Optimizing soil water use in dry-area farming systems of sub-Saharan Africa and the West Asia/North Africa region
Valorisation optimale de l’eau du sol dans les systèmes de cultures en sec de l’Afrique subsaharienne, de l’Asie occidentale et de l’Afrique du Nord

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Introduction
Across wide tracts of Sub-Saharan Africa (SSA) and West Asia-North Africa (WANA), water scarcity is a major factor limiting agricultural production. For millions of resource-poor dryland farmers, small total rainfall amounts and erratic, unreliable distribution constrain the achievement of stable, sustainable production systems providing satisfactory, low-risk livelihoods. The agricultural priority everywhere is to increase biomass or economic yield per unit of water; and, in rainfed farming, all such improvement must come in the farmer's field, holding and storing the water where it falls and using it more efficiently. Even where water is very scarce, indeed 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. Viable farm-level techniques are needed to reduce those losses and so increase the proportion of available water transpired by the crop. The development of water-efficient cultivars may help in this, but in many situations major contributions may be anticipated from improved soil, crop and cropping system management. The challenge is to coordinate land and water management with the use of efficient cultivars in viable cropping systems to increase biological and economic output. To be effective, this challenge must be met primarily by interventions that individual farmers can apply; but recognizing that such interventions often have wider social and hydrological implications, at village or catchment level, they should be developed and utilized within a community and multi-scale perspective.

Another challenge is to overcome the perception that, because all crop husbandry requirements are to a degree site-specific, they can be improved only by local ad hoc problem-solving that simply applies the already well-known general principles of soil-crop-water relations. In fact, it is the gap between 'local' problems (and the
interventions required to solve them) and those general principles that OSWU (the consortium ‘Optimizing Soil Water Use’) sets out to bridge. It starts with the premise that the implications and applications of textbook principles have not yet been fully explored or effectively applied in very dry areas; and, moreover, that there are many commonalities across dry areas in respect of local site-specific issues of water-use efficiency that will be much better addressed through a coordinated global research approach, that promotes the exchange of information and experience and its translation into pragmatic recommendations for both farmers and decision makers.

Optimizing soil water use is concerned with the whole 'water-path', from the moment rain or irrigation water reaches the soil surface until it is productively transpired by the crop plant. At all stages, it is essential to minimise the diversion of water into unproductive side-paths and to ensure that its utilization by crop plants is as efficient as possible. The overall economy of water under rainfed conditions may be most simply expressed by the equation:

\[ \text{T(crop)} = \text{P - R - D - E - T(weeds) - } \Delta S \]

where \( P \) is precipitation, \( R \) is runoff, \( D \) is drainage, \( E \) is evaporation (from the soil), \( T \) is transpiration (by crop or weeds), and \( \Delta S \) is change in soil water storage. This omits an additional term, \( I \), sometimes included to represent canopy interception (Gregory 1991). All intercepted rainwater that does not reach the ground, as drip or stem flow, is subsequently lost by evaporation from leaf surfaces, which may substitute partially for transpiration directly or, indirectly, by humidifying the crop microclimate. As a basis for the planning of future OSWU research activities, the following review examines in turn each component of the water budget, in terms of current research information relevant to the environmental and farming systems conditions found in the dry areas of SSA and WANA.

**Water capture and infiltration.**
The capture of rainwater by soil requires that an infiltration rate equal to rainfall intensity is maintained over the duration of the storm. Otherwise, excess water ponds on the soil, runs off, and is lost to the soil-crop water economy at that place. The occurrence/severity of runoff is a function of: rainfall quantity and intensity, land slope, soil characteristics, and plant cover. Of these, only the last two are potentially subject to control, and most research on infiltration problems has tended concentrate on soil characteristics and how the limitations they impose on infiltration, either directly by surface sealing (or crusting) or indirectly by slow subsurface percolation, may be ameliorated.

Surface crusting and restricted infiltration are widespread problems in dry areas. Crusting results from the dissolution of weak surface aggregates by raindrop impact, but in the more extreme case of hardsetting soils the whole A1 horizon is so unstable that wetting alone causes the slumping of aggregates and mobilization of silt and clay-size particles (Mullins et al 1990). As the soil dries, these particles cement the soil into a massive structure that restricts infiltration and limits tillage opportunities. It also impedes seedling emergence and root growth at soil moisture contents well above wilting point, thus limiting plant access to potentially available soil-stored water (Jones...
Hardsetting (and, under less severe conditions, crusting) occurs where organic matter content is low, typically < 2%, and among soils within the textural range, loamy sand to sandy clay, and having a clay fraction of low shrink/swell potential, i.e. kaolinites rather smectites. According to Mullins et al (1990), such hardsetting soils are widespread in Africa (e.g. in Zambia, Tanzania, Nigeria, Sudan and Senegal) and occur also in Lebanon and Syria. However, the fairly general predominance of smectite clays suggests that such soils are unlikely to be common in WANA. Crusting, where it occurs there, may often be linked to high silt content.

Although occurring widely in both ecoregions, runoff loss seems to be perceived as a more serious problem in SSA than in WANA. Soil differences apart, this may be because rainfall intensities tend to be greater in tropical environments, and the greater access to mechanization through much of WANA may make control appear easier. Actual losses of water to runoff can be quite large, even from sandy soils. Although Klaij & Serafini (1988) reported that weak crusts on sands in Niger seemed not to reduce infiltration, Hoogmoed and Stroosnijder (1984) suggested that in Mali an average of 25% of the rain, mainly in the form of a few large storms, is lost to runoff on sandy Sahel soils from 1-3% slopes cropped to millet - enough to make the difference between a crop yield and crop failure in low rainfall years. Clearly, there is a great deal of local variation, the reasons for which are not well understood. Harris et al (1992) reported extreme variability in infiltration over short distances in Botswana, although net runoff loss from arable fields was small; but such micro-redistribution produces very patchy crops.

Solutions to the runoff problem may be sought at different scales. At the scale of the soil itself, the standard prescription to improve structure by enhancing organic matter content, though valid, is almost always frustrated by the non-availability of substantial amounts of otherwise unwanted organic materials, like crop residues, to incorporate into the soil or apply as mulch. More practicable in the long term may be the encouragement of a positive feedback loop by which enhanced crop growth feeds the soil with a greater volume of root residues, and mineralization is minimized through reduced-tillage systems.

Small-scale soil-forming measures, using hand labour or simple mechanization, are often proposed. Numerous reports from SSA over many years have described ways to manage the soil surface to counter the effects of high-intensity rainfall on crust-prone surfaces and so prevent runoff. These include crust-breaking techniques, employed soon after sowing mainly to assist crop emergence and, more widely, various systems of ridging, 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; Jones & Wild, 1975; Stroosnijder & Hoogmoed 1985; van der Ploeg & Reddy 1988). Similar systems are currently under test in WANA, in Morocco (Karrou, personal communication). Larger-scale alternatives include contour strips (e.g. Carter et al 1988) and various bunding and terracing systems. The latter may possibly be more appropriate in wetter environments where the focus for soil and water conservation efforts is more heavily towards the prevention of massive soil erosion.
There is also ‘water-harvesting’, by which - using soil crusting and hard-setting properties positively - water is encouraged to flow from one part of the surface to concentrate it for more effective agricultural use on another. This may be practised at scales ranging from a few metres to many kilometres. Indigenous systems of water harvesting, past and present, are well documented, particularly for WANA (Evanari et al 1971; Kutsch 1983; Alaya et al 1993; FAO 1994) but also in SSA (eg, Reij et al 1988); and there have been many attempts in recent years to introduce or revitalize such systems in very dry areas (eg. Tabor 1995; Manu et al 1994). Strictly speaking, water harvesting is directly involved in the improved efficiency of utilization of soil water, but it may have complementary role to play in some situations, providing a supply of water to supplement rainfall in particularly dry areas or as a conjunctive strategy to prevent downstream loss of water where full infiltration directly into the soil is undesirable or unattainable. Such systems are not theoretically difficult to devise; the problem always lies in adapting them to local farming realities. Despite decades of technical research, examples of the successful adoption and long-term maintenance of soil and water conservation techniques by dry-area farmers are rather few. To improve upon this record requires critical analysis across both ecoregions of past successes and failures, and, at local level, close research involvement with farmers in renewed attempts that build on past experience.

Drainage losses.
The second mode of soil water loss is deep drainage. For WANA, this is a minor problem, restricted to shallow or very sandy soils. Although some individual storms may be heavy, the total rainfall is spread over a long season, and the top metre of the predominantly clay-rich soils is able to hold 120-180 mm between field capacity and wilting point. In many such soils, it is rare for the annual wetting front to advance much below 1 m depth. So, unless the year is unusually wet or the crop naturally shallow-rooted, the rooting zone is coterminous with the wetting zone, and there is no loss of water out of the bottom of the profile (Cooper et al 1987). One possible exception might be runoff of water from heavy, early-season storms into deep dry-season soil cracks, but this is not widely recognized as a problem.

The situation is different in large parts of dry SSA, where the conjunction of a short season, heavy storms, and coarse-textured soils (with available water-holding capacity perhaps only 25-75 mm per metre depth of soil) can lead to substantial movement of water below the crop rooting zone. Where such ‘lost’ water remains held in the deeper subsoil, as in the deep and uniformly fine sands of the Kalahari, overall efficiency of use may be enhanced by the inclusion in production systems of perennial crops, including forage and pasture species, with deep, established rooting systems. Alternative measures for arable systems include early crop establishment and the use of naturally deep-rooted annual crops, either as components of rotations or crop mixtures. Choice of crops and crop sequence (and their various planting dates) may make a significant difference to the efficiency of total water use. However, attempts to increase soil water-holding capacity, by building up soil organic matter content, appear doomed to play, at best, only a very minor role. Frequent and fairly massive inputs of materials are required to make any large difference; and, as noted above, such materials are rarely available.
**Evaporation and transpiration.**

All water successfully infiltrated into the soil and not lost to drainage is eventually evaporated back into the atmosphere, by three mutually competitive processes: \( T(\text{crop}) \), transpiration by the crop; \( T(\text{weeds}) \), transpiration by weeds; and \( E \), direct evaporation from the soil. So, essential to any increase in the efficiency of soil-water utilization is the maximization of crop competitiveness for water. This has ‘biological’ and ‘management’ components (Gregory 1988). The biological component is a function of transpiration efficiency, or primary biomass assimilation per unit of transpired water. This is crop specific and may, to a small degree, also be genotypically specific. There is a small margin for improvement here that crop breeders might be able to exploit.

More immediately practicable is the identification of appropriate crops and cultivars (their morphology and phenology) to match local environmental conditions and, especially, the pattern of water availability. Since, apart from any species and genotypic differences, transpiration efficiency is a function of the atmospheric saturation deficit (relative dryness of the air), directing biomass production into periods of lowest atmospheric demand confers an advantage (Acevedo et al 1991; Loss & Siddique 1994; Gupta 1995). In the winter rainfall environment of 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). It has been calculated that in northern Syria, each 1-week delay in sowing after the beginning of November will reduce wheat yields by 4.2% (Stapper & Harris 1989). Similar considerations lie behind attempts to persuade WANA farmers to move from spring to winter sowing of chickpeas (Silim & Saxena 1991). Brown et al (1989) reported that the water-use efficiency of chickpeas in northern Syria increased from 8.8 kg dry matter/ha/mm evapotranspiration for spring-sown chickpeas to 15.7 kg for the winter-sown crop.

Whether there is any analogue of this strategy for ‘Sahel’ environments is unclear. There may be cooler, though drier, periods during which atmospheric demand for water is lower than in the peak of the hot, rainy season; but few soils have the moisture-storage capacity that would permit the exploitation of this. It may make sense to use this time to grow crops, other than sorghum or millet, only where irrigation water is available.

Other ‘management’ factors relate to the interception of solar energy. The more of the incoming energy intercepted by the crop, the less there is to promote evaporation from the soil surface or transpiration by weeds. Actual evaporative loss from the soil surface depends also on the soil moisture content at that surface, which in turn depends on the unsaturated hydraulic conductivity of the soil (a function of texture) as well as on the frequency of its rewetting, by rainfall. [Ongoing studies at ICARDA suggest very high values for the hydraulic conductivity of the clay soils in northern Syria, which, by allowing large upward movement of soil water to the surface, encourage evaporative loss and impose a limit on the efficiency of crop water use (Eberbach, personal communication).] Nevertheless, 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. Thus research results in WANA (eg Cooper & Gregory 1987) and also, for instance, under similar conditions in Australia (Hamblin et al 1987)
have emphasized the importance of achieving early crop cover. Practices that particularly contribute to this are:

- early planting;
- selection of varieties with rapid early growth (under cool conditions);
- adequate fertilization;
- adequate plant population and close spacing (Gregory 1991).

Early planting depends on the tillage/crop rotation system employed (see below). However, the development of crop varieties for early growth vigour has been a major concern of winter cereal breeders in WANA for many years (Ceccarelli et al 1991). Given the inherent low fertility of many dry-area soils, judicious use of fertilizer is particularly important. Extensive work in Syria during the 1980's (Cooper et al 1987; Shepherd et al 1987) and also in Turkey (Kalayci et al 1991) and Tunisia (Mechergui et al 1991) demonstrated the efficacy of appropriate fertilization on production and therefore on the water-use efficiency of winter-sown crops, especially wheat and barley. In deficient soils, seedbed phosphate (usually with a small dose of nitrogen as well) enhances the rate of leaf expansion, tillering, root growth, and phenological development, ensuring more rapid canopy closure and earlier completion of the growth cycle before rising temperatures increase the atmospheric demand (Gregory et al 1984; Gregory 1991). Similar effects of fertility on the efficiency of water use have been reported for sorghum and millet in the Sahel (Onken et al 1988). Small additions of NP fertilizer increased yields, particularly of sorghum, under conditions where evapotranspiration ranged from 214 to 390 mm.

The concept of early and complete canopy establishment to shade the soil and reduce evaporative loss from the surface makes good sense for winter-rainfall crops in Mediterranean conditions and also, apparently, for summer-rainfall crops over much of the semi-arid tropics. Wallace et al (1988), working on sparse millet crops in Niger, estimated that about 36% of the seasonal rainfall of 562mm could be lost as direct evaporation from the surface. Similarly, a greater efficiency of resource utilization appears to be expected for intercropping (and mixed cropping) in a wide range of environments (Willey 1979; Francis 1989). However, these generalizations do not necessarily hold true in more extreme environments. If rainfall is infrequent, evaporative losses from the usually dry soil surface may be relatively unimportant; and if it is water rather than radiation that is limiting, intercrops grown beneath a cereal canopy, supposedly to utilize low-intensity radiation that would otherwise be ‘wasted’, may in fact compete vigorously with the cereal for the suboptimal water supply.

Thus, while the densest populations of sorghum at Sebele, Botswana, produced the most dry matter (per unit area and per mm rain), between the infrequent rainstorms they used up the available soil moisture sooner and became stressed earlier than did sparser crops, such that flowering was often delayed or failed completely (Rees 1986a; Jones 1987). Even where flowering occurred, intense competition in denser populations kept individual plants very small, and with decreasing size the transfer of dry matter into the grain became rapidly less efficient. Greatest water-use efficiency of grain production was achieved by sparse populations which left much of the soil surface exposed to solar radiation. This finding applies not only to sorghum; commercial farmers in dry parts of South Africa learned many years ago to grow their maize in rows 2-3 metres apart. Even
in WANA, olive growers in dry areas (eg. in southern Tunisia with mean annual rainfall 200mm) plant trees at very wide spacing, such that canopy cover probably never exceeds 25%. Frequent tillage between the trees controls weeds and may also conserve soil moisture through a ‘dust-mulch’ effect.

Weeds must also be controlled between the rows of maize and sorghum or the benefit of wide spacing is lost. And in the severe Botswana environment, intercropped cowpeas had the same effect as weeds; in dry years even very low populations were able to devastate the adjacent rows of sorghum (Rees, 1986b). It may be that intercrop rooting patterns that are complementary in relatively moist conditions severely handicap one crop component when rains are light. In wet years at Sebele, 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). However, this result contrasts strongly with the report of Swinton & Dueson (1988) that subsistence farmers in Niger practice forms of intercropping that exhibit high complementarity between component crops and reduced risk of crop failure.

Other management interventions.
So far the emphasis has been on ways to optimize the water use of individual crops, but system management strategies and other environmental interventions can also play a role in the economy of soil water use in dry areas. Included in this are:
- windbreaks;
- crop sequences, rotations, fallows and associated soil management;
- supplemental irrigation.

Windbreaks. 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). Further, in such dry environments, windbreaks may have doubly beneficial effect, controlling wind erosion as well as evaporative loss. Nevertheless, windbreaks are rarely part of indigenous systems; and if small farmers are to adopt them, they must be seen to have intrinsic economic value additional to any conservation role - for example in WANA, as fodder shrubs and trees, like Acacia and Atriplex spp. (Jones & Harris 1993). Though potentially important, in neither SSA nor WANA is this innovation likely to make a quick impact.

Crop sequences, rotations, and fallows. More promising for quick impact, because more compatible with current farm practices, is the adjustment of crop sequences and their management to optimize water use. There are several interrelated factors in this:
- the timing of sowing;
- the time interval between each crop (and the nature and form of ‘fallows’);
- complementarities between crops (in time and space) in rooting patterns and depths;
- tillage operations (form, depth and frequency) and the management of crop residues.

Timing of sowing is a vexed topic in nearly all farming systems. Constraints to early seedbed preparation (or direct sowing) often conflict with the need to avoid the yield
losses (and reduced water-use efficiency) that arise from late sowing. Where the land is untilled since the previous harvest, in all but the lightest soils it is necessary to wait until the early rains have cumulatively moistened the soil sufficiently to permit the entry of an implement; and a particularly vicious circle can arise where the compact 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 (sorghum in SSA, barley and wheat in WANA); another that the power available for tillage is inadequate to match the natural strength of the dry soil. The severity of such problems may depend greatly on local soil differences; for example, in eastern Botswana loamy sand soils wet up more easily than the adjacent sandy loams, and in a dry year this may determine whether a crop is sown and a harvest reaped or not (Jones 1987; Siebert & Modiakgotla 1988). Even where land can be tilled in advance of the planting season, tradeoffs must often be made between a second preplanting tillage to control weeds and the delay to planting that this necessarily involves. Such decisions are very delicate ones where rainfall is very erratic and frequently confounded with poor access to the necessary draught power.

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 (overwhelmingly the predominant crop) continue extracting soil moisture 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.

Fallowing simply means leaving arable land free of crops, for periods ranging from a few months to many years. Aside from long-term ‘bush’ fallows, there may be either clean fallows, in which weed growth is controlled by tillage, or weedy fallows, in which there is no control - in many cases to provide grazing for livestock. In WANA, the ‘traditional’ practice was (and in some places still is) to crop the land every two years and leave it fallow for the intervening 12-18 month period. All such fallows must once have been ‘weedy’, but in recent times the trend has been towards clean fallowing and, given increasing demographic pressures, to annual cropping, with only short, dry-season ‘fallow’ between. In SSA, ideally all land cleared for cropping is planted annually, but unplanned fallows may sometimes occur when the pattern of rainfall fails to match planting needs.

The rationale for fallowing varies with location, farming system, and ecosystem. In the bush fallows of low-input tropical systems (including dry SSA environments) and, to a large extent, in the traditional biennial WANA cereal-fallow cropping systems, the restoration of soil fertility and the control of diseases and pests are the predominant processes involved. For all shorter dry-area fallows (including periods between cropping not always explicitly called fallows), water economy is the most important factor. The distinction between clean and weedy fallows is crucial here. Any land abandoned to weed growth, and particularly dry-season weed growth, will soon be
exhausted of available water. However, this loss may be set against the value of any grazing obtained and the possibility that much of the lost water would anyway have been unproductively evaporated from the soil.

One feature of the intensification of cropping inherent in agricultural development worldwide is the shortening and elimination of fallows. In the WANA context, the replacement of weedy fallows by crops, though inconvenient to some livestock producers, probably represents a net gain in water-use efficiency and agricultural output. But the question of clean fallows, specifically those in biennial cropping systems, is more controversial. The presumed justification for keeping the land bare for more than a year, apart from possible benefits to fertility and pest and disease control, is to store one season’s rainwater in the soil to buffer the following crop against possible drought. Undoubtedly, this strategy has a stabilizing effect on barley yields (Jones & Singh 1995), and reports, for instance from northern Iran (Shehoie et al 1991) and from the Negev desert (Amir et al 1988), indicate substantial wheat yield responses to fallowing. However, the actual amounts of water stored between seasons are often very small; and, as land and water become increasingly scarcer, one may doubt whether this is the most efficient way to use either resource.

The storage efficiency of long fallows in WANA (ie. % of previous year’s rainfall held in the soil at the start of the next crop year) seems usually to be rather low. Summarizing a long experience of fallow research in Turkey, Pala (1991) reported values of 25-35% and 15% for highland and lowland areas, respectively, and Guler et al (1991) emphasized the importance of the particular tillage system used over the 14-18 month fallow period. Their preferred ‘soil mulch’ system not only controls weeds but reduces water losses from depth by disrupting capillary continuity and thermally insulating the subsoil during hot weather. Over 6 years in lowland Syria, storage efficiency at Breda (long-term mean rainfall, 280 mm) never exceeded 10%, but under moister conditions at Tel Hadya (330 mm) the range was 8 - 37% (Harris et al 1991b). It seems that, in general, fallingow is least effective in those areas of low and erratic rainfall where crops would benefit most from it. One essential is a deep soil profile having of moderately high water-holding capacity, and this rules out the possibility of storing summer rainfall for subsequent ‘cool-season’ cropping in many dry areas in SSA. However, different subsoil moisture contents at planting, comprising 30, 49 and 83 mm available water held between 30 and 140 cm depth, produced in a very dry summer season in eastern Botswana sorghum grain yields of 70, 450 and 1190 kg/ha, respectively (Jones 1987). Where reasonable soil moisture storage capacity exists, the possibility of its manipulation for increased efficiency should not be ruled out anywhere.

Where long fallows, weedy or clean, have previously been the norm, the trend is now towards fallow replacement - that is, to grow a crop every year. The issue then is one of optimising crop sequence within rotations, to balance such biophysical issues as resource use and pest and disease build-up with the production priorities of farmers. Fairly generally, when farmers intensify their cropping they tend first to grow more of their main staple, and it is now quite common in WANA to find fields that grow wheat or barley nearly every year. As long as biotic stresses are held at bay, and particularly if some fertilizer is used, such systems may be more productive than the ‘traditional’
fallow-cereal sequence, albeit with perhaps greater inter-annual variability; but biophysically they are not usually the most efficient systems. In dryland areas of central Anatolia, although yield was slightly reduced, the water-use efficiency of wheat following vetch, lentil, chickpea or cumin was increased relative to that following fallow (Karaca et al. 1991). And in barley-based systems at Breda, northern Syria, a rotation of barley with vetch cut as hay produced 0.6-0.9 t/ha/annum more biomass than continuous barley. This represented a 20-30% improvement in water-use efficiency: fertilized barley grown after vetch produced 36.7 kg biomass/mm/ha, but after barley only 23.7 kg biomass (Harris 1994). In similar studies at Breda and Tel Hadaya, rotations of barley with vetch grown to maturity almost doubled the net offtake of nitrogen (and therefore protein) relative to barley-barley and fallow-barley sequences, an important consideration in production systems largely dedicated to feeding sheep (Jones & Singh 1995). Moreover, the growth-stage of vetch harvest may significantly affect soil moisture status, producing differences in subsequent barley yield and rotational water-use efficiency (Jones 1995). Such results strongly support earlier reports from Cyprus by Papastylianou (1993a,b).

Where dryland arable land is cropped every year, inter-season management may significantly affect soil moisture. The post-harvest control of weeds, by tillage or grazing, is important whenever the crop, perhaps a shallow-rooted species or harvested pre-maturity, leaves moisture residual at depth. Even in the absence of weeds, soil mulches of the type mentioned by Guler et al. (1991) may have application in some situations. In contrast, in the US, 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 (Bolton 1991; Papendick et al. 1991). Such results have proved hard to reproduce in northern Syria (Jones, 1996). 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 moisture economy was negligible. Small improvements in crop performance occasionally observed may reflect a marginal reduction in evaporation in young plant stands drilled directly into the standing stubble.

Supplemental irrigation. A completely different approach to increasing water-use efficiency in dry environments is supplemental irrigation, defined as the addition of small amounts of water to augment and stabilize yields of essentially rain-grown crops (Perrier & Salkini 1991). Such additions, if well judged, increase the utilization efficiency of the rainfall but also that of the irrigation water compared with most other modes of use. This is particularly true where it is a winter crop that is supplemented and the alternative use for the water source is the full irrigation of a summer crop. When rigorously practised, supplementary irrigation follows the principle of ‘deficit irrigation’; the soil profile is not irrigated fully to field capacity, and the target is not maximum yield but rather the yield that optimizes water-use efficiency.

The first requirement for supplemental irrigation is a water source. In WANA, much of which is underlain by deep limestone strata, this is commonly a small, rechargeable aquifer, although surface water may also be used. One problem is that such aquifers are almost too readily accessible; and in many countries controls on farmers are currently insufficient to curb non-sustainable exploitation. Either farmers cannot see beyond short-term production objectives, or they perceive no long-term threat in the increasing
depths from which they must pump (Smith 1994). Some aquifers may be near to ‘failure’ (Ward & Smith 1994). If future supplies are to be protected and their value optimised, acceptable but mandatory systems of use conjunctive with rainfall must be introduced. Necessary, if this challenge is to be met, are techniques for improved crop-level water-use efficiency.

A different hydrological situation exists in dry areas of SSA, underlain largely by basement complex rocks. The option of supplemental irrigation for rainy season crops is limited to areas adjacent to major rivers, with, additionally, some small-farmer irrigation of dry-season vegetables in ‘fadama’ gardens. However, new potential for supplemental irrigation could arise from water-harvesting developments, where landforms and communal institutions are favourable. Another model is that of the ‘collector wells’ pilot project in Zimbabwe, which provides improved village-level abstraction of water from regolith aquifers in crystalline basement complex rocks, for domestic use and small-scale irrigation (Batchelor et al 1994; Lovell et al 1994; IH/ODA 1996).

**Conclusions.**
The current OSWU consortium is based on the premise that large amounts of rainwater with agricultural production potential are inefficiently utilized in the fields of farmers in the dry areas of WANA and SSA. The possible mechanisms of loss and inefficiency are many, various, and not always well-quantified; and, at different locations, it is different subsets of those mechanisms that need to be understood and remedied - within the local human and socioeconomic context - if actual production is to come closer to the potential. Technically, solutions to many of the problems will require the improvement at farm level of the agronomic management of soil and crop: first, to increase the capture and retention of incoming water; second, to maximize the proportion of that water productively transpired by the crop. Allied to that second objective, is the choice of crop, cultivar, planting density and planting date to best match the local ambient conditions.

Problems of water capture arise from incompatibilities between rainfall intensity and the structure, and structural stability, of the surface soil. In some situations it may be necessary to allow runoff, possibly as ‘water harvesting’ for use in prepared ‘run-on’ areas. The development of applied hydrological methods to facilitate decision-making in such circumstances might be a worthwhile research topic. Nevertheless, the improvement of in situ infiltration is likely to be of wider and more immediate application. For this, the strengthening of surface soil structure, though desirable, will usually be a less promising approach than modifications to surface microtopography. The existence of an already extensive literature on such techniques as contouring, ridging and bunding (and also mulching) suggests that the research focus now should be more towards adaptive and farmer-participatory activities, building on past experience, to identify acceptable techniques that match local need and available resources.

More efficient infiltration can lead, of course, in sandy soils to leaching and drainage losses to below the root zone. In environments thought to be vulnerable, research may be needed to quantify the extent and seriousness of such losses and to appraise the potential of different mixtures, configurations and/or sequences of crops (and even woody species) of deeper rooting habit for reducing them. An alternative view,
however, could be that one man’s loss is another man’s gain; in some environments it may be necessary to assess the effects of enhanced infiltration and/or enhanced crop utilization on aquifer recharge and downstream surface flows.

Soil-crop-water relations have been extensively researched over many years, particularly in temperate environments, and the general principles are said to be well established. Even so, there are a number of fairly fundamental questions still to answer in respect of the application of those principles to cropping systems under low and erratic rainfall. For instance, in tropical summer-rainfall areas, how best may the imbalance between solar radiation and the uncertain supply of water for evapotranspiration be managed so as to minimize the risk of production failure? Given that daily evaporative losses may fall almost to zero during long dry periods, at what point does the transpirative cost of attempting to shade the soil surface become too high? Is it possible to model this and to define threshold conditions? Similar questions arise over intercropping. In humid environments where radiation is the first limiting factor, the development of dual canopies increases production efficiency. But it is the below-ground processes that matter in dry environments: two rooting systems may be complementary, enhancing total water extraction, as long as soil moisture is abundant; but in profiles in which the amount and depth distribution of moisture fluctuate widely between infrequent rainfall events, at what point does complementarity become lethal competition? Not least, in WANA, many questions involving fallows and crop sequences remain. While there are many reports of crop-yield effects, comparative measurements of water budgets have been too few for the development of reliable models of moisture profiles in different soils under different multi-year cropping and falling systems. Yet in environments in which every millimetre counts, the means to appraise tradeoffs between using water now and attempting to store for the next crop is essential to further improvements in water-use efficiency. Altogether, there appears considerable scope for useful research of an applied nature in both SSA and WANA ecosystems.

At a more immediately practical level, local research needs centre around the identification of ways to manipulate crops, planting dates and crop sequences, in order, variously: to facilitate timely tillage; to suppress weeds; to manouevre key growth phases into periods of favourable ambient conditions (eg more reliable rainfall, lower evaporative demand); and to optimize the extraction of soil water. Moreover, it is important in each case to factor in the fertility dimension. Approaches for optimizing soil water use in low-input situations will often be different from those for high-input situations, and soil water research must work in the context of the most practicable regime for soil-fertility maintenance in the system it is targetting. Production improvements will come most readily where new technologies improve crop uptake of water and nutrients concordantly.

References


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