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Managing Soils to Achieve Greater Water Use Efficiency: A Review

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ABSTRACT

Water use efficiency (WUE) represents a given level of biomass or grain yield per unit of water used by the crop. With increasing concern about the availability of water resources in both irrigated and rainfed agriculture, there is renewed interest in trying to develop an understanding of how WUE can be improved and how farming systems can be modified to be more efficient in water use. This review and synthesis of the literature is directed toward understanding the role of soil management practices for WUE. Soil management practices affect the processes of evapotranspiration by modifying the available energy, the available water in the soil profile, or the exchange rate between the soil and the atmosphere. Plant management practices, e.g., the addition of N and P, have an indirect effect on water use through the physiological efficiency of the plant. A survey of the literature reveals a large variation in measured WUE across a range of climates, crops, and soil management practices. It is possible to increase WUE by 25 to 40% through soil management practices that involve tillage. Overall, precipitation use efficiency can be enhanced through adoption of more intensive cropping systems in semiarid environments and increased plant populations in more temperate and humid environments. Modifying nutrient management practices can increase WUE by 15 to 25%. Water use efficiency can be increased through proper management, and field-scale experiences show that these changes positively affect crop yield.

Increasing the efficiency of water use by crops continues to escalate as a topic of concern because of the increasing demand for water use and improved environmental quality by human populations. Efficiency is a term that creates a mental picture of a system in which we can twist dials, tweak the components, and ultimately influence the efficiency of the system. Unfortunately, the system we deal with is much more complex than a factory analogy. Although there are many places where we can manipulate the components, the effect on WUE is often not achieved nor are the results consistent among locations or experiments.

Tanner and Sinclair (1983) summarized the different forms of relationships that have been used to characterize WUE. Most researchers describe WUE as

$$\mathrm{WUE} = Y/ET \quad [1]$$

where Y is the yield of the crop, either in total harvestable biomass or marketed yield, and ET is the evapotranspiration of water from the soil surface, plant leaves, and through the stomates (transpiration). This relationship is traceable back to deWit (1958) who showed that plant yield and transpiration were linearly related in areas with high solar radiation (e.g., western USA) as described by

$$Y/T = \mathrm{m}/T_{\max} \quad [2]$$

where Y is the total dry matter production, T is the transpiration, m is a coefficient, and $T_{\max}$ is the daily free water evaporation. Water use efficiency is estimated using the total water use (ET) from a crop surface, which includes evaporation from soil and plant components because of the difficulty in separating evaporation from transpiration.

Changes in WUE can be manifested through soil management practices via the components of the surface energy balance:

$$ET = R_n - G - H - P \quad [3]$$

where ET is evapotranspiration, R_n is net radiation, G is soil heat flux, H is sensible heat flux, and P is photosynthetic flux. These terms can be expressed in a variety of units (e.g., W m^{-2} and KJ m^{-2} s^{-1}). Soil management practices impact WUE through changes in the energy exchanges (R_n, G, and H) and through the plant photosynthetic (P) efficiency. These terms will affect the water balance in the soil within a growing season and across growing seasons. Throughout this review, we will show where soil management practices modify the energy balance components.

In our review, we discuss the potential implications of soil management practices on WUE in crops. Soil management in our discussion includes any practice that alters any soil component within or on the soil surface. Soil management can affect water and nutrient status within the soil, and the impact of these changes on plant response in terms of increased plant growth or yield offers opportunities to improve WUE. Earlier summaries developed by Unger and Stewart (1983) and Power (1983) provide a strong foundation for understanding the role of soil management on WUE. This report will focus on the more recent literature prepared during the last 30 yr.

PRECIPITATION USE EFFICIENCY

In rainfed agriculture, WUE is linked to the effectiveness of the use of precipitation because there is no other source of water. Precipitation use efficiency has been a surrogate for WUE in rainfed agriculture because soil management practices that increase soil water storage have had a positive impact on WUE. Rainfed agriculture remains the dominant crop and forage production system throughout the world, and the stability of food and fiber production requires that we increase precipitation use efficiency. Although the terms are often used interchangeably, there is a difference between precipitation use efficiency and WUE. Precipitation use efficiency is a measure of the biomass or grain yield pro-

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Abbreviations: WUE, water use efficiency.

duced per increment of precipitation while WUE is based on evapotranspiration. If we assume that all precipitation during the growing season is used for evapotranspiration and that the soil water content in the fall is the same as in the spring for a summer crop, then precipitation use efficiency and WUE would be equal. Jones and Popham (1997) found a difference between WUE and precipitation use efficiency of as much as 50%. In evaluating the response to different management practices, we need to be aware of how water use and crop production are expressed in the study.

Much of the research that forms the foundation for understanding the relationships among precipitation, soil water, plant water use, and crop response has been conducted in semiarid regions. Good and Smika (1978) found that wheat (*Triticum aestivum* L.) yields increased from 1000 to 3000 kg ha^{-1} as available soil water at planting increased from 220 to 400 mm. In semiarid regions, fallow (no crop during the growing season) to increase soil water storage has been considered to be a viable and necessary practice. However, recent research has demonstrated that precipitation use efficiency may increase with reduced tillage systems coupled with more intensive cropping systems. Farahani et al. (1998), among others, have shown that efficiency gains are due to a reduced use of fallow seasons and using water for crop growth that otherwise is lost during fallow by soil water evaporation, runoff, or deep percolation processes. In areas where fallow is practiced, the efficiency of precipitation storage is often low (between 10 and 15%), largely because a large portion of the precipitation falls when no crop is growing and partly due to disturbance of the soil surface to control weeds (Johnson and Davis, 1971). These results would suggest that we need to examine these studies to achieve the next increment in WUE.

Musick et al. (1994), like Good and Smika (1978), found that wheat yields were positively and linearly related to soil water stored at planting and that this relationship was more significant than a relationship to seasonal water use. Their research is illustrative of the need to understand the role that soil modification plays in changing WUE. Modification of the soil surface will lead to changes in the soil water balance in terms of soil water evaporation and infiltration into the soil profile. Soil management practices will ultimately have some effect on how efficiently crops use precipitation as a water supply. There are four major influences on the evapotranspiration flux (Eq. [3]) from a surface for a given period of time. These include the availability of energy (R_n), gradients of water vapor, temperature and wind speed, amount of soil water stored in the soil profile, and the ability of the plant to extract water from the soil profile. These terms are not independent of one another, and throughout the course of this review, we will determine why these interrelationships exist and how they can be modified to improve WUE.

SOIL SURFACE MODIFICATIONS

There are many modifications to the soil surface that influence the components in Eq. [1]. These changes are associated with some type of manipulation of the soil surface by tillage and surface residue management or mulching. The impact of these changes on WUE varies across locations and crops. Within the energy balance (Eq. [3]), soil surface modifications influence R_n, G, and H. A summary of the results of experiments conducted on tillage and crop residue management is shown in Table 1 and represents an attempt to demonstrate the effect of different farming systems and management schemes on WUE. Current studies have often been limited to semiarid conditions because water is considered a scarce commodity and crop yields exhibit a definite response to water management. Summaries from various management practices, shown in Table 1, illustrate the diversity in the values of WUE reported within the literature and the potential for improvement from soil management practices.

Tillage

Increasing water storage within the soil profile is necessary to increase plant available soil water. Tillage roughens the soil surface and breaks apart any soil crust. This leads to increased water storage by increased infiltration into soil as well as increased soil water losses by evaporation compared with a residue-covered surface or an undisturbed surface. There is a change in the surface roughness of tilled fields after the first rainfall. If surface residue is buried, the soil surface can become smooth, and infiltration rates can decrease for subsequent rain events. For example, Burns et al. (1971) and Papendick et al. (1973) showed that tillage disturbance of the soil surface increased soil water evaporation compared with untilled areas. Ritchie (1971) explained that soil water evaporation is affected by the soil water content of the surface and the degree of plant cover. Tillage moves moist soil to the surface where losses to drying may offset increased infiltration rates. Hatfield and Prueger (unpublished data, 1999) found that the total soil water evaporation fluxes in Iowa were 10 to 12 mm for a 3-d period following each cultivation operation in the spring. The total evaporation fluxes from no-tillage fields were <2 mm over this same period. Aggressive field cultivation operations in the spring could reduce soil water availability in the seed zone by as much as 20 to 30 mm. The occurrence of precipitation after planting is necessary to replenish soil water lost from the seed zone. There has not been an evaluation of the impact of initial soil water content on WUE in the Corn Belt. However, in the semiarid areas, the initial water contents of the soil profile are critical to crop production.

Cresswell et al. (1993) found that the tillage of bare soils increased saturated hydraulic conductivity (rate of water movement when the soil is saturated) while soil water content before tillage had no noticeable effect. Unsaturated hydraulic conductivity (rate of water movement at water content less than field capacity) was affected by tillage sequence, and excessive tillage caused the lowest conductivities because of the increase in air-filled pores. The effect of tillage on water infiltration

Table 1. Water use efficiency (WUE) responses to cropping practices.

Reference	Location	Crop	Management practice	WUE	Observations
				$kg\ ha^{-1}\ mm^{-1}$	
Aase and Pikul, 1995	Culbertson, MT	Spring wheat	Tillage	2.9–4.7	N applied at 56 $kg\ ha^{-1}$ in tilled plots; N applied at 34 $kg\ ha^{-1}$ in fallow plots; seeding rate of 74 $kg\ ha^{-1}$; 0.25 row width
Azooz and Arshad, 1998	British Columbia	Barley Canola	Tillage	3.6–6.7	Two different soils in this study—a silt loam and a sandy loam; sandy loam had a lower WUE
Deibert et al., 1986	Minot, ND Williston, ND	Spring wheat	No-till Spring plow Spring sweep	M†-5.3 W‡-5.5	N fertilizer applied at 114–141 $kg\ ha^{-1}$; continuous cropping sequence
Deibert et al., 1986	Minot, ND Williston, ND	Spring wheat	Crop fallow Summer fallow	M-9.0 W-5.8 M-5.7 W-3.4	N fertilizer at 86–103 $kg\ ha^{-1}$
Eck and Winter, 1992	Bushland, TX	Corn Sugarbeet	Soil profile	2.4–8.1 Grain 16.6–23.4 DM§ 6.6–8.3 DM (roots)	Soil modified to 1.5 m with ditching
Gibson et al., 1992	Queensland	Grain sorghum	Tillage	3.5–15.8	Tillage frequency and implements; stubble modification; dryland experiment
Howell et al., 1998	Bushland, TX	Corn	Corn hybrids	15.2–15.7 Grain 27.5–28.8 DM	Compared two hybrids under irrigation
Jones and Johnson, 1991	Bushland, TX	Grain sorghum Grain	Row width Seeding rate	11.5–13.4	Two row widths with two plant populations
Jones and Popham, 1997	Bushland, TX	Grain sorghum Wheat	Tillage	7.8–9.7 2.9–4.3	Cropping sequence and tillage study; compared precipitation and use and WUEs
Liang et al., 1991	Quebec	Corn	Irrigation	10.2	Irrigated and nonirrigated; two hybrids
Musick et al., 1994	Bushland, TX	Wheat	Irrigation	4.0–8.0	Planted in 0.34-m row at 50 $kg\ ha^{-1}$; planted in 0.25-m row at 100 $kg\ ha^{-1}$
Norwood, 1999	Garden City, KS	Corn Sorghum Soybean Sunflower	Tillage	3.0–18.9 7.0–14.2 2.3–3.5 3.8–7.9	Conventional tillage and no till; N applied at 90 $kg\ ha^{-1}$ except soybean; dryland area with no irrigation
Payne, 1997	Niger	Pearl millet	Population	1.3–1.7 Grain 7.6–8.7 DM	Field scale study with plant populations
Payne, 1997	Niger	Pearl millet	Millet varieties	1.0–2.2 Grain 7.6–9.7 DM	Field scale study with three millet varieties
Srivastava and Sidique, 1978	India	Wheat	Row width Seeding rate	16.7–18.3	Two row widths and three plant populations under dryland production practices
Tanaka, 1990	Sidney, MT	Spring wheat	Soil removal	7.1–8.9 N and 6.6–9.1 P	Four soil removal treatments and N rates of 0, 35, and 70 $kg\ ha^{-1}$ and P rates of 0, 20, and 40 $kg\ ha^{-1}$ two plant populations
Tolk et al., 1998	Bushland, TX	Corn	Soil	10.5–16.3 Grain 23.4–30.0 DM	Three soils in this study: Amarillo, Pullman, Ulysses
Tolk et al., 1998	Bushland, TX	Corn	Irrigation	12.2–15.8 Grain 26.5–30.6 DM	Four irrigation treatments
Tompkins et al., 1991	Saskatchewan	Winter wheat	Row width Seeding rate	9.3–10.3	N fertilizer at 100 $kg\ ha^{-1}$; P fertilizer at 33 $kg\ ha^{-1}$; two row widths and two plant populations
Unger, 1991	Bushland, TX	Grain sorghum	Hybrids	8.6–16.3 Grain 20.7–28.7 DM	Eight hybrids in wheat–sorghum–fallow rotation under dryland
Varvel, 1994	Mead, NE	Corn	Crop rotation Tillage	5.8–11.5	Four rotations at three N rates; used precipitation use efficiency; normal plant population
Varvel, 1995	Mead, NE	Soybean	Crop rotation	2.0–4.5	Precipitation use efficiency; crop rotation of soybean with row crops and clovers; N applications at 0, 34, and 68 $kg\ ha^{-1}$
Varvel, 1995	Mead, NE	Grain sorghum	Crop rotation	4.2–8.5	Precipitation use efficiency; crop rotation of sorghum with row crops and clovers; N applications at 0, 90, and 180 $kg\ ha^{-1}$
Zhang and Qweis, 1999	Syria	Bread wheat Durum wheat	Irrigation	2.5 10.9	Multiple cultivars underline source irrigation; N rates at 0–150 $kg\ ha^{-1}$; P rates at 40–50 $kg\ ha^{-1}$; row width of 0.17 m

† M, Minot, ND.
‡ W, Williston, ND.
§ DM, dry matter.

was still considered to be positive; however, these results suggest that excessive tillage may reduce infiltration through the effect on hydraulic conductivity. Christensen et al. (1994) found that more soil water was conserved during fallow periods with no tillage than with clean till, and in contrast to Creswell et al. (1993), the infiltration rates were larger with no tillage as evidenced by the slow rate of the advance of water down irrigation furrows. They reported that sorghum [*Sorghum bicolor* (L.) Moench] grain yields were higher with no tillage, but wheat yields were less with clean-till. More water was conserved during the fallow periods, and there was deeper wetting of the soil profile in no-tillage plots.

A strong relationship has not been developed among types of tillage systems and WUE. It is impossible to discuss the effects of tillage practices without also discussing the effects of mulch or crop residue management because most studies compare residue management with various tillage practices. Infiltration rates under no

tillage are increased. In the northern Great Plains, Pikul and Aase (1995) found that infiltration rates were increased because of the protection of the soil surface and that infiltration over 3 h was 52 mm with conventional tillage in a wheat fallow and 69 mm for the annual cropping system with no tillage. They stated that no tillage has an advantage over tillage because surface cover is maintained, and this reduces the potential for soil crusting and erosion. Aase and Pikul (1995) found that decreasing tillage showed a trend toward improving WUE because of improved soil water availability through reduced evaporation losses.

The management of soil through tillage changes the water storage and evaporation losses. However, maintaining the soil profile is an important factor. Tanaka (1990) concluded that management practices should be developed and practiced that would preserve topsoil depth because soil losses in the northern Great Plains decrease WUE and dry matter production. Studies such as these demonstrate the importance of understanding the role of tillage on efficient water use and crop growth.

Crop Residue Management

Soil Water Availability

Covering the surface with mulch or residue has been studied relative to changes in WUE. Greb (1966) found that residue and mulches reduce soil water evaporation by reducing soil temperature, impeding vapor diffusion, absorbing water vapor onto mulch tissue, and reducing the wind speed gradient at the soil–atmosphere interface. Sauer et al. (1996a) found that the presence of residue on the surface reduced soil water evaporation by 34 to 50% and that creating a 15-cm bare strip increased soil water evaporation by only 7% over the weathered residue cover. Deibert et al. (1986) stated that tillage effects on storage efficiency were minimal; however, they concluded that proper soil management could lead to both increases in precipitation storage efficiency and WUE. Deibert et al. (1986) found that precipitation storage efficiency in the northern Great Plains was similar among tillage systems but varied among years and locations during the nongrowing season under continuous wheat. Precipitation storage efficiency was defined as the amount of soil water stored in the upper 1.2 m relative to the precipitation during the nongrowing season. The difference among tillage systems ranged from 56% with no tillage to 47% with spring sweep operations at Williston, ND, but at Minot, ND, they ranged from 59% with no tillage to 57% with spring sweep. However, among years for a given tillage practice, precipitation storage efficiencies ranged from 20 to 98%. The authors attributed the variation in storage efficiency to variations in the total annual precipitation and variations in precipitation patterns among years. They found that yields under no tillage were lower than with spring sweep or spring plow, which caused WUE to be lower with no tillage. Yield decreases with no tillage were related to increased weed competition, foliar disease, and insect damage (Deibert et al., 1986).

Azooz and Arshad (1995) found higher soil water contents under no tillage compared with moldboard plow in British Columbia. However, Zhai et al. (1990) noted that the presence of corn (*Zea mays* L.) residue intercepted significant amounts of precipitation and reduced soil water evaporation under no-tillage systems in Ontario. Johnson et al. (1984) reported that more soil water was available in the upper 1 m under no tillage compared with other tillage practices in Wisconsin. In the Upper Midwest and Canada, there was generally an increase in soil water content under reduced tillage practices. This increase was caused by residue providing a barrier to soil water evaporation and by less disturbance of the soil surface via tillage operations.

The management of snow represents a significant portion of the water balance in the cropping systems of the northern Great Plains. In the northern portions of the USA, standing residue or stubble increases snow trapping. Aase and Siddoway (1990) showed that standing wheat residue increased the soil water content in spring by 10 to 30 mm. The difference between bare soil and standing residue was not as evident when rain occurred as it was with snow. The presence of crop residue on the surface influences the rates of energy exchange between the soil surface and the atmosphere due to effects on albedo, aerodynamic coefficients, and water vapor exchange rates. Sauer et al. (1996b) showed that the aerodynamic properties of corn stubble changed over the winter. They found roughness lengths and drag coefficients to be highest in the fall and lower in the spring after the residue had been weathered and compacted beneath the snow. The larger roughness lengths and drag coefficients in the fall increased the potential water vapor exchange rates; however, this was offset by the residue having a large amount of air-filled pore space. Although the exchange mechanisms were present for rapid water loss, the limiting factor was the rate of water movement through the stubble. In the spring, the roughness lengths and drag coefficients were reduced and became the limiting factors to the water vapor exchange rates. The seasonal changes in crop residue properties need to be understood to quantify the effects of changing residue management on water exchange processes.

In the southern High Plains, wheat residue is used as a barrier around cotton (*Gossypium hirsutum* L.) to reduce the effect of blowing sand on young cotton plants. Lascano et al. (1994) found that total evapotranspiration was similar between conventional tillage practice (305 mm) and cotton planted into killed wheat residue (304 mm). The largest difference was the partitioning of evaporation into the components. Wheat residue modified the microclimate, which increased transpiration to 69% of the total evapotranspiration compared with 50% for the conventional tillage practice. However, the WUE of cotton was not modified by the presence of wheat residue. Hatfield (1990) found an increase in water vapor content and a decrease in wind speed within wheat residue that reduced the gradient for water vapor transfer in the early season. This increased WUE by 25% in the first part of the season, but the effect did not persist for the entire season because the microclimate changes were diminished when the cotton height ex-

ceeded the wheat residue height. The presence of the wheat residue affected the humidity and wind speed around the young cotton seedling and placed the cotton plant into a microclimate that had a reduced evaporation gradient. Once the plant grew taller than the wheat residue, the effect was no longer present. These studies demonstrate that there are a number of potential options to modifying WUE in cropping systems.

In the Midwest, Sauer et al. (1998) evaluated the surface energy balance of corn residue under field conditions and found large differences in the evaporation fluxes among days. The wetness of the residue layer had a large effect on the partitioning of available energy into evaporation and sensible heat. On overcast days with a dry soil surface, between 50 and 75% of the net radiation was used in evaporation, in contrast to sunny days, when <20% of the net radiation was used in evaporation. If the soil surface was wet, there was little difference in evaporation fluxes as a function of net radiation (Sauer et al., 1998). Sauer et al. (1997) found the radiation components of residue to change over winter because albedo changed with the age of the residue and transmissivity increased as the residue weathered. Transmissivity of radiation through the residue layer was a function of the residue area index and represents a measure of how much energy penetrates to the soil surface. Crop residue is not uniformly distributed across a field, and the spatial distribution changes dramatically with decomposition and as the wind rearranges the residue after harvest. Residue characteristics affect energy balance components and have a large impact on evaporation fluxes. The changes in residue over the year demonstrate that its effectiveness on water storage and evaporation rates will vary throughout the year and spatially across a field because of the nonuniform distribution of residue.

Soil Temperature

One aspect of crop residue management is the effect of residue on soil temperatures. Soils with surface residue management are cooler than tilled soils (Allmaras et al., 1964; Anderson and Russell, 1964; Greb, 1966; Wilhelm et al., 1989). These cooler temperatures cause slower crop growth during the early season and are often the reason cited for a lack of adoption of no-tillage practices in the Upper Midwest. Hammel (1989) found that reduced tillage and no tillage in northern Idaho increased soil impedance, and in combination with the cool, wet soil conditions in the spring, limited root function and decreased crop growth potential.

Kaspar et al. (1990) showed that removing corn residue from the seedbed increased the rate of corn emergence. This was attributed to higher maximum soil temperatures due to residue removal. Hatfield and Prueger (1996) found that average soil temperatures were only slightly affected by the presence of corn residue on the surface and that the greatest effect occurred in the fall when the residue was fresh compared with the spring when it was weathered. Sauer et al. (1996a) showed that there was a different response to corn residue on a Monona silt loam (fine-loamy, mixed, mesic, Typic Hapludoll) than on a Nicollet loam (fine-loamy, mixed, mesic Aquic Hapludoll). The Monona soil was 1 to 2°C cooler than the Nicollet soil when the same levels of residue were placed on the surface. This difference can be explained by the differences in thermal conductivity between the soils and by the effect of soil water on thermal properties.

Unger (1988) found that soil surface temperatures in the High Plains of Texas were more affected by the season of the year than by residue management practices. In the summer, he found the highest soil temperatures after dryland wheat in standing residues, while in the winter, the highest temperatures were in the no-tillage treatment with shredded residue. Although there is an effect of crop residue on soil temperatures, the impact of the residue on the soil water content and the interactions with the soil thermal properties must be considered in interpreting the results of different experiments.

Crop Growth and Yields

Increasing crop residue or adopting no tillage increases soil water availability and affects crop growth and yield. In western Kansas, in a wheat–row crop–fallow rotation, the use of no tillage increased corn yields by 31% (Norwood, 1999). The row crops studied were corn, sorghum, sunflower (*Helianthus annuus* L.), and soybean [*Glycine max* (L.) Merr.]. The effect was not consistent among crops because corn yields were increased in 3 yr, sunflower and sorghum yields were increased in 2 yr, and soybean yields were increased in 1 yr. Unger (1994) addressed the effect of limited irrigation coupled with conservation tillage on wheat and sorghum yields and found that while the use of conservation tillage increased soil water use, these practices did not affect the grain yield of either crop. Similarly, Jones and Popham (1997) found that while continuous sorghum was the most efficient at using precipitation during the growing season, sorghum grain yields were not affected by residue management compared with fallow systems on the southern High Plains. Unger (1991) compared eight sorghum cultivars under no tillage and found that WUE varied among years and cultivars. The highest-yielding cultivars in this study had the highest water use.

In Australia, Gibson et al. (1992) found that retaining sorghum stubble on the soil increased the sorghum yield by 393 kg ha^{-1} due to increased WUE because of a greater amount of water stored in and extracted from the soil profile compared with conventional tillage. They also found that decreasing tillage frequency increased soil water extraction; however, no tillage did not result in the optimum yield or WUE. In the southern High Plains of the USA, WUE for irrigated wheat was 8 kg ha^{-1} mm^{-1} compared with 4 kg ha^{-1} mm^{-1} for dryland wheat (Musick et al., 1994). In this study, there was nearly 100% variation in WUEs for a given amount of crop water use. Increasing the soil water availability to the crop in the absence of any other yield-limiting fac-

tors can lead to increased WUE. Differences in WUE among years for the same set of practices within a location create a dilemma in determining how much of an increase in WUE is feasible under a given management practice.

Tompkins et al. (1991) found that no-tillage winter wheat yields in Saskatchewan increased with an increased seeding rate and decreased row spacing. Water use efficiency increased when row spacing was decreased from 36 to 9 cm and the seeding rate was increased from 35 to 140 kg ha^{-1}. Grain yield increased from 1.49 to 1.68 kg m^{-2} while WUE increased from 9.4 to 10.3 kg ha^{-1} mm^{-1}. The total water use increased with narrow row spacing and high populations, but increased yield was the primary factor associated with the increased WUE (Tompkins et al., 1991). A similar result was found for wheat in India; however, WUE was optimum at the 75 kg ha^{-1} seeding rate (Srivastava and Sidique, 1978). For grain sorghum, WUE was not affected by within-row density, but it decreased in 1 of 3 yr with the use of narrow rows (Jones and Johnson, 1991). Water use efficiency varied among the years of the study by 75% across the row width and plant density treatments.

Barley (*Hordeum vulgare* L.) and canola (*Brassica campestris* L.) had a different response to tillage and residue management in British Columbia (Azooz and Arshad, 1998). Azooz and Arshad (1998) found differences among years when they compared the effects of no tillage and a 75-mm strip till with conventional tillage on the water use and yield of barley and canola on a silt loam and a sandy loam soil. In a dry year, there was an increase in yield with no tillage and strip till; however, in a wet year, yield was higher with conventional tillage. Water use efficiency for barley was increased in the dry year by 21% with no tillage and by 18% with strip till in the silt loam; it was increased by 19% with no tillage and by 10% with modified no tillage in the sandy loam compared with conventional tillage. In wet years, WUE was highest with conventional tillage. Water use efficiency by canola was higher under conventional tillage in the wet year, but data were not available for the dry year. Liang et al. (1991) found that corn yield increased with higher plant populations and higher fertilizer rates in response to increased temperatures (heat units) and water inputs during the growing season. Their study showed a WUE of 10.2 kg ha^{-1} mm^{-1} for these conditions and only a small variation in yield for a given water use. The interaction between heat units and water use on corn yields suggests that early season crop growth affects WUE. Zhang and Qweis (1999) found similar responses for wheat in the Mediterranean region where WUE was increased by agronomic factors that lead to high yields.

Differences in WUE among growing seasons are often observed. Chan and Heenan (1996) showed that for a wheat–lupin (*Trifolium subterraneum* L.) rotation, early season growth of wheat caused differences in crop water use among years. Early season growth affected the ability of the wheat crop to effectively use soil water. There was no effect of soil water differences on the lupin crop. Dao and Nguyen (1989) showed that there were large differences in the growth response of wheat cultivars to different tillage practices at El Reno, OK, but they concluded that it would not be necessary to develop cultivars for specific tillage methods. They also found that no-tillage management showed the greatest response in growth and yield under unfavorable growing conditions.

Eck and Winter (1992) evaluated the effect of modifying the soil profile on sugarbeet (*Beta vulgaris* L.) and corn WUE and found that although water was extracted from deeper depths of the modified soil profile, there was not a consistent increase in yield. They only found an effect on WUE in one year of the study and concluded that modifying the soil profile to increase water use was not warranted because of the limited effect on yield. Under sodic soils in New South Wales, WUE was higher for digitaria (*Digitaria eriantha* spp. *Eriantha*) than for lucerne (*Medicago sativa* L.) (Tow, 1993). Across the three seasons of the study, WUE varied by 110% in the digitaria, 84% in the lucerne, and 72% in the mixture of both. Variation among seasons is a problem in WUE studies, and the role of the soil is not clearly understood.

In comparing different corn hybrids, Howell et al. (1998) found that WUEs for grain yield and biomass were the same for both short-season and full-season hybrids. Soil water extraction patterns during the growing season will vary with hybrid maturity. Tolk et al. (1998) found a soil type effect on water use and corn yield. Much of the effect on yield was due to the water extraction pattern during the season from the different soil profiles. In comparing results shown in Table 1, it is necessary to define the soil profile characteristics and the maturity class of the crop.

SOIL NUTRIENT STATUS

The soil nutrient status has been shown to have a positive impact on WUE. Relationships between nutrients and WUE were first described by Viets (1962). Increases in WUE come from improved plant growth and yield that are a result of a proper soil nutrient status. Davis and Quick (1998) stated that cultivar selection could be made for improved WUE based on an understanding of the role of nutrient management on photosynthetic rate, yield, rooting characteristics, and transpiration. They suggested that to optimize WUE, cultivar and nutrient management decisions would have to be made together. In the Sahel, Payne (1997) found that the WUE of Pearl millet [*Pennisetum glaucum* (L.) R. Br.] was improved through the combination of N management and increased plant populations. A proper nutrient balance of the crop would lead to increased yields, and thus increase WUE. These studies indicate that we need to understand how nutrient management can influence crop growth to have an impact on WUE. A summary of the studies that have been conducted in recent years addressing this topic is provided in Table 2. There is a large divergence of results shown in the literature on WUE related to soil nutrient management.

Table 2. Water use efficiency (WUE) responses to nutrient management practices.

Reference	Location	Crop	Fertilizer practice	WUE	Observations
				kg ha^{-1} mm^{-1}	
Corak et al., 1991	Lexington, KY	Corn	N	6.1–16.6 Grain	N rates of 0 and 255 kg ha^{-1} with additions of hairy vetch residue
Hatfield and Prueger, 1999 (unpublished data)	Ames, IA	Corn	N	18.8–22.8 Grain 0.0–4.2 Grain	N rates of 50, 140, and 190 kg ha^{-1} across different soils
Payne et al., 1992	Lubbock, TX	Pearl millet	P	4.5–6.1 DM†	Container study with varying rates of P
Payne et al., 1995	Lubbock, TX	Pearl millet	N and P	2.5–5.2	Container study to vary N and P levels
Payne, 1997	Niger	Pearl millet	N and P	1.2–1.7 Grain 6.1–9.3 DM	Field-scale study with varying levels of N and P
Singh and Bhushan, 1979	India	Chickpea	P	8.4–15.0 Grain	P rates of 0, 25, 50, 75, and 100 kg ha^{-1}
Stout and Schnabel, 1997	Central PA	Perennial ryegrass	N	7.5–16.5 spring 2.0–7.2 summer	N rates of 0, 42, 84, and 126 kg ha^{-1}; two harvest periods (spring and summer)
Tanaka, 1990	Sidney, MT	Spring wheat	N and P	6.6–9.1	Four soil removal treatments and N rates of 0, 35, and 70 kg ha^{-1} and P rates of 0, 20, and 40 kg ha^{-1}
Tow, 1993	New South Wales	Lucerne Digitaria	N	17.0–30.8 DM 7.5–15.6 DM	Lucerne and digitaria mixtures

† DM, dry matter.

Many of the examples provided in this section demonstrate how nutrient management impacts growth and yield, showing how we could potentially increase WUE.

Nitrogen

Nitrogen is a complex part of the soil system, and its availability is affected by soil type, tillage, N source (e.g., fertilizer and manure), crop rotation, and precipitation. Oberle and Keeney (1990) showed that N rates for optimal corn yields depended on the soil type. In rainfed soils, the amounts of preplant and early season precipitation were important factors in explaining yield responses. Crop yields can vary in response to N management with no change in water use. Reeves et al. (1993) showed that a maximum corn yield was obtained with a range of N fertilizer additions from 93 to 134 kg ha^{-1} across the 3 yr of their study in Alabama. They also found that the most optimum time to apply N in this legume-based conservation tillage system was at corn planting. Jokela and Randall (1989) found that the grain and total dry matter yield of corn in Minnesota was increased by additions of N up to 225 kg ha^{-1}. There was a large difference among the 3 yr of this study and between soils in response to N. They found that there was no response in dry matter or grain yield to delayed N application. This is in contrast to the results for wheat obtained by Wuest and Cassman (1992) who found that applying N at anthesis increased N use efficiency from 55 to 80% compared with N recoveries of 30 to 55% for the preplant application. Fowler et al. (1990) found that grain protein content in wheat was affected by N management and used N use efficiency, defined as kg N ha^{-1} recovered as grain N for each 10 kg N ha^{-1} applied as fertilizer, to compare among practices. In this study, N use efficiency was at a maximum at low levels of applied N and declined rapidly with increasing amounts of applied N. The management of N in wheat can influence both yield and grain quality, and producers that are interested in protein will need to understand the linkages between water and N responses. As an expansion on this concept, the findings of Jeuffroy and Bouchard (1999) demonstrate that N management in wheat influences grain number. Grain number is a critical yield component, and management practices need to ensure a maximum number of grains per unit of land area to achieve a maximum yield potential. Abbate et al. (1995) showed that N deficiency in wheat affects grain number and that grain number is related to the N content of the spikes at anthesis. Water use efficiency can be improved through N management, which in turn, influences yield components like grain number per unit of land area. An evaluation of the impact of N management strategies on crop yield should be more closely linked to WUE to develop better management practices for producers. The information on soil nutrient status in Table 2 is limited in its geographic range. Soil nutrient management and further improvements in WUE and N use efficiency would benefit the producer.

Nitrogen dynamics and availability vary across the landscape. Wood et al. (1991) showed that slope position had little effect on plant N uptake or soil N dynamics. They did find that aboveground biomass and plant residue production increased downslope due to increased soil water availability. Halvorson et al. (1999) showed that N in dryland cropping systems had a positive impact on the amount of residue returned to the soil and to the belowground residue C. Increasing N rates increased soil organic C and total N. Earlier they had found that the increased cropping intensity, as suggested by Farahani et al. (1998), would lead to changes in N management practices because of the low mineralization potential of dryland soils (Halvorson and Reule, 1994). Nitrogen management is linked to water use rates in cropping systems. Maskina et al. (1993) found that growth and N uptake by corn increased as residue amounts from previous crop production increased. They found that N uptake was not affected by tillage in this study. Changes in crop residue management used to increase WUE may be linked to N dynamics in the soil.

In a study in Kentucky, Corak et al. (1991) found that WUE increased with the addition of N fertilizer and hairy vetch (*Vicia villosa* Roth.) residue. Water use efficiency increased from 6.1 to 8.5 kg ha^{-1} mm^{-1} in 1986

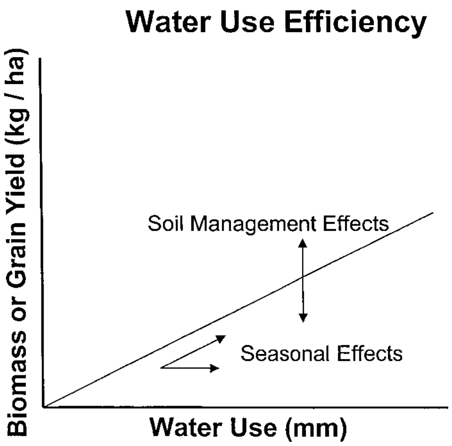

Fig. 1. Changes in water use efficiency (WUE) as affected by seasonal and physical changes in soil and nutrient management.

and from 9.1 to 16.6 kg ha^{-1} mm^{-1} in 1987 with the addition of 255 kg ha^{-1} N. These are large variations between the 2 yr. The addition of hairy vetch residue reduced the effect of N fertilizer on WUE. Varvel (1995) found that adding N fertilizer increased WUE in grain sorghum; Smika et al. (1965) found a similar response for native grasses as did Campbell et al. (1992) for wheat and Varvel (1994) for corn. For these studies, N additions increased WUE through increases in biomass production.

Nitrogen management and its effect on WUE can be different in poorly drained soils. Stout and Schnabel (1997) showed that for perennial ryegrass (*Lolium perenne* L.), WUE decreased with poor drainage because of the loss of available N through denitrification, resulting in poor plant growth. Water use efficiency declined 26% in the spring and 20% in the summer due to decreased biomass production. Water use efficiencies for perennial ryegrass ranged from 2.2 to 7.7 kg ha^{-1} mm^{-1} as N application increased from 0 to 126 kg ha^{-1}. Water use efficiencies were 20.2 kg ha^{-1} mm^{-1} for orchardgrass (*Dactylis glomerta* L.) and 22.7 kg ha^{-1} mm^{-1} for tall fescue (*Festuca arundinacea* Schreb.) (Stout, 1992). These WUEs are much higher than those for perennial ryegrass. Nitrogen dynamics within the soil may have a large impact on WUE.

Phosphorus

The addition of P to soils and it effect on WUE has been documented on a limited number of crops. Singh and Bhushan (1980) found that addition of P to chickpea (*Cicer arietinum* L.) increased yield, water use, and WUE. The increase in WUE was from 8.5 to 12.2 kg ha^{-1} mm^{-1} at 0 and 100 kg P ha^{-1}. This gain was due to a greater depletion of soil water with fertilizer and a yield increase.

Payne et al. (1992, 1995) found that in low-P soils, the addition of P fertilizer increased the dry matter yield and WUE of pearl millet. The soil nutrient status affects the growth efficiency of crops, which leads to improved dry matter production relative to a given amount of water used by the crop. These changes increase the WUE.

SOIL MANAGEMENT PRACTICES

Soil management practices that increase the soil water holding capacity, improve the ability of roots to extract more water from the soil profile, or decrease leaching losses could all potentially have positive impacts on WUE, assuming these changes result in a concurrent increase in crop yield. These practices would affect evapotranspiration rates and potentially increase crop yields, thereby increasing WUE. Improved soil management practices that increase the organic matter content of the soil would have a positive impact on the soil water holding capacity. Hudson (1994) showed that over a wide range of soils, there was an increase in water availability with increases in soil organic matter. There has not been an analysis of the potential impacts of this change on improving WUE. However, any practice that leads to increases in soil water in the upper portion of the root zone may have a positive impact on WUE due to increased water availability and improved nutrient uptake.

If we examine the results shown in Tables 1 and 2, there are a number of features that begin to emerge. First, there is a large amount of variation among studies on WUE. Second, there is large degree of variation among years within locations. These patterns begin to reveal some characteristics about WUE relative to soil management. Variation among years is related more to water use rates caused by changes in precipitation and net radiation. Variation within a location can be attributed to any soil management practice that affects biomass production or the interception of radiation for plant growth. This is illustrated in Fig. 1 where we plotted a distribution of water use relative to biomass production. The distribution of water use rates and the biomass production reveal information about the potential of implementing soil management practices that would have a positive impact on WUE.

CHALLENGES AND IMPLICATIONS

Efficient and sustainable agricultural production requires that we continue to strive for systems that are efficient in their use of water and nutrients. In semiarid regions, WUE has been considered the primary standard by which systems and practices have been compared. East of the Missouri River, WUE has not been a standard by which cropping systems and management practices are evaluated. Tanner and Sinclair (1983) suggested that this region may have the most potential for improvement in WUE because the water vapor gradient between plants and the atmosphere is small and evaporation rates may be reduced. This concept has not been explored in any detail. In water use studies within a field in central Iowa, we found water use rates that varied by twofold due to soil type differences across the field (Hatfield and Prueger, unpublished data, 1999). These water use differences were related to yield variation within the field, soil type, and N management. Within-field studies may provide insight into the WUE dynamics relative to soil management practices because there has been little comparison of WUEs among soils

for a given location. We do see that WUE for wheat declines in the southern High Plains compared with the northern High Plains. Unfortunately, for the Corn Belt, there are too few comparisons across precipitation gradients.

The challenge before us is to continue to develop soil management practices with the goal of increasing WUE. Challenges for research are to understand the water × nutrient interactions for a range of cropping systems and to incorporate this information into tools that can assist producers in making management decisions that will lead to increased WUE and nutrient use efficiency. Variation among genetic material exists for their photosynthetic response, and incorporating this knowledge with light interception patterns during the growing season will reveal how management practices affect biomass and grain yields.

REFERENCES

Aase, J.K., and J.L. Pikul, Jr. 1995. Crop and soil response to long-term no-tillage practices in the Northern Great Plains. Agron. J. 87:652–656.

Aase, J.K., and F.H. Siddoway. 1990. Stubble height effects on seasonal microclimate, water balance, and plant development of no-till winter wheat. Agric. Meteorol. 21:1–20.

Abbate, P.E., F.H. Andrale, and J.P. Culot. 1995. The effect of radiation and nitrogen on number of grains in wheat. J. Agric. Sci. 124: 351–360.

Allmaras, R.R., W.C. Burrows, and W.E. Larson. 1964. Early growth of corn as affected by soil temperature. Soil Sci. Soc. Am. Proc. 28:271–275.

Anderson, D.T., and G.C. Russell. 1964. Effects of various quantities of straw mulch on the growth and yield of spring and winter wheat. Can. J. Soil Sci. 44:109–118.

Azooz, R.H., and M.A. Arshad. 1995. Tillage effects on thermal conductivity of two soils in northern British Columbia. Soil Sci. Soc. Am. J. 59:1413–1423.

Azooz, R.H., and M.A. Arshad. 1998. Effect of tillage and residue management on barley and canola growth and water use efficiency. Can. J. Soil Sci. 78:649–656.

Burns, R.L., D.J. Cook, and R.E. Phillips. 1971. Influence of no tillage on soil moisture. Agron. J. 73:593–596.

Campbell, C.A., R.P. Zentner, B.G. McConkey, and F. Selles. 1992. Effect of nitrogen and snow management on efficiency of water use by spring wheat grown annually on zero-tillage. Can. J. Soil Sci. 72:271–279.

Chan, K.Y., and D.P. Heenan. 1996. Effect of tillage and stubble management on soil water storage, crop growth, and yield in a wheat–lupin rotation in southern NSW. Aust. J. Agric. Res. 47: 479–488.

Christensen, N.B., T.L. Jones, and G.J. Kauta. 1994. Infiltration characteristics under no-till and clean-till furrow irrigation. Soil Sci. Soc. Am. J. 58:1495–1500.

Corak, S.J., W.W. Frye, and M.S. Smith. 1991. Legume mulch and nitrogen fertilizer effects on soil water and corn production. Soil Sci. Soc. Am. J. 55:1395–1400.

Cresswell, H.P., D.J. Painter, and K.C. Cameron. 1993. Tillage and water content effects on surface soil hydraulic properties and short-wave albedo. Soil Sci. Soc. Am. J. 57:816–824.

Dao, T.H., and H.T. Nguyen. 1989. Growth response of cultivars to conservation tillage in a continuous wheat cropping system. Agron. J. 81:923–929.

Davis, J.G., and J.S. Quick. 1998. Nutrient management, cultivar development, and selection strategies to optimize water use efficiency. J. Crop Prod. 1:221–240.

Deibert, E.J., E. French, and B. Hoag. 1986. Water storage and use by spring wheat under conventional tillage and no-till in continuous and alternate crop-fallow systems in the northern Great Plains. J. Soil Water Conserv. 41:53–58.

deWit, C.T. 1958. Transpiration and crop yields. Versl. Landouwk. Onderz. 64.6. Inst. of Biol. and Chem. Res. on Field Crops and Herbage, Wageningen, The Netherlands.

Eck, H.V., and S.R. Winter. 1992. Soil profile modification effects on corn and sugarbeet grown with limited water. Soil Sci. Soc. Am. J. 56:1298–1304.

Farahani, H.J., G.A. Peterson, D.G. Westfall, L.A. Sherrod, and L.R. Ahuja. 1998. Soil water storage in dryland cropping systems: The significance of cropping intensification. Soil Sci. Soc. Am. J. 62:984–991.

Fowler, D.B., J. Brydon, B.A. Darroch, M.H. Entz, and A.M. Johnston. 1990. Environment and genotype influence on grain protein concentration of wheat and rye. Agron. J. 82:655–664.

Gibson, G., B.J. Radford, and R.G.H. Nielsen. 1992. Fallow management, soil water, plant-available soil nitrogen and grain sorghum production in south west Queensland. Aust. J. Exp. Agric. 32: 473–482.

Good, L.C., and D.E. Smika. 1978. Chemical fallow for soil and water conservation in the Great Plains. J. Soil Water Conserv. 33:89–90.

Greb, B.W. 1966. Effect of surface-applied wheat straw on soil water losses by solar distillation. Soil Sci. Soc. Am. Proc. 30:786–788.

Halvorson, A.D., and C.A. Reule. 1994. Nitrogen fertilizer requirements in an annual dryland cropping system. Agron. J. 86:315–318.

Halvorson, A.D., C.A. Reule, and R.F. Follett. 1999. Nitrogen fertilization effects on soil carbon and nitrogen in a dryland cropping system. Soil Sci. Soc. Am. J. 63:912–917.

Hammel, J.E. 1989. Long-term tillage and crop rotation effects on bulk density and soil impedance in Northern Idaho. Soil Sci. Soc. Am. J. 53:1515–1519.

Hatfield, J.L. 1990. Modification of the microclimate in rainfed agriculture by stubble mulch. p. 315–317. *In* P.W. Unger et al. (ed.) Challenges in dryland agriculture: A global perspective. Proc. Int. Conf. on Dryland Farming, Texas Agric. Exp. Stn., College Station, TX. 15–19 Aug. 1998. Texas Agric. Exp. Stn., College Station.

Hatfield, J.L., and J.H. Prueger. 1996. Microclimate effects of crop residues on biological processes. Theor. Appl. Climatol. 54:47–59.

Howell, T.A., J.A. Tolk, A.D. Schneider, and S.R. Evett. 1998. Evapotranspiration, yield, and water use efficiency of corn hybrids differing in maturity. Agron. J. 90:3–9.

Hudson, B.D. 1994. Soil organic matter and available water capacity. J. Soil Water Conserv. 49:189–194.

Jeuffroy, M.H., and C. Bouchard. 1999. Intensity and duration of nitrogen deficiency on wheat grain number. Crop Sci. 39:1385–1393.

Johnson, M.D., B. Lowery, and T.C. Daniel. 1984. Soil moisture regimes of three conservation tillage systems. Trans. ASAE. 27:1385–1390, 1395.

Johnson, W.C., and R.G. Davis. 1971. Research on stubble-mulch farming of winter wheat. USDA Conserv. Rep. 16. U.S. Gov. Print. Office, Washington, DC.

Jokela, W.E., and G.W. Randall. 1989. Corn yield and residual soil nitrate as affected by time and rate of nitrogen application. Agron. J. 81:720–726.

Jones, O.R., and G.L. Johnson. 1991. Row width and plant density effects on Texas High Plains sorghum. J. Prod. Agric. 4:613–621.

Jones, O.R., and T.W. Popham. 1997. Cropping and tillage systems for dryland grain production in the southern High Plains. Agron. J. 89:222–232.

Kaspar, T.C., D.C. Erbach, and R.M. Cruse. 1990. Corn response to seed-row residue removal. Soil Sci. Soc. Am. J. 54:1112–1117.

Lascano, R.J., R.L. Baumhardt, S.K. Hicks, and J.L. Heilman. 1994. Soil and plant water evaporation from strip-tilled cotton: Measurement and simulation. Agron. J. 86:987–994.

Liang, B.C., A.F. MacKenzie, P.C. Kirby, and M. Remillard. 1991. Corn production in relation to water inputs and heat units. Agron. J. 83:794–799.

Maskina, M.S., J.F. Power, J.W. Doran, and W.W. Wilhelm. 1993. Residual effects of no-till crop residues on corn yield and nitrogen uptake. Soil Sci. Soc. Am. J. 57:1555–1560.

Musick, J.T., O.R. Jones, B.A. Stewart, and D.A. Dusek. 1994. Water–yield relationships for irrigated and dryland wheat in the U.S. Southern Plains. Agron. J. 86:980–986.

Norwood, C.A. 1999. Water use and yield of dryland row crops as affected by tillage. Agron. J. 91:108–115.

Oberle, S.L., and D.R. Keeney. 1990. Soil type, precipitation, and fertilizer N effects on corn yields. J. Prod. Agric. 3:522–527.

Papendick, R.I., M.J. Lindstrom, and V.L. Cochran. 1973. Soil mulch effect on seedbed temperature and water during fallow in eastern Washington. Soil Sci. Soc. Am. Proc. 37:307–314.
Payne, W.A. 1997. Managing yield and water use of Pearl millet in the Sahel. Agron. J. 89:481–490.
Payne, W.A., M.C. Drew, L.R. Hossner, R.J. Lascano, A.B. Onken, and C.W. Wendt. 1992. Soil phosphorus availability and pearl millet water-use efficiency. Crop Sci. 32:1010–1015.
Payne, W.A., L.R. Hossner, A.B. Onken, and C.W. Wendt. 1995. Nitrogen and phosphorus uptake in pearl millet and its relation to nutrient and transpiration efficiency. Agron. J. 87:425–431.
Pikul, J.L., Jr., and J.K. Aase. 1995. Infiltration and soil properties as affected by annual cropping in the northern Great Plains. Agron. J. 87:656–662.
Power, J.F. 1983. Soil Management for Efficient Water Use: Soil Fertility. p. 461–470. *In* H.M. Taylor et al. (ed.) Limitations to efficient water use in crop production. ASA, Madison, WI.
Reeves, D.W., C.W. Wood, and J.T. Touchton. 1993. Timing nitrogen applications for corn in a winter legume conservation tillage system. Agron. J. 85:98–106.
Ritchie, J.T. 1971. Dryland evaporative flux in a subhumid climate: I. Micrometeorological influences. Agron. J. 70:723–728.
Sauer, T.J., J.L. Hatfield, and J.H. Prueger. 1996a. Corn residue age and placement effects on evaporation and soil thermal regime. Soil Sci. Soc. Am. J. 60:1558–1564.
Sauer, T.J., J.L. Hatfield, and J.H. Prueger. 1996b. Aerodynamic characteristics of standing corn stubble. Agron. J. 88:733–739.
Sauer, T.J., J.L. Hatfield, and J.H. Prueger. 1997. Over-winter changes in radiant energy exchange of a corn residue-covered surface. Agric. For. Meteorol. 85:279–287.
Sauer, T.J., J.L. Hatfield, J.H. Prueger, and J.M. Norman. 1998. Surface energy balance of a corn-residue covered field. Agric. For. Meteorol. 89:155–168.
Singh, G., and L.S. Bhushan. 1980. Water use, water use efficiency, and yield of dryland chickpea as influenced by P fertilization, stored soil water, and crop season rainfall. Agric. Water Manage. 2: 299–305.
Smika, D.E., H.J. Haas, and J.F. Power. 1965. Effect of moisture and nitrogen fertilizer on growth and water use by native grass. Agron. J. 57:483–486.
Srivastava, V.C., and M. Sidique. 1978. Moisture use efficiency of wheat as influenced by seeding rate and row spacing under limited moisture condition. J. Soil Water Conserv. India 28:42–49.
Stout, W.L. 1992. Water use efficiency of grasses as affected by soil, nitrogen, and temperature. Soil. Sci. Soc. Am. J. 56:897–902.
Stout, W.L., and R.R. Schnabel. 1997. Water-use efficiency of perennial ryegrass as affected by soil drainage and nitrogen fertilization on two floodplain soils. J. Soil Water Conserv. 52:207–211.
Tanaka, D.L. 1990. Topsoil removal influences on spring wheat water-use efficiency and nutrient concentration and content. Trans. ASAE. 33:1518–1524.
Tanner, C.B., and T.R. Sinclair. 1983. Efficient water use in crop production: Research or re-search? p. 1–27. *In* H.M. Taylor et al. (ed.) Limitations to efficient water use in crop production. ASA, Madison, WI.
Tolk, J.A., T.A. Howell, and S.R. Evett. 1998. Evapotranspiration and yield of corn grown on three High Plains soils. Agron. J. 90:447–454.
Tompkins, D.K., D.B. Fowler, and A.T. Wright. 1991. Water use by no-till winter wheat influence of seed rate and row spacing. Agron. J. 83:766–769.
Tow, P.G. 1993. Persistence and water use efficiency of a tropical grass and lucerne on a solodic soil on the far North-West slopes of New South Wales. Aust. J. Exp. Agric. 33:245–252.
Unger, P.W. 1988. Residue management effects on soil temperature. Soil Sci. Soc. Am. J. 52:1777–1782.
Unger, P.W. 1991. Ontogeny and water use of no-tillage sorghum cultivars on dryland. Agron. J. 83:961–968.
Unger, P.W. 1994. Residue management for winter wheat and grain sorghum production with limited irrigation. Soil Sci. Soc. Am. J. 58:537–542.
Unger, P.W., and B.A. Stewart. 1983. Soil management for efficient water use: An overview. p. 419–460. *In* H.M. Taylor et al. (ed.) Limitations to efficient water use in crop production. ASA, Madison, WI.
Varvel, G.E. 1994. Monoculture and rotation system effects on precipitation use efficiency of corn. Agron. J. 86:204–208.
Varvel, G.E. 1995. Precipitation use efficiency of soybean and grain sorghum in monoculture and rotation. Soil Sci. Soc. Am. J. 59:527–531.
Viets, F.G., Jr. 1962. Fertilizers and the efficient use of water. Adv. Agron. 14:223–264.
Wilhelm, W.W., H. Bouzerzour, and J.F. Power. 1989. Soil disturbance-residue management effect on winter wheat growth and yield. Agron. J. 81:581–588.
Wood, C.W., G.A. Peterson, D.G. Westfall, C.V. Cole, and W.O. Willis. 1991. Nitrogen balance and biomass production of newly established no-till dryland agroecosystems. Agron. J. 83:519–526.
Wuest, S.B., and K.G. Cassman. 1992. Fertilizer-nitrogen use efficiency of irrigated wheat: I. Uptake efficiency of preplant versus late-season application. Agron. J. 84:682–688.
Zhai, R., R.G. Kachanoski, and R.P. Voroney. 1990. Tillage effects on the spatial and temporal variations of soil water. Soil Sci. Soc. Am. J. 54:186–192.
Zhang, H., and T. Qweis. 1999. Water-yield relations and optimal irrigation scheduling of wheat in the Mediterranean region. Agric. Water Manage. 38:195–211.