Efficient Water Use in Dryland Cropping Systems in the Great Plains

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ABSTRACT

Successful dryland crop production in the semiarid Great Plains of North America must make efficient use of precipitation that is often limited and erratic in spatial and temporal distribution. The purpose of this paper is to review research on water use efficiency and precipitation use efficiency (PUE) as affected by cropping system and management in the Great Plains. Water use efficiency and PUE increase with residue management practices that increase precipitation storage efficiency, soil surface alterations that reduce runoff, cropping sequences that minimize fallow periods, and use of appropriate management practices for the selected crop. Precipitation use efficiency on a mass-produced basis is highest for systems producing forage (14.5 kg ha^{-1} mm^{-1}) and lowest for rotations with a high frequency of oilseed crops (4.2 kg ha^{-1} mm^{-1}) or continuous small-grain production in the southern plains (2.8 kg ha^{-1} mm^{-1}). Precipitation use efficiency when calculated on a price-received basis ranges from $1.20 ha^{-1} mm^{-1} (for an opportunity-cropped system with 4 of 5 yr in forage production in the southern plains) to $0.30 ha^{-1} mm^{-1} [for a wheat (*Triticum aestivum* L.)–grain sorghum [*Sorghum bicolor* (L.) Moench]–fallow system in the southern plains]. Throughout the Great Plains region, PUE decreases with more southern latitudes for rotations of similar makeup of cereals, pulses, oilseeds, and forages. Forage systems in the southern Great Plains appear to be highly efficient when PUE is computed on a price-received basis. In general across the Great Plains, increasing intensity of cropping increases PUE on both a mass-produced basis and on a price-received basis.

In the semiarid regions of the Great Plains of North America, water is generally the most limiting factor for crop production. Successful dryland agricultural systems in these areas must make efficient use of precipitation that is often limited and erratic in spatial and temporal distribution. The limited and erratic nature of precipitation in this region led to the development of cropping systems in which one crop was grown every other year to allow soil water recharge during a fallow period, which then led to greater yield stability. Those cropping systems traditionally used tillage to control weed growth during the fallow period. But tillage degrades crop residues, making them less effective for reducing evaporation and leaving the soil vulnerable to wind erosion. The development of herbicides for weed control during the fallow period resulted in opportunities for more frequent cropping. A number of methods have been developed for increasing precipitation storage efficiency (PSE) and water use efficiency (WUE) in these dryland systems. This paper reviews several of those methods as they have been used from the Canadian Prairie Provinces to the southern Great Plains of the United States and the resultant effects on system WUE. Additionally, differences in precipitation use efficiency (PUE) between cropping systems across the Great Plains region are identified.

METHODS FOR INCREASING PSE, WUE, AND PUE

Tillage Effects on PSE

Precipitation storage efficiency increases as tillage intensity is reduced during the summer fallow period. The increased soil water storage is a result of both maintaining crop residues on the soil surface and reducing the number of times that moist soil is brought to the surface as tillage intensity is reduced. Data from winter wheat–fallow systems at North Platte, NE (Smika and Wicks, 1968), and Sidney, MT (Tanaka and Aase, 1987), show fallow PSE increasing from under 25% to around 40% as tillage intensity decreased from moldboard plow to no-till (Fig. 1, top). Data collected at Bushland, TX, followed a similar trend with PSE increasing from 15% with disk tillage to 35% with no-till (Unger and Wiese, 1979).

The amount and orientation of crop residue affects PSE and soil water storage. Data from Sidney, MT; Akron, CO; and North Platte, NE; show PSE over the 14-mo fallow period in a winter wheat–fallow system increasing from 15% to almost 35% as wheat residue mass increased from 0 to 10 Mg ha^{-1} (Fig. 1, bottom; Greb et al., 1967). This is a result of increased shading of the soil surface, cooler soil temperature, and decreased wind speed at the soil surface (Hatfield et al., 2001). Crop residues also increase precipitation infiltration by protecting the soil surface from raindrop impact and subsequent crusting, thus reducing runoff. Russel (1939) reported runoff in the April through September period in eastern Nebraska being reduced from 60 mm in a disked field without surface crop residues to only a trace where stubble-mulch reduced tillage had been employed and where 9 Mg ha^{-1} of wheat residue remained on the soil surface (Fig. 2, top). Baumhardt and Lascano (1996) showed cumulative infiltration increasing as amount of standing and flat wheat residue on the soil surface increased up to 2.5 Mg ha^{-1} (Fig. 2, bottom). Other similar results illustrating the decreased runoff and increased infiltration and soil water storage resulting from reducing tillage intensity and increasing amount of surface crop residues were reviewed by Unger et al. (1994), Unger et al. (1998), and Unger and Stewart (1983).

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Abbreviations: PSE, precipitation storage efficiency; PUE, precipitation use efficiency based on crop dry matter or seed yield per millimeter of precipitation received; PUE$, precipitation use efficiency based on dollars returned per millimeter of precipitation received; WUE, water use efficiency.

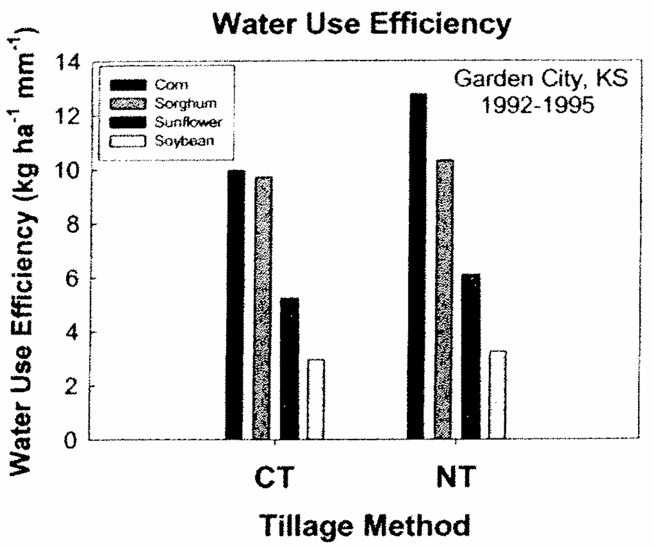

Fig. 4. Changes in water use efficiency due to crop and tillage system at Garden City, KS. CT = conventional tillage; NT = no-tillage. Data from Norwood (1999).

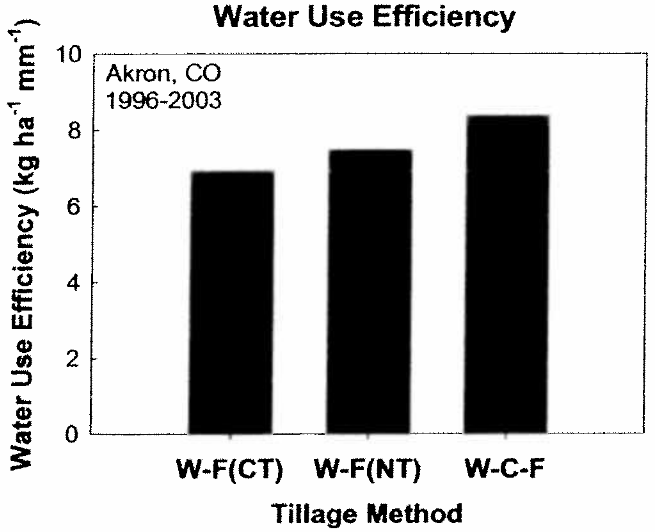

Fig. 5. Changes in water use efficiency due to tillage system at Akron, CO. Data from Nielsen (unpublished data, 2003). See Table 1 for a definition of cropping system abbreviations.

WUE. Norwood (1999) showed WUE of corn (*Zea mays* L.) and sunflower increasing by 28 and 17%, respectively, when the production system moved from a conventional tillage[1] system to a no-till system in a winter wheat–spring crop–fallow rotation (Fig. 4). On the other hand, the increases in WUE that he reported for sorghum (6%) and soybean [*Glycine max* (L.) Merrill] (10%) were not significant. Similarly, WUE of winter wheat at Akron, CO, increased from 6.9 kg ha^{-1} mm^{-1} in a winter wheat–fallow conventional till [W-F(CT)] system to 7.5 kg ha^{-1} mm^{-1} in a winter wheat–fallow no-till [W-F(NT)] system to 8.4 kg ha^{-1} mm^{-1} in a winter wheat–corn–fallow no-till (W-C-F) system (Fig. 5) (Nielsen, unpublished data, 2003[2]). These increases corresponded to increased plant available water at wheat planting (Nielsen et al., 2002), resulting in lower water stress and better plant condition throughout the entire growing season. The longer interval between wheat crops may also have reduced root diseases (Cook and Haglund, 1991), thus improving efficiency of water uptake although root diseases in winter wheat are rarely observed in this region.

Furrow Diking Effects

In the southern Great Plains, attempts have been made to alter the soil surface by use of furrow diking (basin tillage) in which small earthen dams are constructed at short intervals in furrows to increase surface detention storage, thus preventing runoff and increasing infiltration (Jones and Stewart, 1990). In doing so, more efficient use of precipitation should be made as water is retained in the soil system and used for production of yield. Results show furrow diking has not consistently increased yields or WUE. For those increases to occur, precipitation and soil conditions must exist that would result in runoff if the furrow dikes were not present (Gerard et al., 1984). In Texas, Baumhardt et al. (1993) noted that furrow diking sometimes increased soil water losses to evaporation, resulting in lower yields even though runoff was reduced. They also concluded that furrow diking does not always result in large increases in soil water because many rain events are small ($<$20 mm) and are lost to evaporation and that no-tillage of high-residue crops was more effective than furrow dikes for increasing water conservation on nearly level soils in semiarid regions.

Crop Type Effect on WUE

Water use efficiency varies with crop type and plant part being harvested. Water use efficiencies are higher for forage crops where the entire aboveground portion of the plant is harvested compared with WUEs for grain production (Fig. 6). The highest average WUE among forage crops grown over 6 yr at Akron, CO, was 22.8 kg ha^{-1} mm^{-1} for forage pea (*Pisum sativum* L.), declining to 11.4 kg ha^{-1} mm^{-1} for corn silage (Nielsen, unpublished data, 2003). Grain WUE ranged from about 7.5 kg ha^{-1} mm^{-1} for proso millet (*Panicum miliaceum* L.) and corn to 3.0 kg ha^{-1} mm^{-1} for sunflower. Biederbeck and Bouman (1994) reported 6-yr average WUE of 18.7 kg ha^{-1} mm^{-1} for dry pea dry matter and 15.3 kg ha^{-1} mm^{-1} for spring wheat dry matter at Swift Current, SK, Canada. Hatfield et al. (2001) provides an extensive review of literature demonstrating the high WUE observed for forage production compared with seed production (including data from the semiarid southern plains) and the relatively high WUE observed for starch seed production compared with oilseed production.

The relative differences in WUE between crop types

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[1] Conventional tillage consisted of three or four tillage operations during the flow period using a sweep plow.

[2] The unpublished data from Akron presented here and later are from an alternative crop rotation experiment described in Bowman et al. (1999), Anderson et al. (1999), and Nielsen et al. (1999).

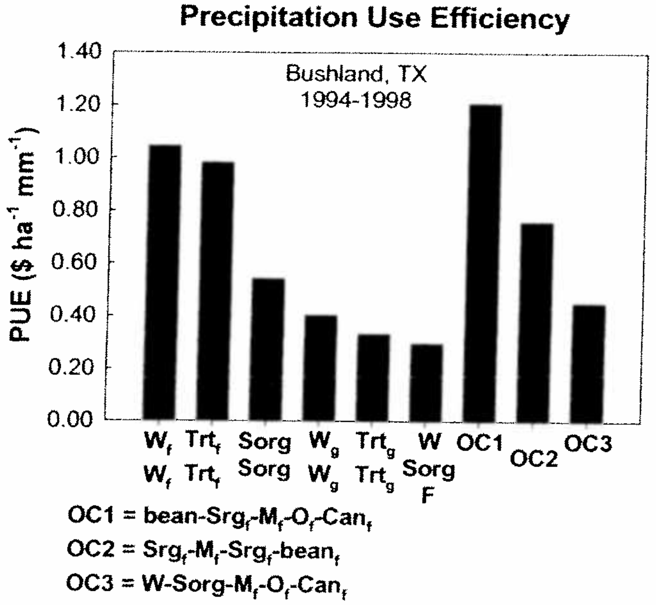

Fig. 16. Precipitation use efficiency (PUE, value basis) for various continuous cropping systems at Bushland, TX. Cropping system abbreviations are defined in Table 1. Data from Unger (2001).

face alterations that reduce runoff and increase infiltration of precipitation, cropping sequences that minimize fallow periods, and use of appropriate management practices for the selected crop (e.g., adapted cultivars, appropriate fertility levels, and effective weed control). Precipitation use efficiency on a mass-produced basis is highest for systems producing forage and lowest for rotations with a high frequency of oilseed crops. Throughout the Great Plains region, PUE decreases with more southern latitudes for rotations of similar makeup of cereals, pulses, oilseeds, and forages. Forage systems in the southern Great Plains appear to be highly efficient when PUE is computed on a price-received basis. In general across the Great Plains, increasing intensity of cropping increases PUE on both a mass-produced basis and on a price-received basis. However, continuous cropping under dryland conditions in the semiarid Great Plains remains risky due to the limited precipitation (erratic in distribution and frequency) and high potential evaporation, especially in the southern Great Plains.

In the future, increases to semiarid dryland system WUE and PUE may come from continued improvement in managing residues, herbicides, and crop choice. We suggest the following as potentially fruitful areas of research that may improve system WUE:

1. Increase amount and persistence of crop residues. Crop residues on the soil surface increase infiltration, reduce runoff, and reduce evaporation. Unfortunately, residue amounts often are limited due to low precipitation during the growing season, rapid decay (especially in the central and southern plains), or partial incorporation into soil by tillage even though the amount of tillage may be reduced. Ways should be sought to increase residue retention on the soil surface. Possible methods include the use of stripper headers for harvesting and development and use of more effective herbicides. By using stripper headers, virtually all of the plant stems remain upright, resulting in slower residue decomposition and greater shading and wind speed reduction, thereby reducing soil water evaporation. Similarly, it may be possible to plan the proper sequencing of crops to provide optimum crop residue type, orientation, and amount for seeding the subsequent crop.
2. Implement flexible rotations (i.e., opportunity cropping). The occurrence of precipitation and, hence, the availability of adequate stored soil water for a crop is highly variable, especially in semiarid regions. Sometimes stored soil water at normal planting times for a crop in a given cropping system is limited; at other times, adequate water for a crop is available when the planting of a crop had not been planned, as is the case periodically in the southern plains late in the season or soon after harvesting a crop. By practicing opportunity cropping, some crop generally could be planted when water becomes available. The goal should be to grow a crop whenever conditions are or become favorable and not according to some predetermined schedule. Implementation of such a system would require careful use of herbicides to avoid adverse carryover effects. Such a system in which crop choice is determined by amount of stored soil water may not be as feasible in the northern plains where crop yields appear to be much more dependent on growing season rainfall than on stored soil water (Miller et al., 2003c).
3. Match crop cultivar selection to prevailing weather conditions. Genetic yield potential is linked positively with maturity, so cultivar evaluation trials conducted under conditions of adequate soil water and N often favor longer-maturity cultivars and influence farmer choice. For example, in the northern plains, summer drought in July typically terminates the growing season and consequently early maturing cultivars, with lower genetic yield potential, may yield relatively greater. In the southern plains, a producer may use a longer-maturity class sorghum when adequate soil water is available at early planting times, but a shorter maturity class when planting is delayed.
4. Improve timeliness of cultural operations, including early seeding of crops and optimum timing of weed control, and time operations to coincide with favorable conditions as predicted by short-term (48–72 h) weather forecasts. The land area-to-farm operator ratio is increasing steadily throughout the Great Plains, resulting in a complex web of activities competing for timeliness. Herbicide application is a critical new attribute of conservation tillage systems, and climatic conditions that permit early seeding for increased yield potential of spring and winter crops may not favor effective pre-emergent weed management. This frequently results in a compromise between pursuing optimal yield goals and weed management. This dilemma is one example that would benefit from system-oriented studies, aiming to increase crop PUE.

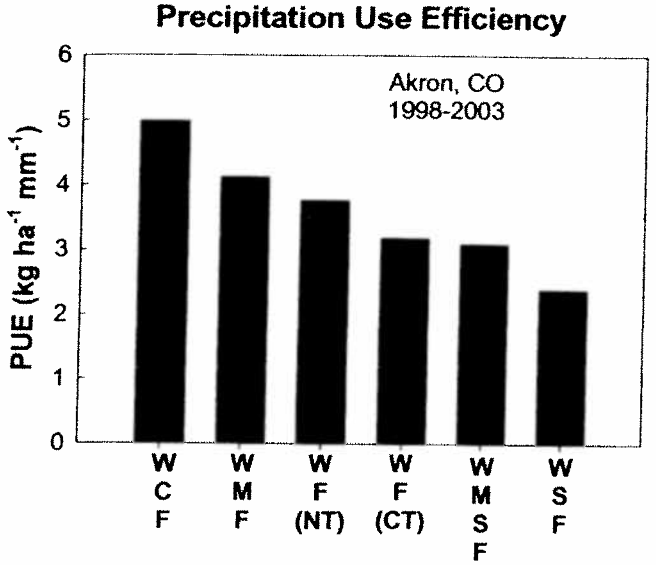

Fig. 9. Precipitation use efficiency (PUE, mass basis) for various cropping systems that include a fallow period at Akron, CO. Cropping system abbreviations are defined in Table 1. Data from Nielsen (unpublished data, 2003).

precipitation received over that period (Fig. 9 and 10). Precipitation use efficiency was improved when cropping intensity increased from one crop in 2 yr to two crops in 3 yr (W-F vs. W-C-F or W-M-F; see Table 1 for definitions of cropping system abbreviations used here and in the figures) but not when sunflower was a part of the system (in either a 3-yr or 4-yr rotation). Nielsen et al. (1999) observed that the very dry soil profile following sunflower production in a W-S-F rotation was frequently not recharged sufficiently during the subsequent fallow period to produce profitable wheat yields (about 2500 kg ha^{-1}). For the continuous cropping systems (Fig. 10), PUE was highest for systems with forage production (range 8.4–5.4 kg ha^{-1} mm^{-1}). The other continuously cropped rotations had PUEs ranging from 5.9 to 2.8 kg ha^{-1} mm^{-1}.

Due to the different photosynthetic costs of producing oil, protein, and starch, the PUE changes with the proportion of crop types in a rotation. These changes in PUE do not necessarily reflect inherent rotation water wastage or crop physiological inefficiencies. The principle of supply and demand generally takes this into account so that the photosynthetically costly plant products (oil) are worth more than the less costly plant products (starch). Using dollars per unit of precipitation received can be a more useful way to determine the efficacy and efficiency with which a given cropping system or rotation makes use of water when comparing across crop types or rotations with different proportions of crop types. Unfortunately, direct comparisons between systems with and without forage crops may still not be applicable or justified due to large differences in forage harvest/transportation costs and differences in forage grade/quality that are not accounted for (Baltensperger and Carr, 2003). Ten-year average market values [1992–2001, www.nass.usda.gov (verified 24 Nov. 2004), Table 2] were applied to the data collected at Akron, CO, to generate Fig. 11 and 12. The W-C-F rotation had the highest PUE based on dollar return per millimeter of water used (PUE$) of all of the rotations that included a fallow period ($0.531 ha^{-1} mm^{-1}; Fig. 11). Precipitation use efficiency was lowest for the W-S-F rotation ($0.338 ha^{-1} mm^{-1}). The highest PUE$ for the continuously cropped rotations (Fig. 12) was seen for the all-

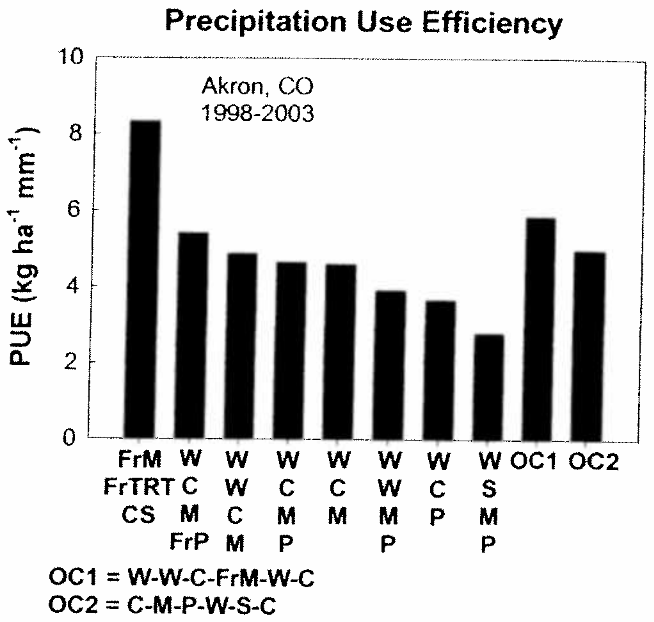

Fig. 10. Precipitation use efficiency (PUE, mass basis) for various continuous cropping systems at Akron, CO. Cropping system abbreviations are defined in Table 1. Data from Nielsen (unpublished data, 2003).

Table 1. Meanings of crop abbreviations used in Fig. 4, 5, 7, and 9–16.

Colorado and Kansas studies		Saskatchewan studies		Texas studies	
Abbreviation	Meaning	Abbreviation	Meaning	Abbreviation	Meaning
W	winter wheat	CP	chickpea	W_f	wheat for forage
F	fallow	M	oriental mustard	Trt_f	triticale for forage
C	corn	C	canola	W_g and W	winter wheat for grain
M	proso millet	DW	durum wheat	Trt_g	triticale for grain
S	sunflower	P	pea	Sorg	grain sorghum
FrM	forage millet	L	lentil	Srg_f	forage sorghum
FrTrt	forage triticale	W	spring wheat	M_f	forage millet
CS	corn silage			bean	dry bean for seed
FrP	forage pea			$bean_f$	dry bean for forage
P	pea			O_f	oat for forage
OC	opportunity cropping			Can_f	canola for forage
CT	conventional tillage			F	fallow
NT	no-tillage			OC	opportunity cropping