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Water Relationships in a Sustainable Agriculture System

E. John Sadler and Neil C. Turner

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INTRODUCTION

Sustainable agriculture requires management of the land so that production and productivity are enhanced while sustaining a healthy ecolog-

ical balance within the agricultural ecosystem (Ruttan, 1990). One of the key inputs to any agricultural system is water. Because of the strong link between photosynthesis and transpiration at the level of the individual leaf, crop and pasture production are usually highly correlated with water use (Fischer and Tumer, 1978). For agricultural systems to be both productive and sustainable in the long term, management of the water resource is required to ensure that sufficient water is available for plant growth and excess water is not allowed to contribute to land degradation (Fillery and Gregory, 1991).

Water is not only important because it contributes to plant growth, but also because it is a transporting agent for dissolved materials, nutrients, chemicals, and solids. Although its ability to transport nutrients, pesticides, and phytohormones is fundamental to plant growth and protection, excess water can lead to pesticides, salts, and nutrients entering the ground water or surface water and to soil particles being moved downslope, resulting in soil erosion and land degradation.

As a framework for our discussion of water in a sustainable agricultural system, we will use the hydrologic cycle because sustainability impacts all aspects of the cycle. We can then discuss these impacts on its individual components. The hydrologic cycle is depicted in Figure 1. The primary input to the cycle is precipitation, which is generally considered to be unaffected by the agricultural system, but which varies enormously both spatially and temporally. In agricultural systems, precipitation is

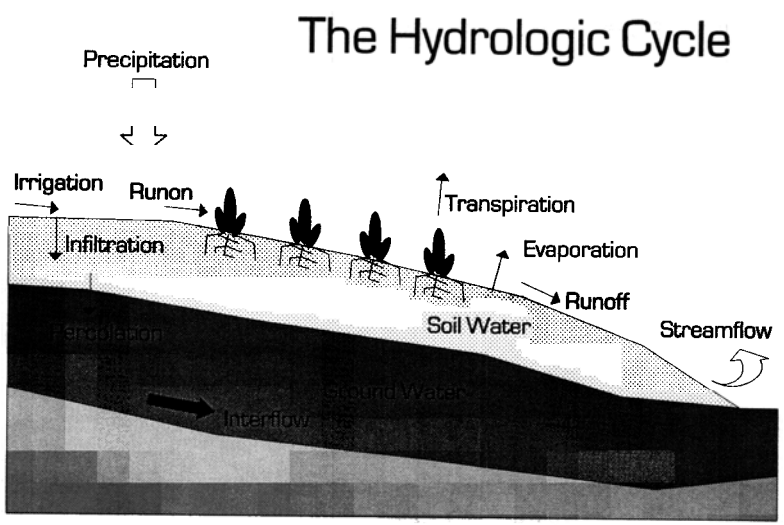

FIGURE 1. A diagrammatic representation of the hydrologic cycle. Terms defined are used in the text.

sometimes supplemented by irrigation or by runon from runoff higher in the landscape. Losses from the system include evaporation from the soil, transpiration from the crop, surface runoff, interflow along an impermeable subsoil layer, and deep percolation. The balance among these fluxes constitutes the soil water storage term, so that the capacity of the soil to store water is a candidate for management in a sustainable system.

In looking at water in sustainable agricultural systems, we draw heavily on modern research findings. However, agricultural systems have changed dramatically in the past half century with energy inputs from petrochemical sources increasing dramatically. On a world scale, water inputs through irrigation have also increased significantly and are likely to continue to increase until and beyond the turn of the century (Alexandratos, 1988). It is, therefore, not clear how sustainable some of the recent agricultural systems are likely to be in the long term. Therefore, in this chapter we will also look at some ancient agricultural systems and their sustainability. Some of these ancient agricultural systems were sustainable over millennia, and an understanding of water use in these systems may be instructive to modern scientists.

PRECIPITATION

The Food and Agriculture Organization of the United Nations estimates that 600 million hectares of potentially arable land is unused because of limited water (Alexandratos, 1988). That area is almost equivalent to the area currently utilized in arable production. In many parts of the world, crop production is limited by rainfall, and production varies markedly from year to year depending on water availability. With precipitation being such a major limitation to crop production its efficient use is an important consideration in any sustainable system. While little can be done to alter the amount of precipitation that is received, current scenarios suggest that global climate change resulting from the increase in greenhouse gases may result in marked regional changes in precipitation in the next half century (Pittock, 1988). Increasing cyclonic activity is predicted to move the subtropical regions polewards, and warmer temperatures are predicted to result in the arid, semiarid, and temperate regions moving closer to the poles. The role of global climate change cannot be discussed in detail in this chapter, but it needs to be recognized that the predicted changes resulting from global warming may have significant effects on water use and the sustainability of future agricultural systems (Adams et al., 1990).

Precipitation at a particular location can be supplemented with water arising from rainfall elsewhere, either by irrigation or by runon farming practices. Alternatively, the rainfall in one season may be supplemented

from storage of prior rainfall. Irrigation from deep aquifers utilizes water accumulated over many years or even centuries. A much more immediate use of rainfall storage occurs when water is stored in one season for use in the subsequent season. This process, fallowing, is widely practiced in dryland agriculture where the seasonal rainfall is limited.

Supplementing Precipitation—Irrigation and Runon Practice

We first discuss larger-scale rainfall harvesting, such as is done where mountain rainfall and snowmelt, or simply large catchment areas, provide water that can be used by producers at lower levels. Areas proximal to mountain ranges (e.g., coastal Peru [Browman, 1983; Ortloff, 1988]) or to major rivers (e.g., the Nile valley and the Dujiang Weir system on the Minjiang River in China) have had extensive development of irrigation based on such practices. The irrigation water may be utilized many kilometers from its collection and river waters may be reused several times. Sustainability of these practices is enhanced by the low cost of the water supply and the natural head that drives the water delivery system. Questions of salinity (Ponting, 1990), luxury consumption, municipal competition for water, and other considerations may decrease the sustainability of these practices, as is already evident in contemporary California (Reisner, 1986). However, irrigation has been used for centuries and, in many places, has allowed food production in areas that otherwise would not support large populations (Ponting, 1990).

The Tigris and Euphrates River valleys in southern Mesopotamia provide the earliest known example both of formal irrigated culture and of decline due to salinization. Agriculture in the area dates to about 5000 B.C., but probably was limited to riverbanks and small-scale irrigation. By 3000 B.C., an irrigation canal over 15 km in length had been built, indicating larger-scale irrigation. By 2400 B.C., a second large and important canal further increased the scope of irrigation (Minc and Vandermeer, 1990). However, salinization had begun to occur within 1500 years of the beginning of irrigation. From 3500 B.C. on, farmers responded to salinization by shifting from wheat to barley, which is more tolerant to salt. During the period from 3500 to 1700 B.C., the area planted to wheat dropped from about equal to that for barley to none at all. Records indicate that crop yields remained high until about 2400 B.C., by 2100 B.C., they had dropped 42%, and by 1700 B.C., yields had dropped by 65% (Ponting, 1990). Similar problems of salinization after irrigation are widely distributed throughout the world, though few have such a historical perspective.

However, not all irrigation schemes have led to salinization and land degradation. In Arizona, ancestors of the Navajo used steep slopes of the

Black Mesa Mountains to funnel water toward small fields at the bases. There, they grew corn, squash, melons, and even fruit trees. Although yields were low relative to modern standards, the practice was successful and continues today (Seery, 1990).

Irrigation from deep aquifers is a more recent phenomenon because it depends on energy, particularly fossil fuels, to pump the water to the surface. However, its sustainability does not only depend on the sustainability of the water supply. Water in deep aquifers has often collected over many years or even centuries and, if not replenished at the rate of utilization, will ultimately be a finite resource. Irrigation from the Ogallala and associated high plains aquifers by U.S. Great Plains farmers has had to be restricted to prevent it from either being quickly depleted or at least dropping too deep for economical pumping. Since pumping began, the water levels in the Ogallala have decreased more than 3 m in 29% of the aquifer, by more than 15 m in 6.9%, and by more than 30 m in 1.4% of the aquifer's 450,000 km^2 (Gutentag et al., 1984). These drops have occurred even though the volume of water in the aquifer has decreased by only 5% (Weeks and Gutentag, 1984).

An interesting form of supplemental rainfall in areas of very low rainfall (100 to 150 mm annual rainfall) was developed by the Nabateans about 2000 years ago in the Negev Desert (Evenari et al., 1982; Hillel, 1982). Rainfall on surrounding barren hills was collected and channeled to the terraced valley floors, which had deep loessal soils. Recent reconstruction of these ancient runoff/runon farming systems indicate that a crop can be grown on a single rainfall event of 20 mm, and fruit trees and other perennial plants can survive and produce in regions in which the annual rainfall is too low to allow normal horticultural production (Evenari et al., 1982). The Nabatean civilization lasted for about 700 years in the Negev Desert, but gradually declined as trading routes and religious and civilian empires in the region changed (Evenari et. al., 1982; Hillel, 1982). The successful reconstruction of these ancient systems in modern Israel is testimony to the fact that the runoff/runon farming system is sustainable and that the decline of agriculture did not arise from land degradation.

Runon farming in dry environments is still practiced in modern agriculture, albeit on a different scale. Evenari et. al. (1982) describe a microcatchment system used in the Negev Desert, in Afghanistan, and in parts of Africa. There, fruit trees are planted in a depression 0.9-m deep and 4-m square at the corner of a microcatchment of 250 m^2, and the rainfall from the entire catchment is channeled to that corner. Depending on rainfall, the microcatchment required for an individual fruit tree will vary, but the principle is that water is not lost but channeled to the plant roots. Conservation bench terraces (Zingg and Hauser, 1959; Jones, 1975, 1981) are also a small-scale application of water harvesting for use

elsewhere. Here, a slightly sloping (1 to 2%) area is modified to provide a watershed area that contributes runoff to a level bench area about half as large. The level area is continuously cropped, and the watershed area is in some rotation that includes fallow. The conservation bench terraces control runoff water, prevent water erosion, and contribute water to the level bench (Zingg and Hauser, 1959; Hauser, 1968). However, the success of the level bench system depends on soil type. Positive results were obtained on a Pullman clay loam soil, but on an Amarillo fine sandy loam with a higher infitration rate and lower water holding capacity, similar terraces provided no yield benefit for either sorghum or cotton (Armbrust and Welch, 1966). Lower water holding capacities and higher infiltration rates resulted in the soil water reservoir being filled before runoff arrived from the contributing watershed, and the impounded water was lost to deep percolation.

While runoff from high in the landscape can be beneficially utilized for crop production lower in the landscape, the management of runoff water is not always easy nor well controlled. As a consequence, water tables exist within a meter or two of the surface in many parts of the world. Where there are shallow water tables, root depth may not be adequate for sustained crop growth. Historically, one procedure that has been used to overcome this has been the use of raised beds and canals.

The Yucatan peninsula was farmed by this technique during the period from 200 B.C. to 850 A.D. Evidence of raised fields, terraces, and possibly irrigation of normally dry areas has been found in Pulltrouser Swamp in southern Quintana Roo, Mexico (Turner and Harrison, 1981; Chen, 1987). In the study area, over 600 ha of channelized or raised fields exist, indicating that extensive effort had been invested to alter the natural landscape. The soils in the area were 0.5- to 1.0-m deep and overlaid weathered limestone. Channels from 2- to 10-m wide were cut up to 1-m deep into the weathered limestone. The soil extracted to make the channels was used to raise the level of the soil surface between the channels. In most cases, the original topsoil was removed and replaced above the fill. Such extensive labor inputs, estimated to be about 12,000 worker-years for the 600-ha site, plus suggestions of mulching and mucking, are indicative of high-output agriculture. The Mexican chinampas, which are the modern equivalent, support about 19 people per hectare. If 70% of the total area were raised fields and 30% canals, then about 8000 people could have been supported by the 600 ha of the Pulltrouser Swamp site. Such intensive agricultural development coincided with the rise in population in the Classic Maya. However, why this civilization rapidly collapsed is not clear. Ponting (1990) argued that the population increase outstripped rural production, causing increased pressure on marginal lands to provide not only food but also timber for construction and fuel. Certainly there is evidence of increased infant and maternal

mortality and signs of nutrient deficiency from about 800 A.D. However, the breakdown of civilization could have arisen as much from internal strife as from land degradation.

Modern research in similar environments emphasizes the importance of controlling the water table by using a combination of drainage and irrigation. Lowland agriculture in the Atlantic coastal plain and Mississippi Delta of the U.S. has been enhanced by water table management using simple or advanced water control structures such as flashboard risers and automated, water-filled fabric dams (Doty et al., 1984b, 1985, 1987). Both act to retain the water resource (about 1000 mm annual rainfall) without leaving the land subject to flooding such as occurs in undrained land. Conventional drainage without water table control causes overdrainage and, ironically, in many cases, results in water shortage between rainfall events (Doty et al., 1984a).

Supplementing Precipitation—Season-to-Season Supplementation

Storing rain during fallow for use in a later cropping season has been used in most semiarid regions of the world to supplement the growing-season rainfall. The primary objective in most fallowing is to store water during the noncrop season for use in the following season, but the efficiency of such storage is, on average, low. Mathews and Army (1960) reported precipitation storage efficiencies from harvest to seeding of 12 to 40% for annual spring wheat and 10 to 28% for annual winter wheat. Similar values for wheat-fallow systems were 10 to 25% for spring wheat and 6 to 22% for winter wheat. These values for the U.S. are similar to ones obtained in Australia (Ridge 1986). Studies show that during periods without rain, water evaporates from the top 0.20 to 0.30 m of the soil profile, while subsoil water is only slowly subject to evaporative loss. The storage efficiency will vary with soil type, with frequency and quantity of rainfall in individual storms, and with the rate of evaporation. Studies in South Australia indicate that the best soil moisture storage after fallow occurs in fine-textured soils or soils with a clay subsoil and a minimum storage capacity of 125 mm in the top 1.2 m of soil. Coarse-textured soils with a moisture storage capacity of 50 to 85 mm in the top 1.2 m gain little from fallowing (Schultz, 1971; French, 1978a; Tennant, 1980). Water from frequent small storms that do not allow penetration of the rainfall below 20 cm will be evaporated away, while infrequent heavy storms allow deeper water penetration and less evaporative loss. Storage efficiencies also tend to increase as one moves north in the U.S. Great Plains, a consequence of reduced evaporative demand. Lavake and Wiese (1979) documented the influence on storage during fallow when different tillage and weed control practices were used. Storage efficiency decreased from

18 to 14% as the delay between weed emergence and tillage increased from 14 to 24 d after emergence. Clearly, control of weeds during fallow is important if fallowing is to be practiced efficiently.

Cereal yields in Australia are usually higher as a result of fallowing (French, 1978b; Tennant, 1980; Ridge, 1986) and yields in the southern Great Plains (Unger, 1983) are 40 to 50% higher for fallow-rotation crops than continuous crops. However, as yields are not doubled, the total production from continuous cropping is higher (as are costs of harvesting greater areas). Nevertheless, the risk of low crop yields is higher where continuous cropping is practiced than where a fallow is included in the rotation. For the central and northern Great Plains, where the storage efficiencies are higher and risk of crop failure (yields below 1000 kg ha^{-1}) is greater, Smika (1970) reported that fallow-wheat yields averaged more than three times the continuous-crop wheat yields. The fallow system had no complete crop failures, whereas the continuous wheat system had 6 out of 27 years with yields less than 100 kg ha^{-1}, and 15 out of 27 years with yields less than 1000 kg ha^{-1}. Tennant (1980) showed a similar increase in the probabilities of low crop yields in marginal areas of Western Australia with continuous cropping compared with fallowing.

There are, however, some drawbacks to fallowing that raise questions regarding its long-term sustainability. The necessity to control weeds may lead to excessive cultivation and the exposure of the soil to wind and water erosion. This risk, together with low storage efficiencies and development of suitable annual medic and clover species, has led to its demise in southern Australia (Tennant, 1980; Ridge, 1986). Also, the lower total production or periods of low production may reduce the organic matter in the soil, with detrimental effects on the water holding capacity, erosion susceptibility, and fertility of the soil (Jennings et al., 1990). However, the use of herbicides to control weeds can reduce erosion risks and reduce the detrimental effects of cultivation on soil organic matter.

We conclude that systems that supplement rainfall can be sustainable in the long term, but for long-term sustainability, the balance of water income to water outflow of the soil/crop system must be maintained. Irrigation management to prevent overwatering, soils impermeable to deep percolation, and crops that utilize water efficiently all contribute to long-term stability. Likewise, runon farming systems need to be carefully balanced to utilize all incoming rainfall without creating excesses in wet years or shortages and crop failure in dry years.

Infiltration

Unless a system of runoff/runon farming as described above is to be practiced, it is important in any sustainable agricultural system for the

water to quickly penetrate the soil and for runoff to be minimized. The infiltration of water into the soil will initially be affected by the soil slope and characteristics at the soil surface. However, subsurface characteristics that prevent water draining to deeper in the soil profile can also ultimately affect infiltration, so modifications to increase infiltration both at and below the soil surface will be discussed.

Anecdotal evidence of southwestern U.S. Indians disturbing crusts during periods between rains to increase infiltration probably constitutes an early example of soil surface modification. With conventional tillage (complete soil surface tillage), examples of techniques for rainfall capture and runoff prevention include contour farming, strip cropping, graded terraces, bench terraces, furrow-diking or tied ridges, basin tillage, basin listing, and microbasins (Lyle and Dixon, 1977; Jones and Clark, 1987), even though the initial objective for some of these may have been to reduce erosion (Unger et al., 1988; Jones et al., 1985).

Other approaches to increase infiltration retain residue on the surface by means of reduced tillage or conservation tillage practices (Laflen et al., 1978; West et al., 1991; Steiner, 1992). Mills et al. (1988) examined the probabilities of rainfall retention for several conventional and conservation tillage systems and showed that the median rainfall retention from six conservation tillage systems was 9% higher than that from four conventional tillage systems. Improvement in rainfall retention was attributed to a buildup of surface residue and improved soil tilth in the surface horizon, especially the protection of the surface from raindrop impact (Laflen et al., 1978).

Surface residues increase the ponding depth, which increases infiltration via the direct effect of increasing the time of ponding. However, a second, less direct effect of surface residue is its effect on the potential infiltration rate at the soil surface. Residues intercept rainfall, absorbing and dissipating impact energy. This transfer of energy reduces degradation of soil aggregates at the surface, which, in turn, reduces the sealing of the surface against infiltration. Residues also shade the soil surface, which reduces the surface temperature during periods of high evaporative demand.

Increased residue on the soil surface has also been associated with increased organic matter content of soils (Karlen et al., 1989) or altered distribution in the profile (Unger, 1991), thereby affecting infiltration. Typically, management to improve organic matter by changes in tillage practice causes relatively subtle effects. Therefore, long-term (~5- to 10-year) studies are normally required to distinguish differences, although Wood et al. (1991) were able to detect changes in 4 years after initiation of a no-till system. Blevins et al. (1977) found higher organic matter in the surface 50-mm layer of a no-till system after 5 years of continuous maize, while Juo and Lal (1979) observed elevated organic carbon in the

upper 100 mm of a tropical Alfisol under no-tillage after 6 years of continuous maize. The increased organic matter may affect infiltration in several ways. For example, organic matter can increase the water holding capacity of the soil, decrease its bulk density, increase its aggregate stability, and increase its cation exchange capacity (Hargrove et al., 1982; Klavidko et al., 1986; Bruce et al., 1987).

Little information exists to separate the effects of surface residues on rainfall capture from the effects of organic matter on infiltration. West et al. (1991) compared runoff and soil loss for conventional and no-till grain sorghum at three Piedmont sites. Under simulated rainfall at 60 mm for 1 hour, the runoff from the conventional-tilled sorghum was 10 mm, compared to 1 mm from no-till sorghum when the previous year's residue was left on the surface. When it was removed, the values were 19 and 5 mm, respectively. Thus, there appear to be benefits in terms of reducing runoff from both the retention of residues at the surface and the improvement of organic matter content and consequent aggregate stability of the soil (West et al., 1991).

Increased porosity of the soil and, in particular, increased macroporosity increase the infiltration of water into soils. As the southwestern U.S. Indians mentioned at the beginning of this section demonstrated, tillage is one of the primary methods employed to accomplish an increase in porosity. Mukhtar et al. (1985) reported infiltration rates varying from 1 to 30 min, depending on whether the soil was plowed in various ways or not tilled. The Paraplow®* (The Tye Co., Lockney, TX), which fractures the subsoil, induced infiltration rates about twice as high as the other treatments. While the primary objective of subsoiling is to create zones acceptable for rooting in lower horizons (Campbell et al. 1974; Doty and Reicosky, 1978), clearly the operations also increase infiltration. There are, however, other methods of increasing macroporosity that do not rely on tillage. For example, burrows of earthworms and other soil fauna provide channels for water infiltration.

Use of tillage to increase the infiltration of rainfall into the soil in the short term may have long-term negative effects. If loosening of the upper soil to increase infiltration comes at the expense of compaction below the tillage zone (Busscher et al., 1986), this can impede infiltration to lower storage zones and can induce a perched water table above the tillage pan. This, in turn, can increase the chance of waterlogging, thereby increasing runoff and decreasing infiltration. Indeed, cultivation may be detrimental to earthworm activity and lead to poorer infiltration and degradation (Abbott et al., 1979; Parker, 1989). Thus, systems that rely less heavily on tillage to increase infiltration have the greatest chance for long-term

*Tradenames are provided for the benefit of the reader, and use does not imply endorsement of the product by the USDA or CSIRO.

sustainability. Hence, there is interest in the use of earthworms and other soil macrofauna to increase the soil macroporosity and, thus, infiltration of rainfall.

SOIL WATER EVAPORATION

In mediterranean climatic regions, water loss by direct evaporation from the soil during the cropping season can represent 30 to 50% of the annual rainfall. This represents a significant loss of water that is potentially available for crop growth. Recent estimates of soil water evaporation under a crop indicate that the rate of soil water evaporation was 1 to 1.6 mm/d in crops of lupin with a leaf area index of 0.5 to 2.5 and a total crop evapotranspiration of 1.8 to 3.4 mm/d (Greenwood et al., 1992). These estimates compare favorably with other estimates of soil water evaporation, which suggest that beneath wheat and barley crops growing in mediterranean climatic zones, the soil water evaporation totals 60 to 120 mm per growing season in regions in which the rainfall is 200 to 500 mm per growing season (French and Schultz, 1984; Shepherd et al., 1987; Perry, 1987; Cooper et al., 1987a,b).

Decreasing water loss by soil water evaporation provides the potential for improved crop production on the same rainfall input, thereby maintaining sustainability as defined by Ruttan (1990). Selection of cultivars of wheat with rapid early growth (Turner and Nicolas, 1987; Whan et al.,1991; Regan et al., 1992) or use of higher plant densities and/or earlier dates of planting to increase early growth (Turner et al., 1987; Turner et al., 1993; Greenwood et al., 1992) are mechanisms for reducing soil water evaporation and increasing crop water use.

Residues and mulches provide a physical barrier to diffusion of water vapor from the soil surface and thus also act to conserve water for later use by the plant (Rosenberg et al., 1983; Steiner, 1992). Mulching has been practiced at least since the ancient Chinese and Romans put pebbles on the soil surface near plants (Unger, 1983). Layers of straw (Unger and Parker, 1976), gravel (Unger, 1971a,b), plastic (Willis et al., 1963), or other materials placed on or just below the surface have been proposed to reduce the rate of soil water evaporation. The addition of external materials, such as gravel or plastic, on the soil surface is generally, but not always, restricted to ornamentals, vegetables, or other high-value crops. The most economical mulch for large-area application is plant residue (standing or flattened) or dust created by tillage.

Willis et al. (1963) found that a plastic-covered ridge between maize rows suppressed soil water evaporation, resulting in higher water use in dry years and relatively higher yields in both wet and dry years. This gave a water use efficiency for grain 44 and 96% higher than the convention-

ally tilled control. Griffin et al. (1966) evaluated the effects of plastic film, asphalt film, and asphalt-covered paper mulches on grain sorghum yield and soil moisture. Under irrigated conditions, all these mulches reduced soil water evaporation and improved water use efficiency, even though yields were higher on the unmulched check. Unger (1971a,b) evaluated the effect of a 25-mm layer of gravel as a surface mulch on growth and water use of a hybrid forage sorghum. The gravel improved the water use efficiency at the first harvest, but not at subsequent harvests when the ground cover by the forage was greater.

When plant residues were used as a mulch, Unger and Parker (1976) found that wheat straw was twice as effective as sorghum residue and four times as effective as cotton residue. For any given material, increasing the amount of residue decreased the evaporation from the soil. Although one cannot partition the effects of decreased evaporation and increased infiltration, both Greb et al. (1967) and Unger (1978) found increased soil water storage levels of wheat residue during fallow. However, where there are frequent small showers, the mulch will intercept the rainfall and evaporation from the mulch will be as high as from the soil. A. P. Hamblin and D. Tennant (personal communication) showed that it required more than 4000 kg ha^{-1} of straw and heavy rainfall events before mulching gave increased soil water storage.

Irrigation placement will also have important effects on water use. Use of subsurface and microirrigation methods provides water to the plant without wetting the soil surface, thereby reducing soil water evaporation and allowing less water to be applied without reduced plant water use or yield reduction (Batchelor et al., 1990; Turner, 1990a).

A problem that has been observed in many regions of the world (Jamison, 1945; Letey et al., 1975; Wallis et al., 1990) and is causing increasing concern in southern Australia is the increased water repellency of the sandy-surfaced soils common in agricultural areas (Bond, 1964; Wetherby, 1984; McGhie and Tipping, 1990). The problem appears to be increasing with the increasing productivity of the region. The water repellency results in poor establishment of crops and pastures (Roberts, 1966; Osborn et al., 1967; Bond, 1972) and greater risk of wind and water erosion (Osborn et al., 1964; McGhie, 1980). One benefit of the increased water repellency is that if the soils are ridged at seeding, subsequent rainfall runs into the furrows under which the seed is sown. Recent studies suggest that with the ridging of nonwetting soils, soil water evaporation is reduced when the crops are small due to the smaller degree of evaporation from the dry soil ridges (Yang et al., 1993).

The reduction in soil water evaporation provides a mechanism for greater water use by agriculturally important crops provided they can capture the water not lost by soil water evaporation. There is, therefore,

the potential to make the system more sustainable by using water more efficiently in crop and pasture production.

MODIFICATION OF TRANSPIRATION

Transpiration for a given crop has been shown to be almost always directly proportional to dry matter production (de Wit, 1958; Fischer and Turner, 1978; Tanner and Sinclair, 1983), so reduced transpiration is generally not desirable for crop productivity and may be detrimental to sustainable agricultural practice. Indeed, the requirement in most agricultural systems is to match crop evapotranspiration with rainfall and to maximize the water use by the crop rather than losses by soil water evaporation and nonproductive losses of water via transpiration of weeds and barren plants. Matching crop water use to rainfall and irrigation supply is necessary for sustainable agricultural production.

The recent history in parts of southern Australia of clearing native vegetation for agriculture provides an example of lack of consideration of water use by crops and pastures leading to unsustainable production systems and land degradation. Replacement of deep-rooted perennial vegetation by shallow-rooted pastures and crops has led to rising water tables, waterlogging, and secondary salinization lower in the landscape (Figure 2), particularly in regions of southwestern Australia, in which the rainfall is less than 1100 mm and where cyclic salt occurs in the profile (Schofield et al., 1988). Figure 2 shows a generalized picture of the impact of clearing in regions of southwestern Australia where the annual rainfall is about 650 to 700 mm. Replacement of deep-rooted perennial native vegetation by annual pastures has resulted in the annual evapotranspiration falling by about 60 to 100 mm. This water percolates to the saline ground water table, causing it to rise, and resulting in waterlogging and salinization of lower parts of the landscape. While the reduction in evapotranspiration may increase the streamflow by about 60 mm, the increase in total soluble salts in the streamflow from 100 mg l^{-1} to 5500 mg l^{-1} reduces the potability of the water. The data in Figure 2 are taken from studies in Western Australia. Greenwood et al. (1981, 1985) and Sharma et al. (1991) showed that the water use by pastures was considerably lower than water use by native vegetation or pines, leading to an additional 20 to 50 mm of rainfall percolating beneath the root zone to ground water annually (Nulsen and Baxter, 1982). Replacement of part of the catchment to evergreen trees is currently being employed to reverse land degradation from secondary salinization and to reduce the salinity of streams and water catchments in the region (Schofield et al., 1989; Schofield and Scott, 1991).

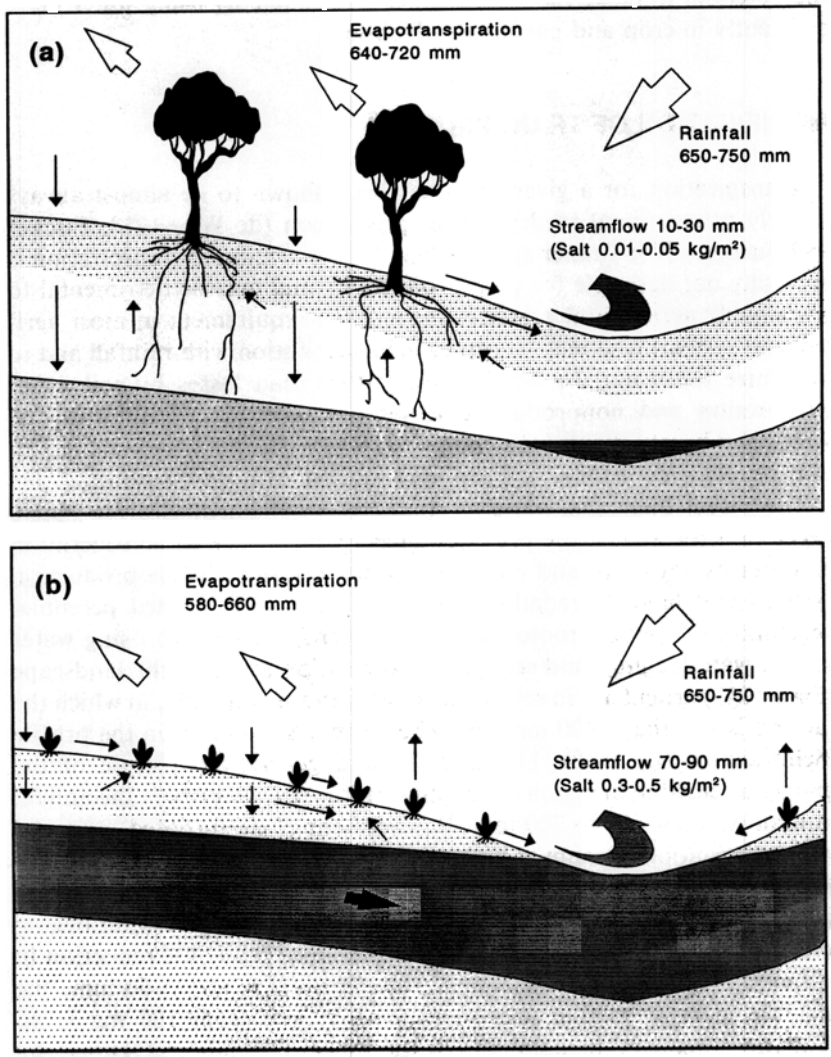

FIGURE 2. The effect of land clearing on the water balance of a forested catchment in a region where the annual average rainfall is 650 to 750 mm. In (a) the vegetation utilizes most of the incoming rainfall resulting in a streamflow of 10 to 30 mm/year and with a low salt concentration. In (b) the vegetation uses less of the annual rainfall resulting in more streamflow with a greater annual output of salt from that stored in the soil profile.

An alternative or complementary solution to the problem is to increase the water use by the crops and pastures in such catchments. Early sowing, use of higher planting densities, use of fertilizers to stimulate early growth, and selection of cultivars with high early growth are all methods that can increase crop water use early in the season leading to potentially higher yields in water-limited environments (Turner and Nicolas, 1987; Shepherd et al., 1987; Whan et al., 1991; Turner et al., 1993) and decrease the flow to the water table, thereby reducing the potential for land degradation (Greenwood et al., 1991).

SOIL STORAGE INCREASERS

Management to increase soil water storage has been discussed above in that all reductions of losses result in increased soil water storage and, therefore, increased water available for evapotranspiration. However, some management techniques act to increase the capacity of the soil to store water, regardless of whether there is more water to store. Storage capacity here is meant to be capacity to store water that will later be available to plants.

One traditional method to increase storage capacity has been to increase the volume of soil suitable for rooting. Subsoiling (Campbell et al., 1974; Doty and Reicosky, 1978), deep tillage (Karlen et al., 1992), the use of gypsum to produce stable aggregates (Blackwell et al., 1991a,b), and breeding programs that select for stronger rooting cultivars (Turner and Nicholas, 1987; Kasperbauer and Busscher, 1991) all act in this manner. Where such methods increase water penetration, root growth, and water use by the crop, they will have a major impact on sustainability.

A second method that acts to increase capacity of storage does so not by increasing volume, but increasing the capacity to store water in a unit volume of soil. Addition of organic matter or other soil amendments should increase the available water holding capacity. This concept receives enthusiastic support in the popular press (e.g., Kendall, 1988). However, the effects may be subtle. Anderson et al. (1990) were able to detect increases in saturated hydraulic conductivity after 100 years of manure additions, but the effect on water retention was not consistent across cropping systems. Unger and Fulton (1990) compared soil properties among a conventional tillage system and two no-till systems that had been in place for 6 and 8 years, respectively. Organic matter concentrations at the 0.04- to 0.07-m depth were, surprisingly, lower in the no-till than in the conventional system. This was attributed to mixing of surface organic matter in the conventional system, whereas the no-till systems had organic matter distributed more toward the surface. Mean weight diameter of water-stable aggregates presents mixed results, with the

conventional system the same as the younger no-till system, and the older no-till system higher than both. For the 0.04- to 0.07-m depth, the water retention curve for both no-till systems was higher than the conventional at saturation, and higher at 4.89 kPa tension for the older no-till system. None of the intermediate tensions and none of the values for the 0.14- to 0.17-m depth were different. Bulk density at the 0.04- to 0.07-m depth was lower for the no-till systems and unchanged from the conventional system for the 0.14- to 0.17-m depth.

Mixing the surface and subsurface soils has been attempted for soils in which a sandy surface layer overlies a clayey subsoil (Miller and Aarstad, 1972; Campbell et al. 1988), in the hope that the retention curve for the composite soil might be superior to that for the sandy surface layer. On a southeastern U.S. typic Paleudult, the result was a sand-clay mix that cemented during dry periods (W. J. Busscher, personal communication). Results for deeper soils suggest that sustained improvements can be made. Chaudhary et al. (1985) found that mixing the surface 0.45-m layer of a coarse-textured soil reduced bulk density, reduced penetration resistance at the 0.2- to 0.4-m depth, and increased maize yields 70 to 350%, even though there were no root-limiting layers in the soil prior to mixing. Measurements made 21 years after mixing a Pullman clay loam to 0.9- or 1.5-m depth (Eck, 1986) indicated that mixing still affected infiltration rate and bulk density. Yield responses were mixed, and Eck (1986) concluded that the benefits did not exceed the cost of mixing.

PERCOLATION REDUCERS

Compaction of the subsoil and placement of relatively impervious materials at depth are methods used to reduce percolation (e.g., Erickson et al., 1968; Robertson et. al., 1973). This may increase sustainability in situations where deep drainage is a problem, such as with irrigated rice cultivation in the New South Wales region of Australia. There, deep percolation of water from rice growing has caused saline water to flow back into the Murray River downstream from the irrigation district. Compaction of the subsoil, as is common in flooded rice culture in Asia, may help to reduce deep percolation (De Datta and Kerim 1974; Saroch and Thakur, 1991) and to increase sustainability.

However, use of artificial barriers to water movement through the soil has been less successful. Willis et al. (1963) tested plastic buried at the 0.2-m depth as well as testing the surface plastic mulches discussed above. Neither a buried ridge nor slanted plastic surface performed as well as the ridged surface with 90% plastic cover in terms of crop growth and water use.

Soil and crop management to reduce the likelihood of wet soil conditions can also reduce the risk of deep percolation or runoff on intersoil layers. Establishment of deeper-rooting crops can reduce percolation by lowering the water content in the subsoil (Unger et al., 1988) and by allowing water to penetrate the clay subsoil in duplex soils in Australia. However, the success of management practices to decrease percolation is strongly dependent on soil type. For instance, conservation bench terraces on a fine sandy loam in Woodward, OK (Armbrust and Welch, 1966) had more percolation than similar terraces on a clay loam in Bushland, TX (Unger, 1983). The lower water holding capacity and higher rainfall in Woodward combined to increase the loss to percolation.

Management of irrigation to avoid overwatering is an important method of reducing deep percolation in many soils. Irrigators frequently overwater, particularly where water is cheap and plentiful and the benefits from irrigation are large. This has led to the problems of salinization and land degradation from irrigation discussed above. Regulated deficit irrigation can not only lead to less deep percolation of water and hence less land degradation, but also can improve crop and pasture production (Turner, 1990a,b) as well as horticultural production and management (Chalmers et al., 1981; Mitchell et al., 1989; English et al., 1990).

OPPORTUNISTIC CROPPING

There remains one class of management tools that can be used to increase sustainability, primarily by conserving water or by increasing beneficial use of water. These techniques share the characteristic that the farmer must adapt not only to soil characteristics and average climates, but must remain sufficiently flexible to adapt his farming enterprise to utilize unusual rainfall events. Bond et al. (1964) reported that yields could be increased in Bushland, TX, by reducing row width from 1.01 to 0.51 m (increasing population from about 45,000 to 90,000 plants ha^{-1}) only if the initial soil water content (0 to 2 m) was above 150 mm. Unger et al. (1988) reported that opportunistic farmers could evaluate soil water conditions at wheat harvest, and plan accordingly. If sufficient moisture existed, they should plant sorghum in a double-crop sequence. If not, they could defer the decision until it is time to plant wheat. With sufficient autumn rains, they could then plant wheat. If not, they should defer planting until the next summer. Flexibility to implement such decisions may not be available to all farmers because of residual herbicides, farm programs, or restrictions by landlords or lenders. In spite of these potential limitations, the potential appears high for increasing total production per unit water.

Another, similar technique is termed "response farming" (Stewart, J. I., 1988). Here, the probable seasonal rainfall is inferred from the timing of the onset of monsoon rains. With an early onset, decisions are made that make use of the likely higher rainfall, and for late onset, decisions are made that increase the chance of surviving the likely lower rainfall. A final example of dynamic management is limited-irrigation dryland farming (Stewart et al., 1983; Stewart, B. A., 1988). Here, the extent of irrigation in a furrow-irrigated field depends upon the rainfall; if more rain falls, the irrigated area is extended because less irrigation is needed per unit land area. This extension can be achieved by adjusting seeding densities and fertility down the field. Alternate furrows are diked or used for irrigation. The upper one half of the field is irrigated normally. The lower one half uses a lower planting density, and the first half of this (the 3rd quarter of the field) is irrigated by tailwater from the upper half. The lower quarter of the field is normally dryland, but if rain follows an irrigation, the runoff from the upper area will reach this zone. The system maximizes production per unit of water for systems with fixed water supplies, whether fixed by physical or regulatory limitations, and reduces the risk of waterlogging and loss of excess water. The fact that crops can withstand extraction of 50 to 60% of the water in the root zone without detrimental effects on yield (Ritchie, 1981; Turner et al., 1986; Turner 1990a) can be used to irrigate larger areas where water supply is limited (Hearn and Constable, 1981, 1984).

The dynamic management techniques listed above accomplish several things relative to water use that pertain directly to sustainability. First, they decrease the chance of crop failure (as can a rotation with fallow), yet they take advantage of the better years, in which rainfall is sufficient for continuous or even double cropping. Moreover, in good years they do not waste the rain that happens to fall during a fallow period.

SUMMARY

We have tried to develop the hypothesis that for agriculture to be sustainable and productive, crop water use must balance water available from rainfall, irrigation, and soil storage. Both crop and soil management strategies are available to enable this balance to be achieved. Where farm management systems have not taken water use into consideration and imbalances have occurred, land degradation has often ensued by soil erosion, waterlogging, and salinization.

Moving toward sustainability is an important goal for agriculture. Historical examples suggest that agricultural systems can be sustainable in the long term if water is managed wisely. History also shows that sustainable production can decline even in systems that initially appeared sustainable. Agriculture will need to be responsive to declines in sustaina-

bility in order to avoid land and water degradation. Recent examples of increased fertilizer and pesticide use resulting in contamination of ground water, streams, and lakes indicate areas where new technologies and farming systems need to be developed. Likewise, the clearing of native vegetation that leads to secondary salinization and waterlogging lower in the landscape is being reversed by strategic use of evergreen trees, perennial pastures, and better management of the annual crops and pastures to increase water use. Thus we conclude that management of water to match supply with demand is important for sustainable agricultural production. Nevertheless, subtle changes in climate and increased climatic variability may make currently sustainable practices unsustainable in the future. Being able to predict and adapt to these changes will be an important component of future crop production.

REFERENCES

Abbott, I., C. A. Parker, and I. D. Sills. 1979. Changes in abundance of large soil animals and physical properties of soils following cultivation. *Aust. J. Soil Res.* 17:343–353.

Adams, R. M., C. Rosenzweig, R. M. Peart, J. T. Ritchie, B. A. McCarl, J. D. Glyer, R. B. Curry, J. W. Jones, K. J. Boote, and L. H. Allen, Jr. Global climate change and U.S. agriculture. *Nature.* 345(6272):219–224.

Alexandratos, N. 1988. *World Agriculture: Toward 2000—An FAO Study.* Food and Agriculture Organization, Rome.

Anderson, S. H., C. J. Gantzer, and J. R. Brown. 1990. Soil physical properties after 100 years of continuous cultivation. *J. Soil Water Conserv.* 45(1):117–121.

Armbrust, D. V. and N. H. Welch. 1966. Evaluation of Zingg conservation bench terraces on Amarillo fine sandy loam soil. *J. Soil Water Conserv.* 21:224–226.

Batchelor, C. K., G. C. Soopramanien, J. P. Bell, R. Nagamuth, and M. G. Hodnett. 1990. Importance of irrigation regime, dripline placement, and row spacing in the drip irrigation of sugar cane. *Agric. Water Manage.* 17:59–73.

Blackwell, P. S., N. S. Jagawardane, T. W. Green, J. T. Wood, J. Blackwell, and H. J. Beatty. 1991a. Subsoil macropore space of a transitional red-brown earth after either deep tillage, gypsum, or both. I. Physical effects and short term changes. *Aus. J. Soil Res.* 29:123–140.

Blackwell, P. S., N. S. Jagawardane, T. W. Green, J. T. Wood, J. Blackwell, and H. J. Beatty. 1991b. Subsoil macropore space of a transitional red-brown earth after either deep tillage, gypsum, or both: II. Chemical effects and long-term changes. *Aus. J. Soil Res.* 29:141–154.

Blevins, R. L., G. W. Thomas, and P. L. Cornelius. 1977. Influence of no-tillage and nitrogen fertilization on certain soil properties after 5 years of continuous corn. *Agron. J.* 69:383–386.

Bond, J. J., T. J. Army, and O. R. Lehman. 1964. Row spacing, plant populations, and moisture supply as factors in dryland grain sorghum production. *Agron. J.* 56:3–6.

Bond, R. D. 1964. The influence of microflora on the physical properties of soil: II. Field studies on water repellant sands. *Aus. J. Soil Res.* 2:123–131.

Bond, R. D. 1972. Germination and yield of barley when grown in a water-repellant sand. *Agron. J.* 64:402–403.

Browman, D. L. 1983. Tectonic movement and agrarian collapse in prehispanic Peru. *Nature.* 302:568–569.

Bruce, R. R., S. R. Wilkinson, and G. W. Langdale. 1987. Legume effects on soil erosion and productivity. In: *The Role of Legumes in Conservation Tillage Systems.* J. F. Power, Ed. Soil Conservation Society of America, Ankeny, IA. pp. 127–138.

Busscher, W. J., R. E. Sojka, and C. W. Doty. 1986. Residual effects of tillage in Coastal Plain soils. *Soil Sci.* 141(2):144–148.

Campbell, R. B., D. C. Reicosky, and C. W. Doty. 1974. Physical properties and tillage of paleudults in the southeastern coastal plains. *J. Soil Water Conserv.* 29:5.

Campbell, R. B., W. J. Busscher, O. W. Beale, and R. E. Sojka. 1988. Soil profile modification and cotton production. Proc. Beltwide Cotton Prod. Res. Conf., January 3 to 8, New Orleans, LA. National Cotton Council of America, Memphis, TN.

Chalmers, D. J., P. D. Mitchell, and L. van Heek. 1981. Control of peach tree growth and productivity by regulated water supply, tree density, and summer pruning. *J. Am. Soc. Hortic. Sci.* 106:307–312.

Chaudhary, M. R., P. R. Gajri, S. S. Prihar, and R. Khera. 1985. Effect of deep tillage on soil physical properties and maize yields on coarse-textured soils. *Soil Tillage Res.* 6:31–44.

Chen, A. 1987. Unraveling another Mayan mystery. *Discover.* June:40–49.

Cooper, P. J. M., P. J. Gregory, J. D. H. Keatinge, and S. C. Brown. 1987a. Effects of fertilizer variety and location on barley production under rainfed conditions in Northern Syria. II. Soil water dynamics and crop water use. *Field Crops Res.* 16:67–84.

Cooper, P. J. M., P. J. Gregory, D. Tully, and H. C. Harris. 1987b. Improving water use efficiency of annual crops in the rainfed farming systems of west Asia and north Africa. *Exp. Agric.* 23:113–158.

De Datta, S. K. and M. S. Kerim. 1974. Water and nitrogen economy of rainfed rice as affected by soil puddling. *Soil Sci. Soc. Am. Proc.* 38:515–518.

de Wit, C. T. 1958. Transpiration and Crop Yields. Agric. Res. Rep. No. 646. Wageningen, The Netherlands.

Doty, C. W., R. B. Campbell, and D. C. Reicosky. 1975. Crop response to chiseling and irrigation in soils with a compact A2 horizon. *Trans. ASAE.* 18(4):668–672.

Doty, C. W., J. E. Parsons, A. W. Badr, A. Nassehzadeh-Tabrizi, and R. W. Skaggs. 1985. Water table control for water resource projects on sandy soils. *J. Soil Water Conserv.* 40(4):360–364.

Doty, C. W., J. E. Parsons, A. Nassehzadeh-Tabrizi, R. W. Skaggs, and A. W. Badr. 1984a. Stream water levels affect field water tables and corn yields. *Trans. ASAE.* 27(5):1300–1306.

Doty, C. W., J. E. Parsons, and R. W. Skaggs. 1987. Irrigation water supplied by stream water level control. *Trans. ASAE.* 30(4):1065–1070.

Doty, C. W. and D. C. Reicosky. 1978. Chiseling to minimize the effects of drought. *Trans. ASAE.* 21(3):495–499.

Doty, C. W., W. B. Thayer, and R. G. Jessup. 1984b. Automated fabric dam aids water research project. In: *Proc. Int. Conf. Geomembranes 2C 127,* Denver, CO. p. 132.

Eck, H. V. 1986. Profile modification and irrigation effects on yield and water use of wheat. *J. Soil Sci. Soc. Am.* 50:724–729.

English, M. J., J. T. Musick, and V. V. Murty. 1990. Deficit irrigation. In: *Management of Farm Irrigation Systems.* G. J. Hoffman, T. A. Howell, and K. H. Solomon, Eds. American Society of Agricultural Engineers, St. Joseph, MI. p. 631–663.

Erickson, A. E., C. M. Hansen, and A. J. M. Smucker. 1968. The influence of subsurface asphalt barriers on the water properties and the productivity of sandy soil. In: *Trans. 9th Int. Congr. Soil Sci.* Elsevier, New York. pp. 331–337.

Evenari, M., L. Shanan, and N. Tadmor. 1982. *The Negev—The Challenge of a Desert.* Harvard University Press. Cambridge, MA.

Fillery, I. R. and P. J. Gregory. 1991. Defining research goals and priorities for sustainable dryland farming. In: *The Nature and Dynamics of Dryland Farming Systems—An Analysis of Dryland Agriculture in Australia.* V. R. Squires and P. Tow, Eds. Sydney University Press, Sydney, Australia. p. 162–168.

Fischer, R. A. and N. C. Turner. 1978. Plant productivity in the arid and semiarid zones. *Annu. Rev. Plant Physiol.* 29:277–317.

French, R. J. 1978a. The effect of fallowing on the yield of wheat. I. The effect of soil water storage and nitrate supply. *Aust. J. Agric. Res.* 29:653–666.

French, R. J. 1978b. The effect of fallowing on the yield of wheat. II. The effect on grain yield. *Aus. J. Agric. Res.* 29:666–684.

French, R. J. and J. E. Schultz. 1984. Water use efficiency of wheat in a mediterranean-type environment. I. The relation between yield, water use, and climate. *Aust. J. Agric. Res.* 35:743–764.

Greb, B. W., D. E. Smika, and A. L. Black. 1967. Effect of straw mulch rates on soil water storage during summer fallow in the Great Plains. *Soil Sci. Soc. Am. Proc.* 31:556–559.

Greenwood, E. A. N., N. J. Beresford, and J. R. Bartle. 1981. Evaporation from vegetation in landscapes developing secondary salinity using the ventilated chamber technique. III. Evaporation from a *Pinus radiata* tree and surrounding pasture in an agroforestry plantation. *J. Hydrol.* 50:155–166.

Greenwood, E. A. N., L. Klein, J. D. Beresford, and G. D. Watson. 1985. Differences in annual evaporation between grazed pasture and *Eucalyptus* species in plantations on a saline farm catchment. *J. Hydrol.* 78:261–278.

Greenwood, E. A. N., N. C. Turner, E.-D. Schulze, G. D. Watson, and N. R. Venn. 1992. Groundwater management through increased water use by lupin crops. *J. Hydrol.* 134:1–11.

Griffin, R. H., B. J. Ott, and J. F. Stone. 1966. Effect of water management and surface applied barriers on yield and moisture utilization of grain sorghum in the southern great plains. *Agron. J.* 58:449–452.

Gutentag, E. D., F. J. Heimes, N. C. Krothe, R. R. Luckey, and J. B. Weeks. 1984. Geohydrology of the high plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. *U.S. Geol. Surv. Prof. Pap.*, No. 1400-B.

Hargrove, W. L., J. T. Reid, J. T. Touchton, and R. N. Gallaher. 1982. Influence of tillage practices on the fertility status of an acid soil double-cropped to wheat and soybeans. *Agron. J.* 74:684–687.

Hauser, V. L. 1968. Conservation bench terraces in Texas. *Trans. ASAE.* 11:385–386, 392.

Hearn, A. B. and G. A. Constable. 1981. Irrigation for crops in a semi-humid environment. I. Stress day analysis for soybeans and an economic evaluation of strategies. *Irrig. Sci.* 3:1–15.

Hearn, A. B. and G. A. Constable. 1984. Irrigation for crops in a semi-humid environment: VII. Evaluation of irrigation strategies for cotton. *Irrig. Sci.* 5:75–94.

Hillel, D. 1982. *Negev—Land, Water, and Life in a Desert Environment.* Praeger, New York.

Jamison, V. C. 1945. The penetration of irrigation and rain water into sandy soils of central Florida. *Soil Sci. Soc. Am. Proc.* 10:25–29.

Jennings, M. D., B. C. Miller, D. F. Bezdicek, and D. Granatstein. 1990. Sustainability of dryland cropping in the Palouse: An historical view. *J. Soil Water Conserv.* 45(1):75–80.

Jones, O. R. 1975. Yields and water-use efficiencies of dryland winter wheat and grain sorghum production systems in the southern high plains. *Soil Science Soc. of America Proc.* 39:98–103.

Jones, O. R. 1981. Land forming effects on dryland sorghum production in the southern Great Plains. *J. Soil Sci. Soc. Am.* 45:606–611.

Jones, O. R. and R. N. Clark. 1987. Effects of furrow dikes on water conservation and dryland crop yields. *J. Soil Sci. Soc. Am.* 51(5):1307–1314.

Jones, O. R., H. V. Eck, S. J. Smith, G. A. Coleman, and V. L. Hauser. 1985. Runoff, soil, and nutrient losses from rangeland and dry-farmed cropland in the Southern High Plains. *J. Soil Water Conserv.* 40(1):161–164.

Juo, A. S. and R. Lal. 1979. Nutrient profile in a tropical Alfisol under conventional and no-till systems. *Soil Sci.* 127(3):168–173.

Karlen, D. L., W. R. Berti, P. G. Hunt, and T. A. Matheny. 1989. Soil-test values after eight years of tillage research on a Norfolk loamy sand. *Commun. Soil Sci. Plant Anal.* 20:1413–1426.

Karlen, D. L., W. J. Busscher, S. A. Hale, R. B. Dodd, E. E. Strickland, and T. H. Garner. 1992. Conservation tillage implement effects on energy use and soil strength, *Trans. ASAE.* 34(5):1967–1972.

Kasperbauer, M. J. and W. J. Busscher. 1991. Genotypic differences in cotton root penetration of a compacted subsoil layer. *Crop Sci.* 31:1376–1378.

Kendall, D. 1988. Good soil eases drought worries. *The New Farm.* 10(7):44–47.

Kladivko, E. J., D. R. Griffith, and J. V. Mannering. 1986. Conservation tillage effects on soil properties and yield of corn and soya bean in Indiana. *Soil Tillage Res.* 8:277–287.

Laflen, J. M., J. L. Baker, R. O. Hartwig, W. F. Buchele, and H. P. Johnson. 1978. Soil and water loss from conservation tillage systems. *Trans. ASAE.* 21(5):881–885.

Lavake, D. E. and A. F. Weise. 1979. Influence of weed growth and tillage interval during fallow on water storage, soil nitrates, and yield. *J. Soil Sci. Soc. Am.* 43:565–569.

Letey, J., J. F. Osborn, and N. Valoras. 1975. Soil water repellancy and the use of nonionic surfactants. Tech. Rep. 154, California Water Resource Center. University of California, Davis, CA.

Lyle, W. M. and D. R. Dixon. 1977. Basin tillage for rainfall retention. *Trans. ASAE.* 20(6):1013–1017, 1021.

Mathews, O. R. and T. J. Army. 1960. Moisture storage on fallowed wheatland in the Great Plains. *Soil Sci. Soc. Am. Proc.* 24:414–418.

McGhie, D. A. 1980. The contribution of the Mallet Hill surface to runoff and erosion in the Narrogin region of Western Australia. *Aust. J. Soil Res.* 18:299–307.

McGhie, D. and P. Tipping. 1990. *The Alleviation of Water Repellance in Soils.* Western Australian Department of Agriculture, South Perth.

Miller, D. E. and J. S. Aarstad. 1972. Effect of deep plowing on the physical characteristics of Hezel soil. *Wash. Agric. Exp. Stn. Circ.*, No. 556. Washington State University, Pullman, WA.

Mills, W. C., A. W. Thomas, and G. W. Langdale. 1988. Rainfall retention probabilities computed for different cropping-tillage systems. *Agric. Water Manage.* 15:61–71.

Minc, L. D. and J. H. Vandermeer. 1990. Origin and spread of agriculture. In: *Agroecology.* C. R. Carroll, J. H. Vandermeer, and P. Rosset, Eds., McGraw-Hill, New York. p. 65–111.

Mitchell, P. D., B. van den Ende, P. H. Jerie, and D. J. Chalmers. 1989. Responses of 'Bartlett' pear to withholding irrigation, regulated deficit irrigation, and tree spacing. *J. Am. Soc. Hortic. Sci.* 114:15–19.

Mukhtar, S., J. L. Baker, R. Horton, and D. C. Erbach. 1985. Soil water infiltration as affected by the use of the Paraplow. *Trans. ASAE.* 28(6):1811–1816.

Nulsen, R. A. and I. N. Baxter. 1982. The potential of agronomic manipulation for controlling salinity in Western Australia. *J. Aust. Inst. Agric. Sci.* 48:222–226.

Ortloff, C. R. 1988. Canal builders of Pre-Inca Peru. *Sci. Am.* December:100–107.

Osborn, J. F., J. Letey, L. F. DeBano, and E. Terry. 1967. Seed germination and establishment as affected by non-wettable soil and wetting agents. *Ecology.* 48:494–497.

Osborn, J. F., R. E. Pelishek, J. S. Krammes, and J. Letey. 1964. Soil wettability as a factor in erodibility. *Soil Sci. Soc. Am. Proc.* 28:294–295.

Parker, C. A. 1989. Soil biota and plants in the rehabilitation of degraded agricultural soils. In: *Animals in Primary Succession—The Role of Fauna in Reclaimed Lands.* J. D. Majer, Ed. Cambridge University Press, Cambridge, UK. pp. 423–438.

Perry, M. W. 1987. Water use efficiency of non-irrigated field crops. In: Proc. the 4th Aust. Agron. Conf., Melbourne. August. pp. 83–99.

Pittock, A. B. 1988. Actual and anticipated changes in Australia's climate. In: *Greenhouse—Planning for Climate Change*. G. I. Pearman, Ed. E. J. Brill, Leiden. pp. 35–51.

Ponting, C. 1990. Historical perspectives on sustainable development. *Environment*. 32(9):4–9, 31–33.

Regan, K. L., K. H. M. Siddique, N. C. Turner, and B. R. Whan. 1992. Potential for increasing early vigour and total biomass in spring wheat. II. Characteristics associated with early vigour. *Aust. J. Agric. Res.* 43(3):541–553.

Reicosky, D. C., R. B. Campbell, and C. W. Doty. 1976. Corn plant water stress as influenced by chiseling, irrigation, and water table depth. *Agron. J.* 68:499–503.

Reisner, M. 1986. *Cadillac Desert: The American West and Its Disappearing Water*. Viking Penguin, New York.

Ridge, P. E. 1986. A review of long fallows for dryland wheat production in southern Australia. *J. Aust. Inst. Agric. Sci.* 52:37–44.

Ritchie, J. T. 1981. Water dynamics in the soil-plant-atmosphere system. *Plant Soil*. 58:81–96.

Roberts, F. J. 1966. The effects of sand type and fine particle amendments on the emergence and growth of subterranean clover with particular reference to water relations. *Aust. J. Agric. Res.* 17:657–672.

Robertson, W. K., L. C. Hammond, G. K. Saxena, and H. W. Lundy. 1973. Influence of water management through irrigation and a subsurface asphalt layer on seasonal growth and nutrient uptake of corn. *Agron. J.* 65:866–870.

Rosenberg, N. J., B. L. Blad, and S. B. Verma. 1983. *Microclimate: The Biological Environment*. John Wiley & Sons, New York.

Ruttan, V. W. 1990. 'Alternative Agriculture' sustainability is not enough. In: *'Alternative Agriculture' Scientists' Review*. Spec. Pub. No. 16. Council for Agricultural Science and Technology, Ames, IA. pp. 130–134.

Saroch, K. and R. C. Thakur. 1991. Effect of puddling (wet tillage) on rice yield and physico-chemical properties of soil. *Soil Tillage Res.* 21:147–157.

Schofield, N. J. and P. R. Scott. 1991. Planting trees to control salinity. *West Aust. J. Agric.* 32:3–10.

Schofield, N. J., I. C. Loh, P. R. Scott, J. R. Bartle, P. Ritson, R. W. Bell, H. Borg, B. Anson, and R. Moore. 1989. Vegetation strategies to reduce stream salinities of water resource catchments in south-west Western Australia. Rep. WS 33, Water Authority of Western Australia. Leederville, Western Australia.

Schofield, N. J., J. K. Ruprecht, and I. C. Loh. 1988. The impact of agricultural development on the salinity of surface water resources of southwest Western Australia. Rep. WS 27, Water Authority of Western Australia. Leederville, Western Australia.

Schultz, J. E. 1971. Soil water changes under fallow crop treatments in relation to soil type, rainfall, and yield of wheat. *Aust. J. Exp. Agric. Anim. Husbandry*. 6:425–431.

Seery, D. 1990. Navajos grow corn as their elders did. *Soil Water Conserv. News*. 11(3):12.

Sharma, M. L., R. J. Barron, and A. B. Craig. 1991. Land use effects on groundwater recharge to an unconfined aquifer. Div. Rep. 91/1, CSIRO Division of Water Resources. Wembley, Western Australia.

Shepherd, K. D., P. J. M. Cooper, A. Y. Allan, D. S. H. Drennan, and J. D. H. Keatinge. 1987. Growth, water use, and yield of barley in Mediterranean-type environments. *J. Agric. Sci.* 108:365-378.

Smika. D. E. 1970. Summer fallow for dryland winter wheat in the semiarid Great Plains. *Agron. J.* 62(1):15-17.

Steiner, J. L. 1992. Crop residue effects on water conservation. In: *Managing Agricultural Residues*. Unger, P. W., Ed. CRC Press, Boca Raton, FL.

Stewart, B. A. 1988. Dryland farming: the North American experience. In: *Challenges in Dryland Agriculture: a Global Perspective*. P. W. Unger, W. R. Jordan, T. V. Sneed, and R. W. Jensen, Eds. Proc. Int. Conf. Dryland Farming. August 15 to 19, Amarillo/Bushland, TX. pp. 54-59.

Stewart, B. A., J. T. Musick, and D. A. Dusek. 1983. Yield and water use efficiency of grain sorghum in a limited irrigated-dryland farming system. *Agron. J.* 75:629-634.

Stewart, J. I. 1988. Risk analysis and response farming. In: *Challenges in Dryland Agriculture: a Global Perspective*. P. W. Unger, W. R. Jordan, T. V. Sneed, and R. W. Jensen, Eds. Proc. Int. Conf. Dryland Farming. August 15 to 19, Amarillo/Bushland, TX. pp. 322-324.

Tanner, C. B. and T. R. Sinclair. 1983. Efficient water use in crop production: research or re-search? In: *Limitations to Efficient Water Use in Crop Production*. H. M. Taylor, W. R. Jordan, and T. R. Sinclair, Eds. Agron. Monogr. American Society of Agronomy, Madison, WI. pp. 1-27.

Tennant, D. 1980. Effect of fallowing on cereal yields. *West Aust. J. Agric.* 21:38-41.

Turner, B. L. and P. D. Harrison. 1981. Prehistoric raised-field agriculture in the Maya lowlands. *Science*. 213:399-405.

Turner, N. C. 1990a. Plant water relations and irrigation management. *Agric. Water Manage*. 17:59-73.

Turner, N. C. 1990b. The benefits of water deficits. In: *Proc. Int. Congr. Plant Physiol.* S. K. Sinha, P. V. Sane, S. C. Bargava, and P. K. Agrawal, Eds. Society for Plant Physiology and Biochemistry, New Delhi. pp. 806-815.

Turner, N. C., A. B. Hearn, J. E. Begg, and G. A. Constable. 1986. Cotton (*Gossypium hirsutum* L): physiological responses to water deficits and their relationships to yield. *Field Crops Res.* 14:153-170.

Turner, N. C. and M. E. Nicolas. 1987. Drought resistance of wheat for light-textured soils in a mediterranean climate. In: *Drought Tolerance in Winter Cereals*. J. P. Srivastava, E. Porceddu, E. Acevedo, and S. Varma, Eds. John Wiley, Chichester, U.K. pp. 203-216.

Turner, N. C., P. Prasertak, and T. L. Setter. 1994. Influence of plant spacing and planting density on wheat subjected to post-anthesis water deficits. *Crop Sci.* In press.

Turner, N. C., D. Tennant, A. P. Hamblin, I. E. Henson, C. R. Jensen, and M. W. Perry. 1987. Influence of nitrogen on the yield water use and water deficits of wheat grown in a mediterranean climate. *Proc. 4th Aust. Agron. Conf.* Melbourne. August. 254 pp.

Unger, P. W. 1968. Soil organic matter and nitrogen changes during 24 years of dryland wheat tillage and cropping practices. *Soil Sci. Soc. Am. Proc.* 32:427–429.

Unger, P. W. 1971a. Soil profile gravel layers. I. Effect on water storage, distribution, and evaporation. *Soil Sci. Soc. Am. Proc.* 35:631–634.

Unger, P. W. 1971b. Soil profile gravel layers. II. Effect on growth and water use by a hybrid forage sorghum. *Soil Sci. Soc. Am. Proc.* 35:980–983.

Unger, P. W. 1978. Straw-mulch rate effect on soil water storage and sorghum yield. *Soil Sci. Soc. of Am. J.* 42:486–491.

Unger, P. W. 1983. Water conservation: Southern Great Plains. In: *Dryland Agriculture*. Agron. Monogr. American Society of Agronomy, Madison, WI. pp. 35–55.

Unger, P. W. 1991. Organic matter, nutrient, and pH distribution in no- and conventional-tillage semiarid soils. *Agron. J.* 83:186–189.

Unger, P. W. and L. J. Fulton. 1990. Conventional- and no-tillage effects on upper root zone soil conditions. *Soil Tillage Res.* 16:337–344.

Unger, P. W., O. R. Jones, and J. L. Steiner. 1988. Principles of crop and soil management procedures for maximizing production per unit rainfall. In: *Drought Research Priorities for the Dryland Tropics*. F. R. Bidinger and C. Johansen, Eds. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Center, Patancheru, India.

Unger, P. W. and J. J. Parker. 1976. Evaporation reduction from soil with wheat, sorghum, and cotton residues. *Soil Sci. Soc. Am. Proc.* 40:938–942.

Wallis, M. G., D. J. Horn, and K. W. McAuliffe. 1990. A study of water repellancy and its amelioration in a yellow-brown sand. I. Severity of water repellancy and the effects on wetting and abrasion. *N. Z. J. Agric. Res.* 33:139–144.

Weeks, J. B. and E. D. Gutentag. 1984. High plains regional aquifer—Geohydrology. In: *Proc. Ogallala Aquifer Symp. II*, Lubbock, TX. p. 6.

West, L. T., W. P. Miller, G. W. Langdale, R. R. Bruce, J. M. Laflen, and A. W. Thomas. 1991. Cropping system effects on interrill soil loss in the Georgia Piedmont. *J. Soil Sci. Soc. Am.* 55:460–466.

Wetherby, K. G. 1984. The Extent and Significance of Water Repellant Sands on Eyre Peninsula. Tech. Rep. No. 47, Department of Agriculture, South Australia.

Whan, B. R., G. P. Carlton, and W. K. Anderson. 1991. Potential for increasing early vigour and total biomass in spring wheat. I. Identification of genetic improvements. *Aust. J. Agric. Res.* 42:347–361.

Willis, W. O., H. J. Haas, and J. S. Robins. 1963. Moisture conservation by surface or subsurface barriers and soil configuration under semiarid conditions. *Soil Sci. Soc. Am. Proc.* 25:577–580.

Wood, C. W., D. G. Westfall, and G. A. Peterson. 1991. Soil carbon and nitrogen changes on initiation of no-till cropping systems. *J. Soil Sci. Soc. Am.* 55:470–476.

Yang, B. J., P. S. Blackwell, and D. F. Nicholson. 1993. Numerical simulation of heat movement and water loss from furrow-sown water repellant sand. *Aust. J. Soil Res.* In press.

Zingg, A. W. and V. L. Hauser. 1959. Terrace benching to save potential runoff for semiarid land. *Agron. J.* 51:289–292.