.* (1988), working on sparse millet crops in Niger, estimated that about 36% of the seasonal rainfall of 562 mm could be lost as direct evaporation from the surface. Higher plant densities, therefore, increase WUE and yield (Gandah, 1988).

However, while the densest populations of sorghum in Botswana produced the most dry matter (per unit area and per mm of rain), they used up the available soil water sooner between the infrequent rainstorms. Thus, they became stressed earlier than did sparser crops, such that flowering was often delayed or failed completely (Rees, 1986b; Jones, 1987). Even where flowering occurred, intense competition in the denser populations kept individual plants very small, and with decreasing size the transfer of dry matter into the grain became rapidly less efficient. The greatest WUE of sorghum grain production was achieved by the sparser populations, which left much of the soil surface exposed to solar radiation. This finding is also applied by commercial farmers in the dry parts of South Africa growing their maize in rows 2–3 m apart. Van Averbeke & Marais (1992) found that the maize plant population for optimum yield decreased from 60 000 plants ha^{-1} with 650 mm water supply to 10 000 plants ha^{-1} when 240 mm water is available. Similarly, olive growers in the dry areas of WANA plant trees at very wide spacing, such that the canopy cover remains mostly below 25%. Frequent tillage between the trees controls weeds and also conserves soil water through a 'dry-mulch' effect.

Soil fertility management

Given the inherent low fertility of many dry-area soils, judicious use of farmyard manure and inorganic fertilizer is particularly important. Extensive work in Niger (e.g. Onken *et al.*, 1988; Payne *et al.*, 1991; Klaij & Vachaud, 1992), Mali (e.g., Penning De Vries & Djitèye, 1982), Syria (e.g., Cooper *et al.*, 1987; Pala *et al.*, 1996b; Ryan, 1997), Turkey (Kalayci *et al.*, 1991), and Tunisia (Mechergui *et al.*, 1991) has demonstrated the benefits of appropriate fertilization on WUE and therefore on production and yield stability of millet in SSA and of winter-sown crops, especially wheat and barley, in WANA. All farmers in semi-arid environments face limits to crop and animal productivity. Yet, the use of fertilizer, hired labour, and other inputs can still make a difference for farmers wealthy enough to secure such inputs. For example, it has been found in the marginal regions of Burkina Faso and Ethiopia that the average grain yield from the wealthier farmers can be twice that of the poorer farmers cultivating adjacent fields in the same communities (Webb & Reardon, 1992).

Weed control

Weeds compete with crops for water, nutrients, and light. In dry areas, however, the main objective of weed control is to increase the water supply available to the crop.

But factors such as early sowing (affecting transpiration efficiency) and mulching (reducing soil evaporation) affect both weed infestation as well as crop water availability and use (Amor, 1991). Also other management practices such as tillage, seed density, fertilizer application, and crop rotations are interrelated with both weed control and water-use efficiency (Cornish & Lymberg, 1986; Durutan *et al.*, 1991). To minimize the competition between weeds and crops for water, it is therefore important to adopt an integrated approach to the control of weeds. Rather than relying on only one method of weed control, several possible alternatives should be used in a systematic manner, thus increasing the chance of developing economic and sustainable farming systems which are also efficient in water use (Amor, 1991). The components of integrated weed control may include, for instance, preventing weed infestation by using clean seed (to prevent weed infestation), proper and timely cultivation, crop competition, early crop development, crop rotation, grazing, hand weeding, herbicide use, and biological control.

Crop rotations

There is increasing concern about the deterioration of integrated crop/livestock systems because of the high pressure put on these systems by the ever-rising demand for food and feed. Continuous cereal systems are increasing, parallel to the increasing demand for human and animal consumption. The decline in yield under continuous cereal cropping constitutes a major problem, but the causes of the poor productivity are not yet completely clear. Part can be explained by negative effects on physical and chemical soil properties (soil mining, organic matter content, aggregate stability, etc.), and the buildup of noxious weeds, pests, and pathogens, besides accumulation of allelophatic compounds (Pala *et al.*, 2000).

Including legumes in the rotation has proved to be beneficial for sustainable crop production in both regions. For instance, in southern Niger, millet-cowpea or millet-groundnut rotations doubled millet production over a four-year period (A. Bationo, 1999, personal communication) compared with continuous millet. Similarly, it was observed that millet-cowpea rotation had an effect equivalent to the addition of approximately 30 g N ha^{-1} yr^{-1} based on on-farm trials. Rotation trials in WANA demonstrated that wheat (Cham 1) yields were lowest (1000 kg ha^{-1}) under continuous cropping. Yield increases following various crops in a rotation compared with that of continuous wheat were for medic 39%, chickpea 46%, lentil 82%, vetch 84%, melon 119%, and fallow 126% (Harris, 1994).

Legumes grown in a crop sequence with cereals have a positive effect on the system's overall WUE. Because of their usually shorter growing period, some water may be left in the soil profile for the subsequent cereal crop, increasing the latter's productivity (Karaca *et al.*, 1991; Harris, 1995). Compared with the cereal-fallow system, cereal-legume rotations produce yields every year, thus increasing the system's overall WUE and its output in terms of quantity as well as nutritional quality (Pala *et al.*, 1997).

Example of recommendations

From the part above, it is evident that developing recommendations for optimizing soil water use is not an easy task. Nevertheless, we developed a simple decision tree for the choice of technological options that can be used to optimize the use of rainfall (and thus soil water). The choice depends on the degree to which the water requirements of the crops are met by rainfall (first column in Table 2), and on the relative risk of occurrence of climatic and edaphic drought (2^{nd}, 3^{rd} and 4^{th} columns). Edaphic drought risk can be based on the actual amount of rainfall infiltrating into the soil and on the relative amount of plant available water (PAW). PAW is calculated on the basis of the maximum amount of water that can be stored within the rooting zone of the soil profile and that is potentially extractable by crops. It therefore reflects both the water retention properties of the soil and the ability of the roots of a given crop to explore a given soil volume and extract water from it. Edaphic drought risk will therefore be high if PAW is low, if the runoff potential is high, or both. In essence, the table argues that if a high risk of climatic or edaphic drought exists, technologies should be implemented to deal with these problems first, to ensure that technologies aimed at optimizing soil water use will be profitable.

Examples of impact of research on optimizing soil water use techniques

In contrast to research on irrigated agriculture, to our knowledge no formal impact assessments of rainfed systems technologies have been carried out in OSWU member countries, except in Syria and Turkey. In addition to increases in yield and economic returns, and reduced labour (Table 3), non-quantified reports of impacts on the environment exist. For instance, mulching helps in reducing wind erosion and reduces soil surface sealing (e.g. Beukes *et al.*, 1999). In Syria, about 23% of the increase in durum wheat production is due to effects of irrigation, 34% to the use of improved varieties, 24% to fertilizer, and 19% to land and crop management (Table 3), with 37% of the impact coming from rainfed areas (Mazid *et al.*, 1998). In Turkey, improved varieties and efficient crop husbandry practices resulted in a three-fold wheat yield in the last 50 years, from 0.8 to 2.4 t ha^{-1} (Avci *et al.*, 1999). This increase is predominantly caused by timely soil management with proper implements (timely tillage, sowing, weeding, etc.), phosphorus application, and improved varieties (Avci *et al.*, 1987). The other impacts listed in Table 3 may be obtained in quite short periods of one to a few years. Finally, impact of this type of research is also obtained (but difficult to quantify) as improved knowledge of farmers on soil and water conservation principles and technologies through use of visual teaching aids (Chuma & Murwira 1999), and institutional capacity-building of the National Agricultural Research and Extension Services.

Table 2. Decision tree for priority actions and technical options for optimizing rainfall water use according to environmental conditions in Sub-Saharan Africa.

Rainfall crop water requirement satisfaction	Climatic drought risk	Edaphic drought risk		Required priority actions and technical options
		Plant available water (PAW)	Runoff potential	
Sufficient	Low	High	Low	1. Ensure optimal use of stored water through adequate soil and crop management practices (e.g. fertilization, tillage and residue management, cropping system, choice of crops)
			High	2. Improve soil surface characteristics such as roughness, barriers, crusts (e.g. tillage, residue management, crop management)
				3. Reduce the effect of low permeability layers in the soil (e.g. deep plowing, subsoiling)
		Low	Low	4. Correct soil chemical deficiencies preventing full root development (e.g. fertilization, micro-nutrients, liming, residue management)
				5. Correct soil physical factors limiting root development (e.g. tillage, subsoiling)
				6. Increase soil water holding capacity (theoretically feasible but not practical in most cases)
			High	• Correct low PAW and high runoff potential simultaneously: apply no 2, 3, 4, 5, and 6.
	High	High	Low	7. Use supplemental irrigation from tanks and reservoirs (e.g. water harvesting from areas with high runoff potential in the landscape).
			High	8. Take advantage of runoff to increase locally the amount of water infiltrating into the soil during rainy periods, thereby increasing soil water storage in the root zone for use during dry spells (e.g. water collection, Zai, demi-lunes)
		Low	Low	• Apply 4 or 5 in addition to 7
			High	• Apply 4 or 5 in addition to 8
Insufficient	High	High	Low	• Apply 7
			High	• Apply 7 or 8
		Low	Low	• Apply 4 or 5 in addition to 7
			High	• Apply 4 or 5 in addition to 7 or 8

Table 3. Selected examples of impact of various optimizing soil water use techniques on produce, labour or economic return on farmers' fields in dry areas of WANA and SSA. S = Sunflower; D. wheat = Durum wheat.

OSWU-Technique	Crop	Country	Impact	Reference
Soil erosion/water catchment				
Stone rows	Millet	Burkina Faso	+35–65% yield	Ouattara *et al.*, 1999
Zai	Millet	Burkina Faso	+35–220% yield	Ouattara *et al.*, 1999
Tied ridges	not specified	Zimbabwe	+22% economic	Mzezewa & Gotosa, 1999
Mini-mound tillage	Maize	Malawi	-40% labour	Materechera, 1999
Cropping techniques				
Intercrop	Maize/S	Zimbabwe	+3% economical[1]	Nyakatawa & Nyati, 1998
Relay	Maize/S	Zimbabwe	+32% economical[1]	Nyakatawa & Nyati, 1998
Other techniques				
No-till drill	Cereals	Morocco	+50% yield	Boutfirass *et al.*, 1999
No tillage	Maize	South Africa	+27% yield	Beukes *et al.*, 1999
Minimum tillage	Maize	South Africa	+20–33% yield (< 400 mm) +46% yield (550 mm) +5% yield (900–1100 mm)	Beukes *et al.*, 1999
Residue mulch	Maize	South Africa	+16% yield	Beukes *et al.*, 1999
Improved cultivar	D. wheat	Syria	+34% yield	Mazid *et al.*, 1998
Fertilizer use	D. wheat	Syria	+24% yield	Mazid *et al.*, 1998
Land management	D. wheat	Syria	+19% yield	Mazid *et al.*, 1998
Improved cultivar + management package	Wheat	Turkey	+300% yield	Avci, 1999
Improved cultivar	Wheat	Turkey	+35% yield	Avci, 1999
Timely tillage + proper implementation	Wheat	Turkey	+55% yield	Avci, 1999
Nitrogen application	Wheat	Turkey	+15% yield	Guler *et al.*, 1991
Phosphate application	Wheat	Turkey	+40% yield	Avci, 1999
Weed control	Wheat	Turkey	+15% yield	Avci, 1999

[1]) in comparison with a monoculture system

Conclusions and future research needs

Irrespective of the research results mentioned in this paper relating to improving water use efficiency and hence production levels, stability, and sustainability particularly under rainfed conditions, large amounts of rainwater are still lost and/or inefficiently utilized in farmers' fields. The possible mechanisms of losses and inefficiency are many, varied, and not always well quantified. Further, at different locations, it is different subsets of those mechanisms that need to be understood and remedied – within the local human and socio-economic context – if actual production per unit area is to reach the agricultural production potential in the dry areas of WANA and SSA. Biophysically, solutions to many of the problems will require the improvement of soil, water, and crop management at the field, plot, and farm level: first, to increase the capture and retention of incoming (rain)water; and second, to maximize the proportion of that water productively transpired by the crop. The choice of crops for the production systems, cultivar, sowing date, plant density, fertilizer management, and control of diseases, insects, and weeds needs to best suit the local environmental conditions.

Given the low and erratic precipitation for crop production in the dry areas, further research should focus on improving water-use efficiency associated with increased production per unit area, and improved production stability. Adaptive research and a farmer-participatory approach, building on past experience, are key issues for identification of acceptable techniques that match local needs and available resources, if potential yield levels obtained in on-station research are to be achieved in farmers' fields. The established collaboration and exchange of information between agricultural scientists, and close linkages between scientists, extension workers, and farmers within the OSWU consortium will allow a more rapid and sustainable solution to the food production problems and inefficient use of limited water resources. There is also an integrated approach being tested to simultaneously optimize soil water and nutrient use by crops in dry areas for greater efficiency and sustainability as for too long have these two aspects been researched independently. The decision support tool indicated also the need for considering downstream effects. An integrated catchment management approach where soil water and nutrient balances are determined per land-use pattern is therefore considered to be investigated within the consortium research agenda but awaits further funding for execution. This broader natural resource management perspective will also supply information to off-site, downstream soil and water users.

Although it has been reported that soil water conservation techniques are not economically attractive, observations by, for instance, Van Dijk (1997) demonstrate that other factors (risk avoiding in dry years, income diversification in normal years) in a risky climatic environment determine investments in these techniques. Following her conclusion and those of Ouattara *et al.* (1999), the OSWU consortium proposes also to execute more research in the antroposophic/social research domain.

In the future, investigations on optimizing the use of water for a cropping system should focus not only at the level of a single field, but rather at the level of a watershed. Crop simulation modeling linked to GIS to capture spatial variability can facilitate the development of recommendations for possible techniques or strategies for farmers in a specific biophysical environment, and allow identification of eventual positive or negative off-site effects. Futher, including these biophysical strategies in a bio-economic model is considered a valuable approach to match the identified strategies with the socio-economic conditions of resource-poor farmers in the semi-arid regions of WANA and SSA, and to identify the best-bet options that the farmers can test.

It is recommended that careful attention should be paid to the definition of WUE, with regard to inputs and outputs and the time and spatial scales at which it is being estimated, in order to facilitate comparison between different studies. Whenever possible, the term WUE should be replaced with more specific definitions, and the calculation procedures should be clearly explained.

The focus for further research on optimizing soil water use in the dry areas will have to be on impact assessment of research efforts so far, and the identification of the reasons behind the still existing gap between known principles and the situation in the farmer's fields. Further, recommendations need to be developed in a more site- and situation-specific way, considering not only the farmer's bio-physical, but also his socio-economic environment. Modeling techniques in combination with GIS may facilitate the development of management options, which are better tailored to a specific farmer's conditions and, therefore, have a better chance of being adopted.

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