Efficient Crop Water Use in Kansas

K·STATE
Research and Extension

Kansas State University Agricultural Experiment Station and Cooperative Extension Service

Contents

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Introduction and Kansas Climate Overview

1
CHAPTER

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The Great Plains is an important center of agricultural production for both the United States and worldwide grain export. However, it is also a region that has numerous challenges to the sustainability of agricultural production, including soil losses from erosion, low precipitation in the west, intense thunderstorms, and declining aquifer levels that threaten availability of water for irrigation.

Water is the resource that most limits maximum crop yield potential. Through increased efforts on not only conserving but also improving soil and water resources, the region's production potential can be sustained or even increased for future generations of agricultural producers.

Kansas is at the geographic center of the United States and a crossroads in terms of climate. A water gradient, wet to dry, exists across the state from east to west, and an increasing temperature gradient occurs from north to south.

Four recognized climatic regimes are present in Kansas. Traveling from east to west, the climate transitions from humid in the extreme southeast corner, to moist subhumid in the eastern half, to dry subhumid in the western half, to semiarid in the extreme southwest corner (Keim, 2010). Limited precipitation in western Kansas is a result of both blockage created by the Rocky Mountains and distance from the Gulf of Mexico. In contrast, southeast Kansas receives significant rainfall derived from the Gulf of Mexico (Bark and Sunderman, 1990). Rainfall ranges from greater than 45 inches per year in southeast Kansas to less than 18 inches per year in the southwest portion of the state (Figure 1). Statewide, the majority of the annual precipitation occurs in the late spring and early summer (Figures 2 and 3).

Temperature (Figure 4) and growing period as indicated by frost-free days (Figure 5) increase from north to south across the state. The coolest mean annual

Figure 1. *Average annual precipitation distribution in Kansas from 1981 to 2010.*

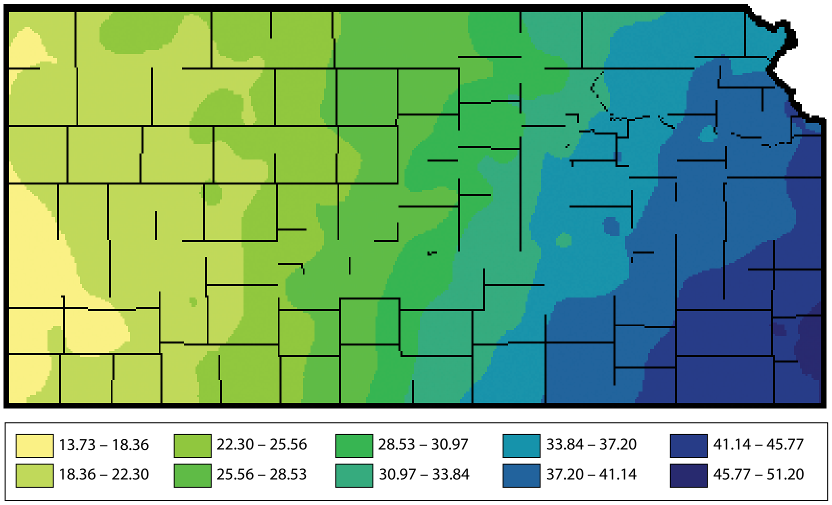


Figure 2. *Long-term and 30-year monthly average precipitation for periods ending in 1990, 2000, and 2010 in southwest Kansas.*

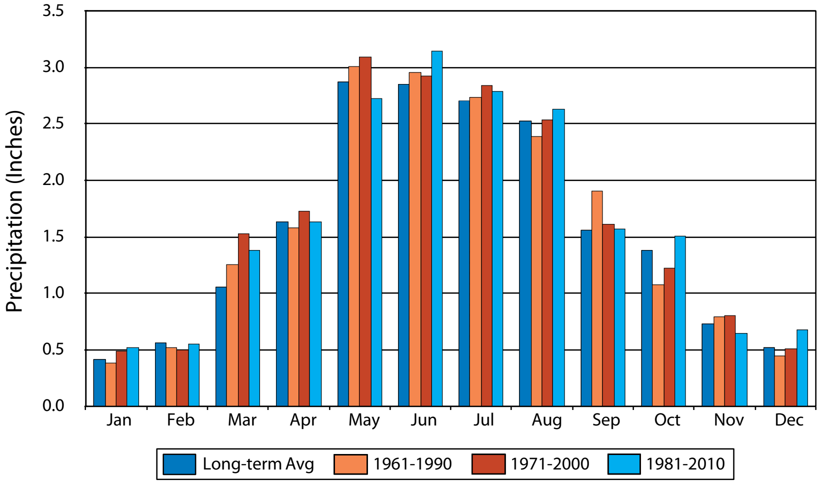


Figure 3. *Long-term and 30-year monthly average precipitation for periods ending in 1990, 2000, and 2010 in southeast Kansas.*

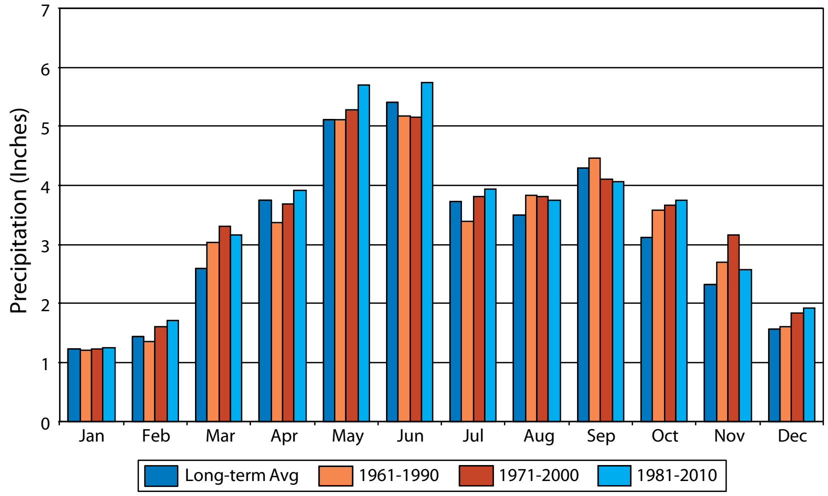


Figure 4. *Mean annual temperatures in degrees Fahrenheit, 1981 to 2010.*

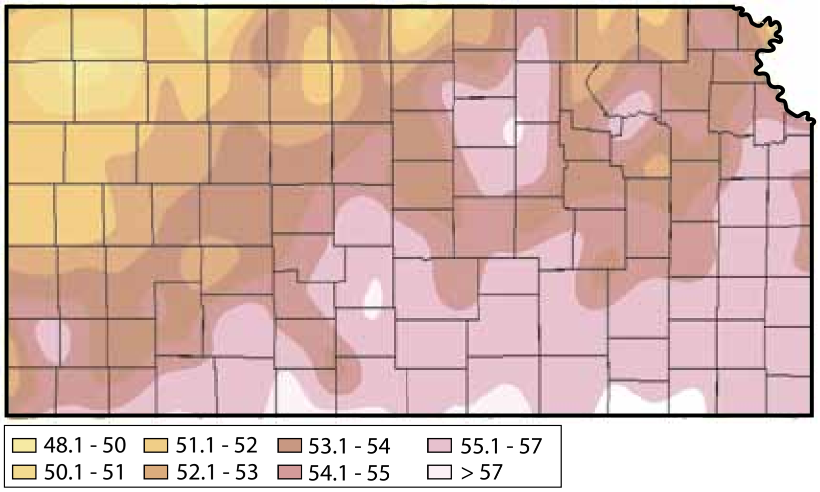
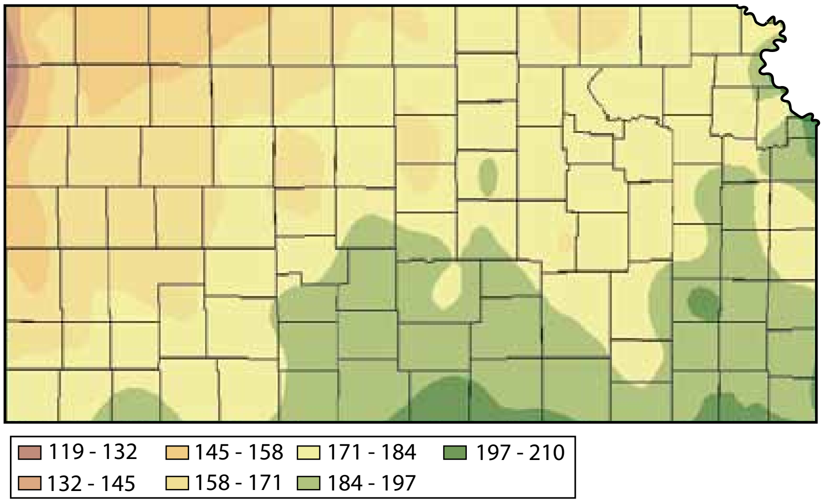


Figure 5. *Distribution of annual frost-free days across Kansas, 1981 to 2010.*



temperatures (48.1 to 50 degrees Fahrenheit) occur in northwest Kansas, and the warmest mean annual temperatures (greater than 57 degrees Fahrenheit) occur in south central Kansas (Figure 4). Similar to temperature, the fewest frost-free days (119 to 132 days) occur in the northwest and the greatest number of frost-free days (197 to 210 days) occurs in south central and southeast region of the state (Figure 5).

Tillage and Residue Effects on Crops and Soils

2
CHAPTER

DeAnn Presley
Soil and Water Management Specialist

The most effective way to increase soil water is to optimize the soil's ability to capture water and then maximize the storage by reducing evaporation and increasing the soil's organic matter. Tillage and residue management decisions can have either a positive or negative effect on the soil's physical properties, organic matter, and water content.

Residue abundance and persistence depend on the amount of crop residue that was produced, the carbon to nitrogen ratio of the residue, and the rate of microbial decomposition, which is in turn affected by temperature and moisture conditions. Tillage and other residue management factors, such as cutting height, can have a significant influence on soil water.

This chapter presents information on crop water dynamics and how tillage and residue management affect crop yield and water use.

Water Budget

Understanding some principles of water conservation and soil quality helps identify appropriate and sustainable management technologies. The hydrologic cycle and climatic factors related to crop production are the first part of this understanding.

Precipitation and irrigation are additions to the cycle. Evaporation, caused by the sun and wind; transpiration, water used by the crop; drainage through the soil profile; and runoff are losses (Figure 6).

Storage

Soils have the ability to store water, and that ability varies primarily based on soil texture and soil organic matter. Soil texture is difficult to alter, but loss of the surface horizon to erosion has had a significant effect on many agricultural soils in Kansas.

Field capacity refers to the amount of water that is stored in the soil after the excess (gravitational) water has drained away. As shown in Table 1, some water is still present in the soil at the permanent wilting point, but plants are not able to extract this water. The available water is the water between the field capacity and the permanent wilting point.

For example, for the deep, silt loam soils in western Kansas, a soil at field capacity will contain an average of 1.8 inches of water per vertical foot of soil or approximately 10.8 inches of available soil water in the upper 6 feet of the soil profile. A range of values is given for each soil texture class, and one reason for this relates to the amount of organic matter in the soil. In other words, it would be expected that a silt loam soil with 1 percent organic matter would hold less water at field capacity than the same soil texture with 2 percent or even 3 percent organic matter, because organic matter has a tremendous amount of water-holding capacity.

Crop Water Usage

Whether irrigated or rain fed, a certain amount of water is required to produce a crop. The water that enters the plant roots is used by the plant in a process called transpiration.

Figure 6. *The water budget illustration depicts sources of water (inputs) and losses of water (outputs). In the western two-thirds of Kansas, water losses exceed water inputs and can reduce crop yield potential. In the eastern third of Kansas, it is possible to have excess water, particularly in spring for earlier planted crops (such as corn), that can delay planting and emergence.*

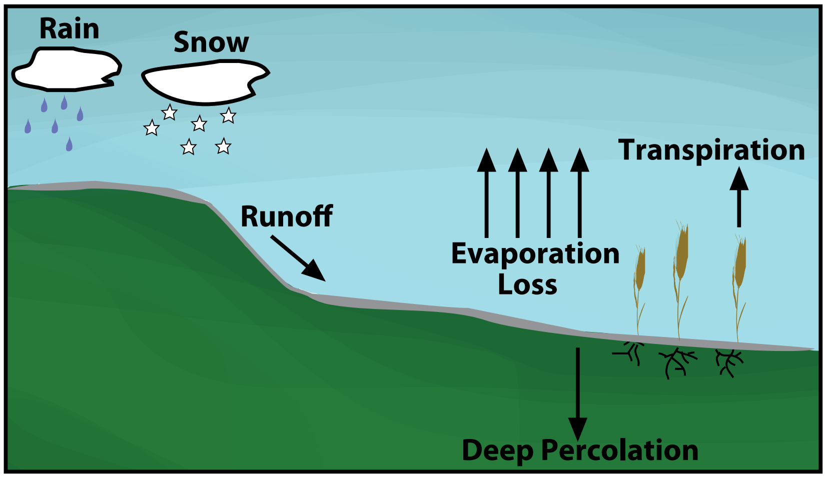
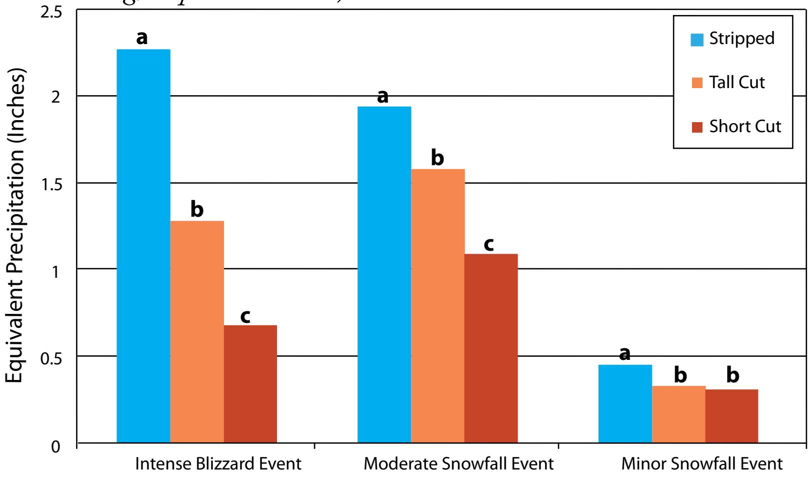


Figure 7. *Standing crop residue catches snow, which is often an important component of the annual precipitation total in the Great Plains.*

Presley

Figure 8. *The effect of residue cutting height on the amount of snow (expressed as the amount of water) caught in a western Kansas experiment (Lucas Haag, unpublished data).*



The letters above the bars indicate whether or not there are significant differences between the treatments. For example, for both the intense and moderate snowfall events, each of the stubble cutting heights was different, while there was no difference between the tall- and short-cut residue during the minor snowfall event.

Evaporation is water that is lost from the soil and not actually used by the plant. These two values are grouped together into the term *evapotranspiration*, or ET. The values are expressed in units of inches.

Scientists in Kansas have determined crop water requirements for the growing season of major crops. In Table 2, the "Threshold ET" refers to the amount of water required to get to the first unit of yield. The "Slope of Yield vs. ET" is the amount of yield gained for each additional inch of water. The difference between the "Slope of Yield vs. ET" and the last column, the "Slope of Long-term Yield vs. ET," is that the amounts in the column on the far right are lower because they include nonwater-related factors that reduce yield, such as hail, freeze damage, insects, and disease.

Precipitation capture and storage are critical to crop production. Maximizing the capture of either irrigation water or precipitation and then increasing the storage of that water by reducing runoff and evaporative losses could create gains in crop production. Strategies that affect the amount of precipitation that is captured and stored include reduced tillage or no-till (Table 3), increased residue, increased residue cutting height, and keeping residue upright. Residue on the surface reduces evaporation by physically shading the soil surface. Also, increasing the residue cutting height reduces the wind speed at the soil surface, decreasing the wind's drying potential. In addition, having taller residue results in greater snow catch (Figures 7 and 8).

Having crop residues in place on the soil surface is critical for reducing soil water

Table 1. *Water-holding capacities for soils.*

	Soil Water Content on Volumetric Basis (%)							
	Field Capacity		Permanent Wilting Point		Available Water		Water-Holding Capacity (in/ft)	
Texture Class	Average	Range	Average	Range	Average	Range	Average	Range
Sand	12	7 – 17	4	2 – 7	8	5 – 11	0.96	0.60 – 1.32
Loamy Sand	14	11 – 19	6	3 – 10	8	6 – 12	0.96	0.72 – 1.44
Sandy Loam	23	18 – 28	10	6 – 16	13	11 – 15	1.56	1.32 – 1.80
Loam	26	20 – 30	12	7 – 16	15	11 – 18	1.80	1.32 – 2.16
Silt Loam	30	22 – 36	15	9 – 21	15	11 – 19	1.80	1.32 – 2.28
Silt	32	29 – 35	15	12 – 18	17	12 – 20	2.04	1.44 – 2.40
Silty Clay Loam	34	30 – 37	20	17 – 24	15	12 – 18	1.80	1.44 – 2.16
Silty Clay	36	29 – 42	21	14 – 29	15	11 – 19	1.80	1.32 – 2.28
Clay	36	32 – 39	21	19 – 24	15	10 – 20	1.80	1.20 – 2.40

Source: Jensen et al., 1990.

evaporation, even in sprinkler-irrigated fields. In a long-term experiment conducted at Garden City, Kan., scientists quantified the amount of water that evaporated from fields that were bare (cropped and then had the residue removed) versus fields that had the residue left on the surface (Klocke et al., 2009). Crop residues that completely covered the soil surface reduced evaporation by 50 to 65 percent compared to bare soil. Klocke also observed, however, that there is no reduction in evaporation once the residue coverage is lower than 70 to 75 percent of the soil surface.

Since the average amount of water used through ET by the crop during the growing season is 24 to 26 inches, this would translate into 3.4 to 3.6 inches of water savings during the growing season. An additional 2 inches of soil moisture can evaporate in the absence of residue during the winter, adding up to 5 inches of water that can be lost in one year with low residue coverage.

This lost water can be converted into lost potential yield by multiplying by the slope of yield columns in Table 3. Alternatively, a producer could consider how much money could be saved by avoiding the costs of pumping an extra 5 or more inches of irrigation water annually. These values vary since both calculations take into consideration the market price of grain and fuel.

Research from dryland experiments has shown that crop residues are worth 2 to 4 inches annually in the central Great Plains states as well. This means that having the full surface covered by residue can conserve about 5 inches of water per year, which can be converted into yield by multiplying by the slope of yield columns in Table 3.

Fallow and Water Storage

Fallow is a common practice in the western Great Plains, with the goal being to store water in the soil profile for future crops. A common rotation has been wheat-fallow or wheat-summer crop-fallow. Wheat-summer crop-fallow is more efficient in its water use than wheat-fallow, but the fallow period in both systems is inefficient. Research shows that often less than 25 percent of the precipitation that falls during the 14-month fallow period between wheat crops is stored in the soil, and this value can be even lower in low residue situations. One solution to this issue is to avoid or reduce tillage during the fallow period, as evaporation spikes by 0.5 to 0.75 of an inch following each tillage pass. Instead of fallowing the soil, the most profitable way to take advantage of the available water is to intensify the cropping rotation (discussed in Chapter 4 of this publication).

Tillage Practices and Yields

Tillage selection depends on a variety of factors. Data in Kansas indicate that the adoption of no-till has increased to 41.5 percent of the acres planted in 2009 (Figure 9).

Tillage comparisons have been researched for many years at several experiment stations and research fields throughout Kansas. No-till and strip-till have performed well, to the extent that conventional tillage has been discontinued in several experiments.

At Tribune (western Kansas), the grain yields of wheat and sorghum have been increasing gradually in a wheat-sorghum-fallow rotation. Averaged over the past 10 years, no-till wheat yields have been 6 bushels

Table 2. *Yield vs. evapotranspiration (ET) relationship for crops of the central High Plains (Stone et al. 2006).*

Crop	Max. ET for Full-season Variety	Threshold ET	Slope of Yield vs. ET	Slope of Long-term Yield vs. ET *
Corn	25 in	10.9 in	16.9 bu/a/in	13.3 bu/a/in
Grain sorghum	21 in	6.9 in	12.2 bu/a/in	9.4 bu/a/in
Sunflower	22 in	5.4 in	218 lb/a/in	150 lb/a/in
Winter wheat	24 in	10.0 in	6.0 bu/a/in	4.6 bu/a/in
Soybean	24 in	7.8 in	4.6 bu/a/in	3.8 bu/a/in

** Long-term (multi-year) slope is less than full slope due to yield reducing factors such as hail, freeze damage, insects, diseases, etc.*

Table 3. *Wheat response to tillage in a W-S-F rotation, Tribune, 2001-2010 (Schlegel et al., 2011).*

Year	Conventional Till (bushels per acre)	Reduced Till (bushels per acre)	No-Till (bushels per acre)
2001	17	40	31
2002	0	0	0
2003	22	15	30
2004	1	2	4
2005	32	32	39
2006	0	2	16
2007	26	36	51
2008	21	19	9
2009	8	10	22
2010	29	35	50
Mean	16 bushels per acre	19 bushels per acre	25 bushels per acre

per acre greater than with reduced tillage and 9 bushels per acre greater than conventional tillage. Reasons for these gains in yields are likely due to a combination of factors, including increased storage capacity because of improvements in soil quality, discussed in the next section of this chapter, as well as decreased evaporation. For these reasons, researchers have observed 1.5 to 2 inches of additional water stored at planting as a result of no-till techniques compared with conventional till in the High Plains. Table 4 illustrates grain sorghum yields in a tillage experiment conducted at Tribune, Kan. These yields varied widely from year to year, but no-till was consistently higher yielding than reduced-till, and reduced-till was consistently higher yielding than conventional tillage.

Figure 9. *Trends in no-till adoption in Kansas, 1989 to 2009. Values shown are an average of 22 counties and for all crops (Source: Presley, 2010).*

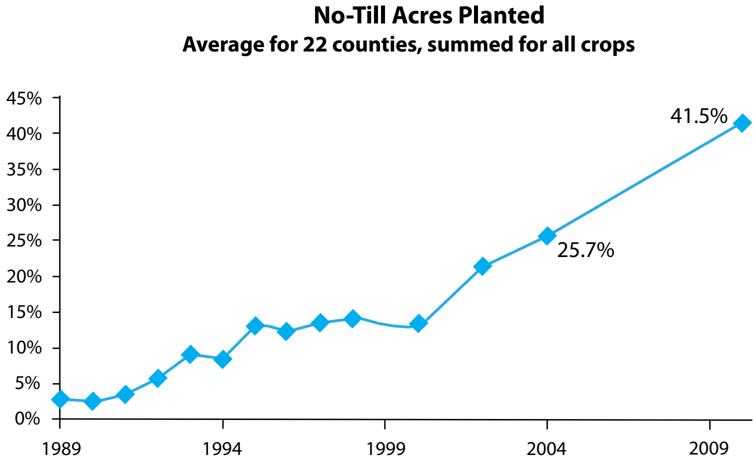


Table 4. *Grain sorghum (bu/a) response to tillage in a W-S-F rotation, Tribune, 2001-2010 (Schlegel et al., 2011).*

Year	Conventional (bushels per acre)	Reduced (bushels per acre)	No-Till (bushels per acre)
2001	6	43	64
2002	0	0	0
2003	7	7	37
2004	44	67	118
2005	28	38	61
2006	4	3	29
2007	26	43	62
2008	16	25	40
2009	19	5	72
2010	10	26	84
Mean	16	26	57

In eastern Kansas, several large-scale replicated strip experiments were completed on cooperators' fields between 2004 and 2009 (Keith Janssen, unpublished data). Table 5 shows the corn yields from 10 site-years.

Strip-tillage in eastern Kansas is advantageous because the soils can be cool and wet at corn planting. Moving residue away from the strip, combined with placing nutrients below the residue, can be positive while still gaining the previously mentioned benefits of retaining large quantities of residue on the soil surface.

Tillage Practices and Soil Properties

Another effect of tillage on soil is the subsequent changes in the soil properties, which influence the soil surface's ability to capture water, and to a certain extent, the ability to store water.

Several long-term tillage experiments exist in Kansas, and in 2006, McVay et al. documented the condition of the soil's physical properties. The study sites had been in place on average 23 years. Decreased tillage intensity led to higher organic matter content

Table 5. *Corn yields from tillage research completed in eastern Kansas.*

	Eastern Kansas tillage experiments: County Location and Year									
	FR 04	AL 04	CR 04	MG 04	AL 05	CR 06	MG 06	CR 07	SH 08	SH 09	Avg. 10 sites
Treatment	Corn grain yield, bushels per acre										
Conventional Till	185	141	154	120	145	78	105	166	183	217	149
Strip-till	199	146	167	138	147	110	106	159	189	221	158
No-till	199	146	143	125	153	109	107	164	184	218	155
LSD 0.05	13	NS	9	14	NS	6	NS	4	NS	NS	

Column abbreviations are Kansas counties: AL = Allen, CR = Crawford, FR = Franklin, MG = Montgomery, SH = Sherman

LSD: Least significant difference. The reader can use this value to determine if any two values in a column are significantly different from each other. For example, the Franklin County 2004 LSD value is 13, meaning that both the no-till and strip-till yields were 199. Since these are 14 bu/a greater than the conventional till treatment, and the difference (14) is greater than the LSD (13), both no-till and strip-till results outperformed conventional tillage that year at that site.

and better soil structure (greater aggregate stability) in the upper 2 inches of the soil profile, with no differences at greater depths. The study sites included Tribune, Hays, two sites near Manhattan, and Parsons, Kan. One of the sites near Manhattan was at the Ashland Bottoms site along the Kansas River. At this site, the water-holding capacity of the soil in the no-till sites was greater than at the conventional tillage sites.

The effect of greater soil organic matter in the surface 2 inches might seem minor, but, infiltration is defined as the movement of water through the soil surface into the soil profile. If the soil surface has a stable structure and good residue coverage, those factors make a tremendous difference in the soil tilth — how well the soil can be planted, and how well it resists crusting. It also affects both the air and water relations.

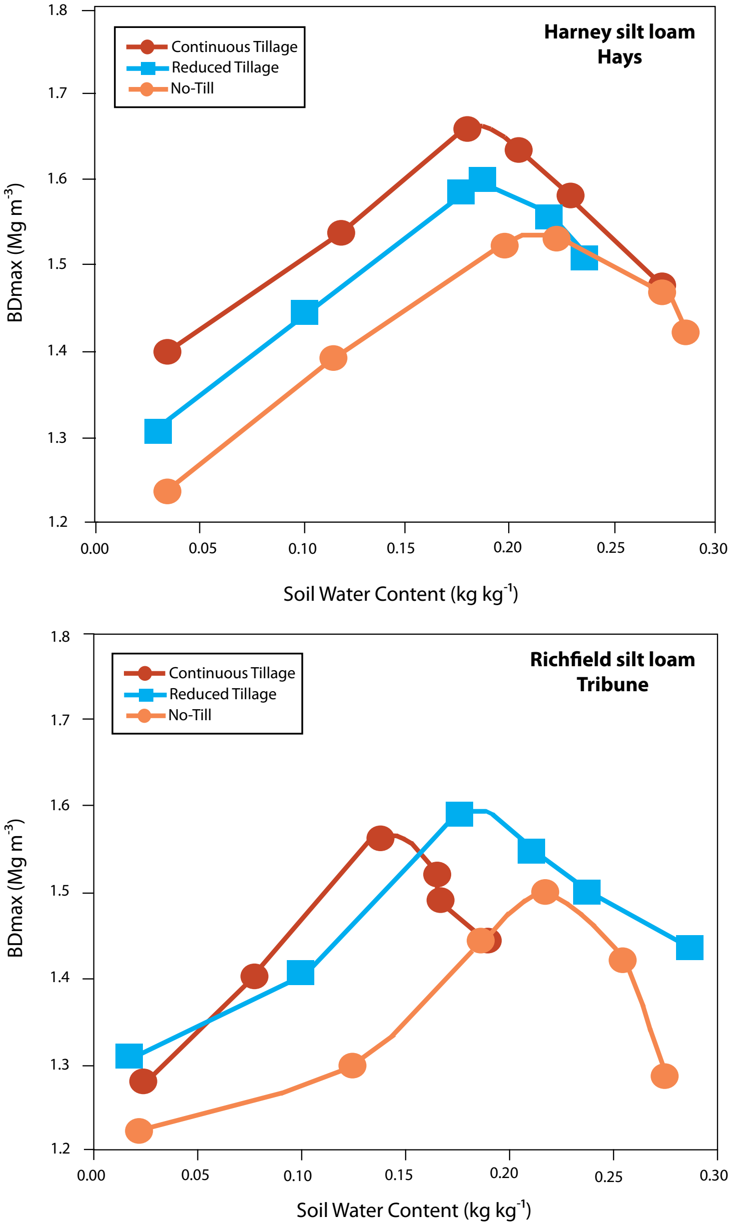
In a long-term experiment at the North Agronomy Farm in Manhattan, Kan., Presley et al., (2012) observed steady-state infiltration rates of 3.2 inches per hour for no-till, versus 2.3 inches per hour for conventional tillage in a long-term tillage trial. In this study, no-till also accumulated more organic matter than the conventional tillage and was less dense throughout the upper 6 inches of the soil. Eliminating tillage may improve soil's ability to resist compactive forces, which in turn, allows a soil to more effectively capture water when rain falls (Figure 10). Blanco et al. (2009) collected soil from two long-term tillage studies at Tribune and Hays, Kan. They observed that no-till soils had the lowest maximum bulk density (BDmax), which means they resisted compaction better than either reduced or conventionally tilled soils. Also, notice the BDmax peaks at a higher water content for the no-till, meaning that it could be withstand traffic at a higher water content and still resist compaction, compared with the other tillage practices.

Plants that grow in compacted soils experience water-related stresses, as plant roots are not able to penetrate and proliferate into the entire soil profile in drought conditions. In times of high precipitation, these soils will not allow water to move through the soil and can cause poor aeration.

Summary

Improvements in soil quality lead to increases in hydraulic properties and will aid in more effectively capturing unpredictable precipitation. This further underscores the usefulness of no-till and residue-conserving management practices for the central Great Plains region.

Figure 10. *Soils that are tilled are more compactable than soils in a no-till program, and no-tilled soils can be traversed by equipment at relatively higher water contents. Data shown are from Blanco et al., 2009, for analyses done in long-term studies at Hays and Tribune, Kan.*



3

CHAPTER

Evaluating Center Pivot Nozzle Package Performance

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Performance is a process or manner of functioning or operating. The primary function of a center pivot nozzle package is to deliver irrigation water to a targeted area. Successful irrigation performance with a growing crop requires irrigation water to be distributed across the soil surface and to infiltrate into the crop's root zone. If, at full irrigation capacity, the irrigation water is uniformly distributed and evenly infiltrates the soil, individual plants can equally access the water in sufficient quantity to prevent yield-limiting water stress. Minimal losses in the irrigation application, or high irrigation efficiency, are an indicator of the successful performance of a center pivot nozzle package.

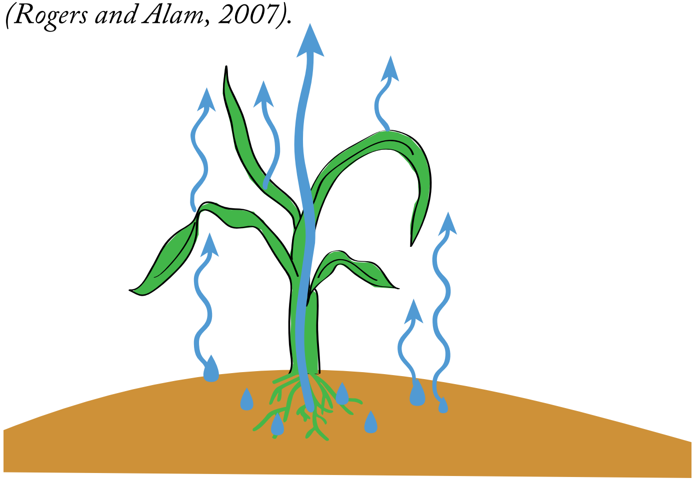
Effective management of off-season and in-season precipitation increases irrigation efficiency by reducing total irrigation water requirements and improving its productivity. Irrigation scheduling, most often used during the growing season, is important for determining when and how much to irrigate. Irrigation scheduling also minimizes irrigation water application relative to crop-water demands. It is essential to minimize irrigation need and improve water productivity in conjunction with beneficial cultural practices. Some important cultural practices involve the tillage system (surface residue management) along with planting date and density.

Table 6. *Typical range of crop-water use for crops in the Central Plains.*

Crop	Seasonal Crop-water Use (ET) (inches)*	Ratio of max daily crop ET as compared to grass reference ET**
Alfalfa	32 – 48	1.20
Corn	22 – 30	1.20
Wheat	16 – 22	1.15
Sorghum	16 – 22	1.10
Sunflowers	16 – 20	1.15
Soybeans	18 – 24	1.15

* *adapted from Shawcroft, 1989.*
** *Doorenbos and Kassam, 1979.*

Figure 11. *Illustration of evaporation and transpiration (Rogers and Alam, 2007).*



Crop Water Use

Different crops require varying amounts of water for optimum yield. This amount also varies with seasonal growing conditions and cultural practices, such as planting date. Daily water use rates also will vary based on the growth stage of the crop and weather conditions, although crops in general can use about the same amount of water on a daily basis. Typical crop water use values are shown in Table 6. The atmospheric demand (temperature, solar radiation, wind, and humidity) is the major influence on crop water use for a given crop, but planting date and planting density also can alter water use. These same factors also influence water productivity, or the amount of yield per unit of water, measured as either total water use or irrigation water use.

An accepted method of estimating crop water use is through evapotranspiration (ET), which is calculated using weather information. The term evapotranspiration is the combination of two terms: evaporation and transpiration (Figure 11). Evaporation is water that returns to the atmosphere directly from wetted plant surfaces, wetted soil surfaces, or wetted residue cover. Transpiration refers to the water that is transported from soil water reserves through the root system, stems, and leaves of a plant before being released to the atmosphere. A primary function of transpiration is the cooling of the plant. A small amount (approximately 1 percent) of the water absorbed by the plant is used for photosynthesis. Nutrients are also transported as water moves from the soil into the plant.

Evaporation (E) and transpiration (T) are difficult to measure separately, hence the combined term, ET. In conventionally tilled irrigated crops, the evaporation portion of ET is generally about 30 percent of the seasonal crop-water budget but may be reduced by half when high-surface-residue tillage systems are used (see Chapter 2). Early in the season, when the crop is small and does not cover or shade the soil surface, more sunlight and wind energy reach the soil surface and a higher portion of the ET comes from evaporation. After the canopy closes, almost all ET becomes transpiration. Evaporation can be suppressed in irrigated agriculture by increasing planting density to encourage rapid ground cover and by minimizing the frequency of canopy wetting by irrigation events when using sprinkler systems. Crop yield is generally proportional to the amount of crop water use.

A study in southwest Kansas (Klocke et al., 2007) measured soil water evaporation under sprinkler irrigation for various levels of crop residues. Figure 12 shows that soil evaporation was reduced for the treatments with either corn stover or wheat stubble. The soil evaporation ratio was reduced from 0.3 to approximately 0.15 for the residue treatments. Figure 13 shows that the average soil evaporation decreases with increasing residue levels. In addition to suppressing soil evaporation during the growing season, especially when the crop canopy is small, residue also suppresses soil evaporation in the non-growing season and helps capture more off-season precipitation. High surface residues are usually associated with both no-till and limited tillage practices that conserve soil water otherwise lost during a tillage operation.

Irrigation Requirement

Average annual precipitation in Kansas ranges from 15 inches on the western border to more than 40 inches in southeast Kansas. While much of the precipitation falls during the spring and summer growing seasons, almost all summer-grown crops in Kansas experience some yield-limiting water stress. Rainfall distribution rarely matches the varying crop water use requirements across the state. The net effect is that irrigation needs are greatest in western Kansas and less in eastern Kansas, as depicted in Figure 14. An 80 percent chance rainfall is a low rainfall amount or a dry year. The annual rainfall

Figure 12. *Average daily evaporation (Avg E), crop evapotranspiration (ETc), and the ratio of E and ETc for bare, corn stover, or wheat stubble soil surface treatments (Klocke et al., 2007).*

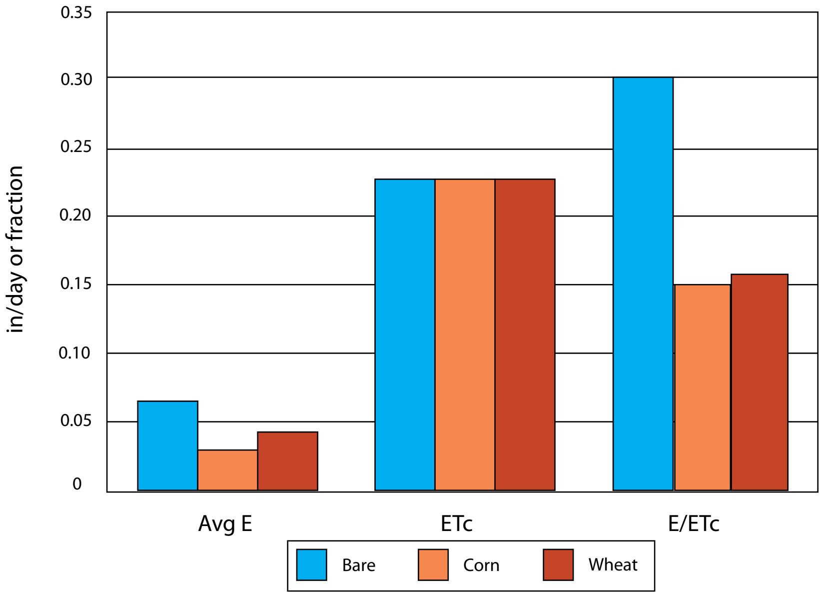
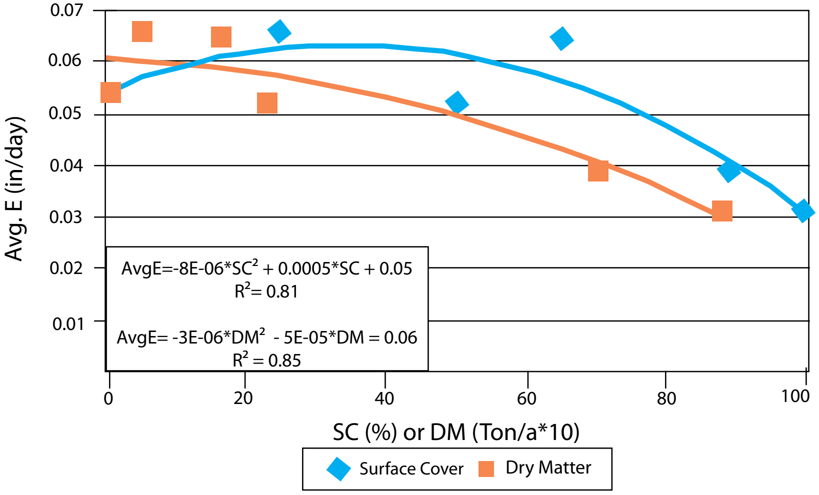


Figure 13. *Correlation of average daily evaporation (Avg E) with either percent of surface coverage (SC) or crop residue dry matter (DM) (Klocke et al., 2007).*



received at a given location would be expected to exceed the 80 percent rainfall amount in 8 out of 10 years on average.

Irrigation Capacity

Crop irrigation helps prevent yield-limiting water stress. Typical seasonal crop water requirements were shown in Table 6. For example, the irrigated corn growing season is usually from early May to early September. The average water-use rate may be 24 inches per 120 days or 0.20 inch per day. This is much less than the peak rates, which can approach or exceed 0.5 inch per day. A more typical peak water use rate, however, is considered to be about 0.35 inch per day.

Figure 14. *Net irrigation requirement for corn in inches for 80 percent chance rainfall (dry year) (NRCS Kansas Irrigation Guide).*

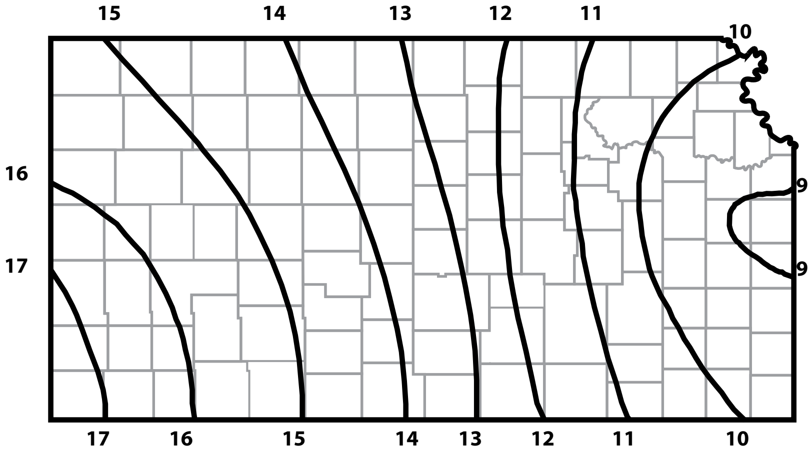
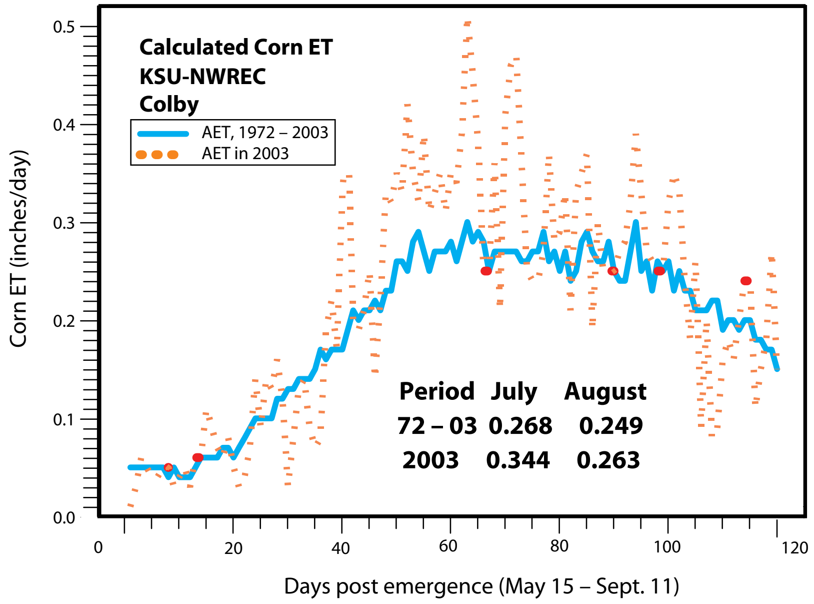


Figure 15. *Long-term corn evapotranspiration (ET) daily rate and ET rates for 2003 at the KSU Northwest Research-Extension Center, Colby, Kan. (Lamm and Stone, 2005). ET rates calculated using a modified Penmen approach (Lamm et al., 1987).*



These ranges provide some insight to the required system irrigation capacity needed to meet the crop-water requirement.

Irrigation system capacity is the average depth of water applied to a field if the entire field was watered in one day. It can be calculated by the following equation:

$$\text{System Capacity} = \frac{\text{gpm (hrs)}}{\text{450 (acres)}}$$

450 is a conversion factor; 450 gpm = 1 acre-inch per hour
gpm = flow rate to irrigation system in gallons per minute
acres = irrigated area, acres
hrs = hours of operation per day; usually 24 hours per day

For example, a system irrigating 128 acres with 650 gallons per minute, running continuously, will have a gross system irrigation capacity of 0.27 inch per day. To obtain the net irrigation system capacity, multiply the gross capacity by the system irrigation efficiency.

In this example, the irrigation time refers to the continuous operation of the system. In-season pumping hours can be lost due to electrical load interruption or regular system maintenance activities, such as oil changes. To maintain consistent irrigation capacity during times when the system must be shut down, the flow rate into the system must be increased to compensate for lost irrigation time.

The day-to-day and season-to-season rate of use of crop water varies depending on factors such as crop type and weather conditions, as illustrated in Figure 15. As a result, no exact answer exists as to what specific irrigation capacity is needed. Soil water storage provides a buffer or water reserve for the crops, so system irrigation capacity is generally less than peak daily-use rate. Deep-rooted crops and soils with high water-holding capacity need less irrigation capacity for reliable crop production than shallow-rooted crops and sandy soils. Many irrigation systems have a capacity of much less than the peak-use rate. Systems in Kansas with capacity greater than 0.25 inch per day are typically low risk when operated on soils with high water-holding capacity, as shown in Figure 16. On soils with low water-holding capacity, such as sand, the water reserves are much less, and system irrigation capacities of 0.3 inch per day or greater are needed to prevent yield-limiting water stress. Irrigation systems with irrigation capacities less than these examples are considered to have low irrigation capacity.

Irrigation capacity is an important consideration when designing an irrigation system. An oversized irrigation capacity results in underused resources and increased investment costs. Low irrigation capacity increases the risk for yield-limiting water stress and, in extreme cases, results in severe economic loss and a waste of applied water (Figure 17).

Irrigation Efficiency

Irrigation efficiency is defined as the percentage of beneficial water of the total water delivered to a field. While the most common use of delivered water is meeting crop-water requirements, other beneficial uses include salt leaching, crop cooling, and chemical applications. Most Kansas irrigation systems, however, are used primarily to supply water for crop use (Figure 18). For irrigation efficiency to have practical meaning, the quantity of water delivered to the crop is assumed to be in economic quantities. For center pivot systems, the delivery also is presumed to be uniformly applied (see the *Distribution Uniformity* section).

Most irrigation systems, even when the water is used to apply chemicals, are single purpose in that the water is applied to meet crop requirements. Water application efficiency (E_a) is the percentage of water delivered to the field that is used by the crop or

$$E_a = 100\,(W_c/W_f)$$

W_c = water available for use by the crop
W_f = water delivered to the field

Since most Kansas systems are single-purpose, the terms water application efficiency and irrigation efficiency are used interchangeably.

Irrigation water losses, as shown in Figure 19, can be divided into air losses, canopy losses, and soil losses. The center pivot nozzle package system design and management should minimize or eliminate surface

Figure 16. *Corn, Colby, Kan., Normal Probability, 1972 – 95 Full-sized 126-acre sprinkler (F.R. Lamm) for high water-holding capacity soils for two application efficiencies (AE).*

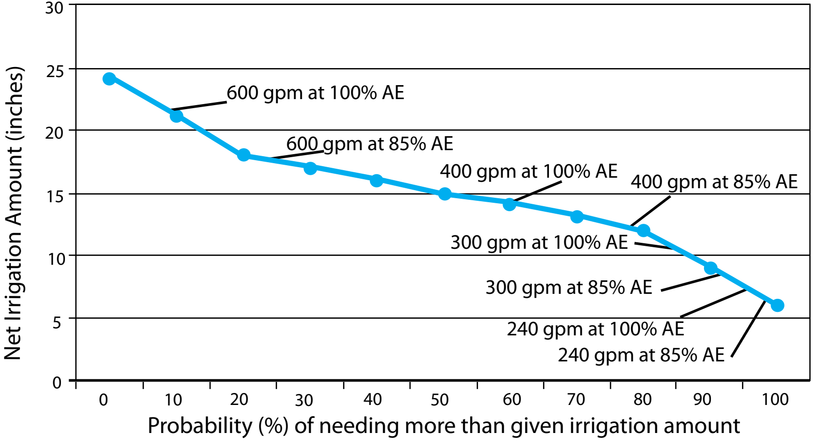


Figure 17. *Drought-stressed irrigated corn, summer 2002 in western Kansas. The pivot was operating when the picture was taken.*

Figure 18. *A modern center pivot irrigation system delivers water to a growing corn crop.*

runoff and deep percolation. Percolation losses may still occur during unusually large precipitation events.

Although surface runoff or water redistribution still occurs on individual fields, surface water losses have generally decreased due to sprinkler package designs that are more closely matched to field conditions. Also, the adoption of no-till or limited-tillage on fields results in high crop-residue covers that reduce the potential for surface runoff and early season soil evaporation losses. Deep percolation losses also have been minimized as more irrigators incorporate irrigation scheduling into their management practice. An increase in the number of low-irrigation capacity systems also means that during the crop season, over-irrigation is less likely.

More than 90 percent of irrigated acreage in Kansas is watered by center pivot irrigation systems, which, with proper package design and operation, could eliminate irrigation water runoff. Deep percolation losses also should be minimized with proper irrigation scheduling. The remaining irrigation losses, as shown in Figure 19, occur either in the air, from the crop canopy, or from the soil. These losses occur as evaporation to the atmosphere, so the irrigation water is consumed just as the water involved in the crop transpiration process. Summarily, if an irrigation system is properly designed and operated (no surface runoff) and properly scheduled (no deep percolation), then essentially all applied water is used consumptively during a single irrigation event. This conclusion, however, may be different when viewed on a longer time scale, as will be discussed in the *Annual Irrigation Consumptive Use Analysis* section.

Figure 19. *Locations of irrigation water losses for a center pivot nozzle package (Rogers et al., 1997).*

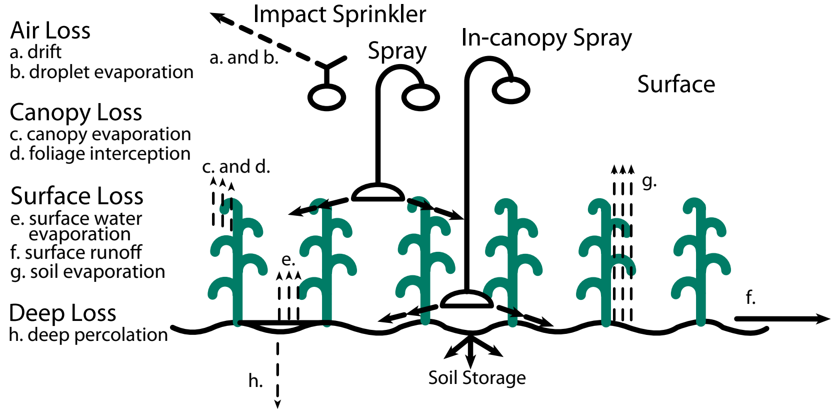
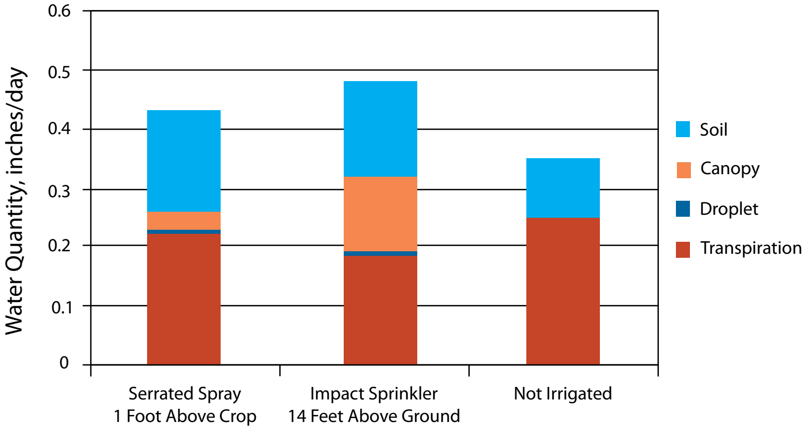


Figure 20. *Evaporative losses for impact and spray nozzle devices (Thompson, et al., 1997) Data was collected at Bushland, TX; 90° F, 15 mph wind speed, and dry.*



An example of how design criteria affect irrigation losses is illustrated in Figure 20. Three water-use scenarios are shown for two irrigated conditions and one nonirrigated condition. For the nonirrigated condition, no water losses occurred due to canopy or drop evaporation since no irrigation occurred. Some soil evaporation took place, but there was a high level of transpiration. For the two irrigated conditions, a small sliver is shown to represent droplet evaporation, or the evaporation that occurs while the water droplet is in flight. The soil evaporation was greater in the irrigated condition as compared to nonirrigated due to the recently wetted soil surface from the irrigation. Between the two irrigated conditions, the spray just above the crop canopy had less canopy evaporation than the impact sprinkler. Spray nozzles have a much smaller wetted diameter than an impact sprinkler, watering a specific location in a field for less time and reducing the opportunity for canopy evaporation.

Distribution Uniformity

Distribution uniformity is discussed by Rogers et al., 1997 and illustrated in Figure 21. This term indicates the consistency in the depth of irrigation water applied to the soil and the amount of the water infiltrated into the soil. The former may be associated with depths applied at the surface based on catch-can measures for sprinkler systems. The latter is associated with soil water measurements after infiltration, which are much more difficult to collect than surface measurements.

The concept of uniformity for sprinkler systems was developed by Christiansen in 1942. High uniformity is generally associated with optimum crop-growth conditions, since each plant has equal opportunity to use applied water. Nonuniformity results in areas that receive too much or not enough water. In particular, overwatered areas may cause a decrease in irrigation efficiency if the water moves below the crop root zone and is lost for crop water use.

Example of a Center Pivot Irrigation Uniformity Test

Sprinkler irrigation systems should be designed for the most uniform application possible. A nonuniform application will result in areas of a field receiving too little water (deficit irrigated or under-watered), as well as areas receiving too much water (excess irrigation or overwatered). Either condition can result in lower yields and decreased system efficiency. The uniformity of the sprinkler nozzle package design is affected by the operating conditions and environmental factors, especially wind. Wear of nozzles, incrustation buildup, and canopy interference also affect uniform distribution. Uniformity also decreases if system pressure is not kept at the design pressure.

Figure 22 shows the results of a center pivot uniformity test. Section A of the pivot illustrates a portion of the sprinkler package that performed well and had a uniformity coefficient of almost 90 percent. In section B, a leaky boot connection between two spans was caught in one container. Section C represents the area covered by the outer two spans of the system and shows areas of excess and deficient watering. In this case, the problem was improper installation. The nozzle sizes for the two spans were switched during installation. Section D of Figure 22 demonstrates the effect of a malfunctioning end gun. In this case, the operation angle of the end gun was improperly set and was overspraying the nozzles of approximately one-third of the last span as well as the overhang of the center pivot. In this example, all the causes of poor uniformity were easy and inexpensive to correct.

Irrigation Efficiency Influence on Irrigation Schedules and Crop Water Use

Table 7 illustrates the effect of improving irrigation efficiency on a water budget for a corn crop during an example year with average seasonal ET and rainfall. The water budgets were made using KanSched, an

Figure 21. *Illustration of a sprinkler package water distribution uniformity versus infiltrated water distribution uniformity in the soil (Rogers et al., 1997).*

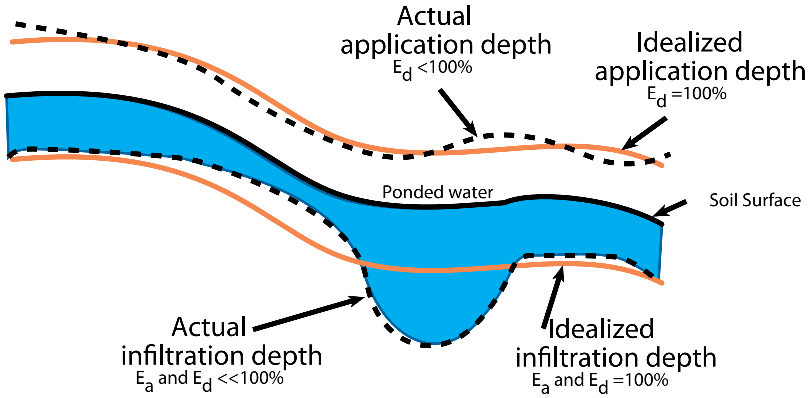


Figure 22. *Uniformity test results for a Mobile Irrigation Lab uniformity evaluation (Rogers et al., 2008).*

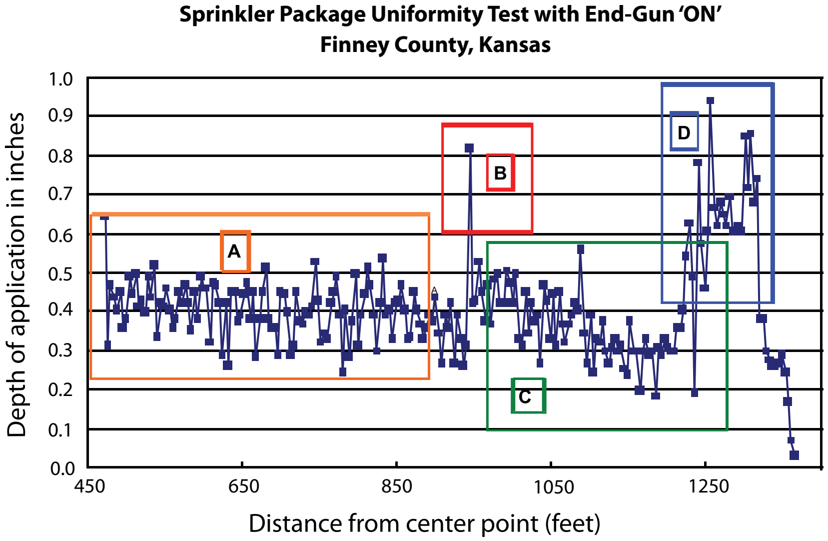


Table 7. *Effect of improving irrigation efficiency on gross irrigation requirement for corn under a low-capacity irrigation system.*

Irrigation Efficiency %	Crop ET Inches	Effective Rain Inches	Gross Irrigation Inches	Net Irrigation Inches	Number of days < 50% MAD	Lowest Soil Water Value
No Irr	17.23	12.57	0.00	0.00	51	16.1%
70	21.00	11.60	11.00	7.70	5	39.7%
80	21.09	11.49	10.00	8.00	3	46.7%
90	21.13	11.52	8.00	7.20	0	52.2%

ET-based, irrigation-scheduling program (Rogers and Alam, 2008). While the rainfall was near normal for the growing season, it was less than normal early in the season and heavier than normal late in the season. The non-water-stressed ET for the year is 21.13 inches, which would be associated with "full" yield. Three water budgets are shown in Table 7 using a low-capacity irrigation system (1 inch per 6 days). All field and crop characteristics were identical (118-day corn emerging May 1, loam soil with a 42-inch managed root zone). All irrigation water was scheduled whenever 1 inch of root zone, soil-water deficit existed and the previous irrigation was already completed. The only difference between schedules was irrigation efficiencies that were selected to be 70 percent, 80 percent, or 90 percent.

At 70-percent irrigation efficiency, there were 5 days when the root zone's soil-water content dropped below the recommended managed-allowable deficient (MAD) of 50 percent. The actual ET was 21 inches, only slightly lower than a "full" ET of 21.13 inches. The most severe stress, however, occurred during the pollination period, which is the most water-sensitive stage of growth for corn. The lowest predicted root zone soil-water level was 39.7 percent of available water, but since the stress occurred at pollination, grain yield would likely decrease. When irrigation efficiency was increased to 80 percent, the number of days below MAD decreased to 3 days, and crop ET was increased to 21.09 inches. The lowest predicted root zone, soil-water level was 46.7 percent of available water. This stress still occurred at pollination, though, so grain-yield may decrease but not to the degree of the previous example. The length and severity of the stress were also not as great as the previous example. "Full" ET was still not achieved at 80-percent efficiency, but the gross amount of irrigation water was reduced. For the 70-percent efficiency level, 11 inches of gross irrigation water was applied, as compared to 10 inches for the 80-percent efficiency level.

When irrigation efficiency is improved to 90 percent, the crop ET increases to 21.13 inches, which is the maximum for the climatic conditions and maturity length of corn used in this example. Table 7 indicates this by noting zero days of soil-water levels below 50 percent MAD. The gross irrigation application dropped to 8 inches as compared to the 11 or 10 inches of the previous examples. As irrigation efficiency was changed for this example, the irrigation schedule was also altered. In this case both gross and net irrigation applications were reduced as compared to the less efficient schedules. By chance, the high-efficiency schedule was well matched to the rainfall sequence to allow improved use of the in-season rainfall. This may not always occur.

It is possible to have an increase in irrigation efficiency that does not result in reduced gross irrigation application but instead results in an increase in the amount of water used beneficially by the crop. The data shown in Table 8 represents an increase in irrigation efficiency that did not result in a drop in gross irrigation application depth. The same weather record is used as for the example in Table 7 with the exception of the soil type and rooting depth. At 70-percent irrigation efficiency schedule, there were 9 days when soil water in the root zone dropped below the recommended managed allowable deficient (MAD) of 50 percent, and the gross irrigation application was 11 inches. Increasing efficiency to 80 percent still resulted in 11 inches of gross irrigation application, but the number of stress days was reduced to 5 and the level of stress was lower. No reduction in gross irrigation application occurred with an increase in efficiency since all the "saved" water went into meeting the water-use demand of the crop. Increasing irrigation efficiency in this example did not result in a decrease in overall pumpage because both the 70-percent and 80-percent systems pumped 11 inches of water. However, the water-use efficiency or water productivity should have been improved as the net irrigation application increased from 7.70 inches to 8.80 inches and the crop experienced stress fewer days. Since the irrigations were scheduled, meaning the water was not applied

Table 8. *Effect of improving irrigation efficiency on gross irrigation requirement for corn under a low-capacity irrigation system.*

Irrigation Efficiency %	Crop ET Inches	Effective Rain Inches	Gross Irrigation Inches	Net Irrigation Inches	Number of days < 50% MAD	Lowest Soil Water Value
70	20.80	12.10	11.00	7.70	9	38.4
80	21.04	11.44	11.00	8.80	5	44.5
90	21.12	11.45	10.00	9.00	1	49.8

unless sufficient root zone storage was available, the applied irrigation water should not be lost to deep percolation. Instead, the water loss would be associated with evaporation processes such as soil, canopy, or air losses. In this case, increased irrigation efficiency did not change the amount of water consumed from the aquifer, as the pumped water was either consumed by the crop and returned to the atmosphere or lost to evaporation due to inefficiencies of the irrigation system.

When irrigation efficiency was increased to 90 percent, a day of crop-water stress was still predicted. The example system, however, can only apply 1 inch every 6 days, a rate that is unable to meet the crop-water needs during the extended dry period of the actual weather record. For the entire season, though, the higher efficiency allowed more net irrigation water to be available, resulting in less gross pumping for the season.

When the majority of irrigation systems were surface (gravity-flow) systems, large application depths were required to advance the water across the field in the furrows. This was to ensure the root zone of the crop was filled along the entire length of the field but often resulted in deep percolation losses in the upper part of the field. A zone of deep percolation at the end of the field also occurred if excess water was diked at the bottom end. Deep percolation losses may have eventually returned to the groundwater aquifer. As irrigators in Kansas switched from surface irrigation to primarily center pivot sprinkler systems, irrigation losses changed from deep percolation to surface evaporation losses. These evaporative losses are considered "consumed" since the water is transferred to the atmosphere and not back to the aquifer.

Consumptive Use

With the exception of domestic water use, water diverted in Kansas for beneficial use is subject to the terms and conditions of the Kansas Water Appropriation Act. This act allows the transfer of water use from one type to another as long as the use of water is not increased beyond the original consumptive use, or the amount of water actually consumed while being beneficially applied. However, the amount of consumptive use may vary widely. For example, the consumptive use of water diverted for a cooling tower, resulting in evaporation, is 100 percent, while water passing through a turbine of a hydroelectric power plant has essentially zero consumptive use.

The range of consumptive use for irrigation can be large as well. For example, large-scale irrigation systems from a river diversion and canal system may have return flows of up to 50 percent, whereas a deficit-irrigated field from a groundwater well in a low rainfall area may have little or no return to the groundwater. For many properly designed and operated irrigation systems in low rainfall areas, consumptive use is often confused with crop water use.

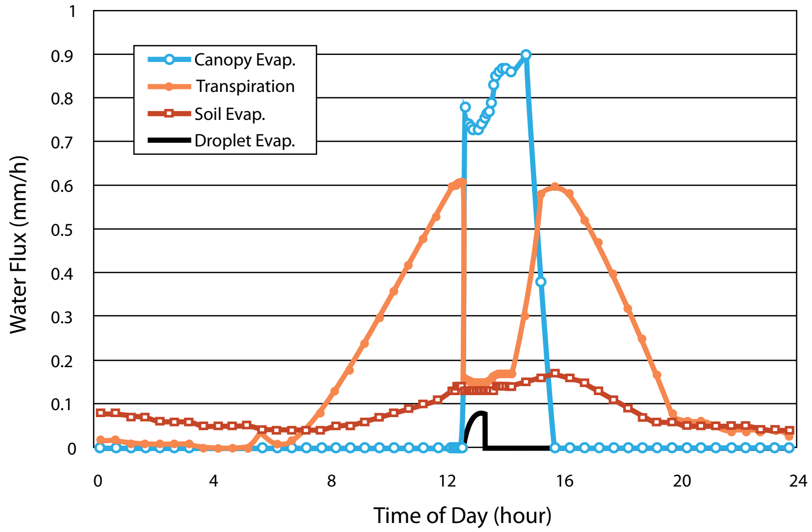
Modern center pivots and linear-move nozzle packages that are properly designed, installed, and managed minimize irrigation losses by reducing the wetted radius of the nozzles and the height of the nozzles above the crop canopy, while also selecting and operating the systems to eliminate surface runoff. Under a center pivot irrigation system, surface water movement should be eliminated with either a change in the operating procedures or a change in the nozzle-package design. Deep percolation of irrigation is minimized with proper depth of application and irrigation scheduling, although total elimination of deep percolation or drainage is not always possible due to large rainfall events. The remaining losses are due to water evaporation while the irrigation water is in flight, on the plant, or on the soil surface. These losses are, in essence, consumed, or returned to the atmosphere.

Water evaporation from a plant surface suppresses transpiration because the evaporation process cools the plant, as illustrated in Figure 23. Canopy evaporation greatly increases during irrigation, and evaporation from surfaces should not be encouraged since the evaporation process occurs much more rapidly than plant transpiration. As much as 0.20 inch of water may be needed to wet a crop canopy, although more commonly reported amounts are approximately 0.10 inch. Depending on the type of day, this water could evaporate in several hours, while on other days that same amount of water may be sufficient for the entire day if available for transpiration to the plant via the soil root zone. Therefore, many nozzle-package designs attempt to minimize evaporation losses using various nozzle configurations and placement strategies.

Annual Irrigation Consumptive Use Analysis

A simulation model was used to examine the effects of several irrigation schedules for two soil types. The average results, using multiple years of actual weather data for each of the water-budget components on an annual basis, are shown in Table 9. Silt-loam soils with high water-holding capacity were used for the northwest Kansas location, while sandy soils were used for the south central Kansas location. The application amounts used for each site were selected as typical for the region. Irrigation was limited to the frequency shown but was scheduled based on available soil water of 50, 60, and 70 percent, so a range of the total irrigation application amount was applied. A baseline crop was needed to determine how the different water-budget components would change with the addition of irrigation water and what portion of the irrigation water was associated with each change.

Figure 23. *Water use for the rotator sprinkler placed on top the pivot lateral. (Martin et al., 2010).*



For the northwest Kansas location (19.24 inches of average annual precipitation), the average ET for the simulation period was 14.40 inches for the baseline dryland corn crop. The average amount of runoff for dryland corn was estimated to be 0.94 inch, with zero predicted percolation and 3.90 inches of interception. As irrigation was added, water-budget components increased. Using the three irrigation schedules, irrigation amounts ranged from 13.90 to 16.71 inches, and ET values increased in various

Table 9. *Water budget comparisons using the Potential Yield Revised (POTYLDR) model (Koelliker, 2010) comparisons for two soil types.*

	Silt Loam Soil in Northwest Kansas				Sandy Soil in South Central Kansas			
Application Amount (inches)	1.00	1.00	1.00	Dryland Corn	0.75	0.75	0.75	Dryland Corn
Frequency in days, if needed	3	3	3		2	2	2	
@ ASW* water, %	50	60	70		50	60	70	
Irrigation, in.	13.90	15.69	16.71	None	9.39	10.99	12.24	None
Runoff, in.	1.42	1.45	1.52	0.94	1.20	1.27	1.33	1.05
Percolation, in.	0.22	0.44	1.21	0.00	6.38	7.12	8.02	4.05
Intercept, in.	4.68	4.77	4.85	3.90	3.51	3.65	3.74	2.64
ET, in.	26.74	28.18	28.26	14.40	24.33	24.98	25.18	18.34
	Additional Amounts as Compared to Dryland Corn							
	Amount of Gross Irrigation Lost				Amount of Gross Irrigation Lost			
Runoff, in.	0.48	0.51	0.58		0.15	0.22	0.28	
Percolation, in.	0.22	0.44	1.21		2.33	3.07	3.97	
Interception, in.	0.78	0.87	0.95		0.87	1.01	1.10	
ET	12.34	13.78	13.86		6.03	6.68	6.88	
Eff., % (ET/Irr)	89	88	83		64	61	56	
CU** (ET+Intc)	13.12	14.65	14.81		7.77	7.69	7.98	
CU eff, %	94	93	89		73	70	65	

* *Available soil water*

** *Consumptive use*

amounts above the baseline dryland value of 14.40 inches. The dryland water-budget components were then subtracted from the corresponding irrigated-condition water-budget component and are shown in the lower portion of Table 9. For example, for the 50-percent schedule, runoff was estimated to be 1.42 inches. However, 0.94 inch occurred under dryland conditions and, therefore, the increased runoff contribution due to irrigation is 0.48 inch. In the same example, ET increased by 12.34 inches due to the 13.90 inches of irrigation. When the two numbers are divided, the estimate of the seasonal irrigation efficiency is 89 percent. The amount of water consumed is estimated by adding ET and interception since these two amounts are returned to the atmosphere. The fate of runoff is less certain because it still may be lost to evaporation, but it was not consumed within the field.

Dividing the amount of water consumed by the irrigation amount calculates an estimate of consumptive use efficiency, or in this example, the value is 94 percent.

As irrigation water is added, both seasonal irrigation efficiency and consumptive use efficiency decrease. Since water levels in the crop root zone increase, the likelihood of losses to runoff and percolation increases due to occasional large precipitation events within the irrigation season and during the nonirrigated portion of the year.

The results for the south central location (26.08 inches of annual precipitation) on sandy soil follow the same trend as the silt loam example for both seasonal irrigation efficiency and consumptive use efficiency, but the efficiencies are considerably lower. Sandy soils have less water storage capacity and, therefore, are more prone to deep percolation losses. Also, the greater annual precipitation of south central Kansas provides more opportunities for percolation losses.

Summary

Center pivot irrigation systems can be equipped with a variety of nozzle packages that can effectively deliver water to crops. Proper design and operation of the systems are essential for high efficiency and good distribution uniformity. Irrigation application depths, total seasonal application amount, soil type, and precipitation all have an effect on seasonal irrigation efficiency and consumptive water use.

4

CHAPTER

Cropping Systems and Cover Crops

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A basic principle of efficient crop water use is shifting as much of the total water use, or evapotranspiration (ET), to crop transpiration and away from evaporation. As discussed in the previous section, increasing and maintaining crop residues reduces evaporation.

Evaporation also can be minimized by selecting crops and crop sequences that shift timing of crop growth to occupy portions of the growing season that are most susceptible to evaporation (i.e., growing a crop when precipitation is greatest).

Increasing crop intensity can reduce evaporation. Crop intensity is increased by having a greater portion of the annual cropping cycle dedicated to growing a crop versus fallow. This can be achieved either by increasing intensity of grain or forage crops or by using cover crops. Either practice can result in greater amounts of residue, helping reduce evaporation. In practice, both parts of the water-use equation (decreasing evaporation and maximizing transpiration) work together to make the most efficient use of crop-available water. This section focuses on maximizing transpiration by crop selection, sequencing, and increasing crop intensity.

Increasing crop intensity depends on balancing crop water use with available soil water, largely determined by annual precipitation and the soil's water-holding capacity. In water-limited areas, there is a point where cropping intensity is too great and not enough water can be stored during fallow periods to successfully grow a subsequent crop. A cropping system that is too intense may result in crop failure. A system that is not intense enough results in inefficient water use. Actual rainfall amount and distribution, as well as experience with particular soils and crops will influence which crops to plant and in what sequence. Dynamic rotations that base crop selection and management decisions on actual soil water conditions and realistic precipitation expectations have the greatest probability of success, both in terms of profitability and water-use efficiency. This type of crop rotation, often referred to as "opportunistic cropping," takes maximum advantage of water when the conditions are right for success.

Table 11. *Growth and water use for corn hybrids of different maturities.†*

	Short-season (98 RM)	Full-season (115 RM)
Days to physiological maturity	132	144
Grain yield, bushels per acre	180	210
Biomass yield, tons per acre	9.09	10.83
ET, emerge-phys. maturity, inches	26.5	31.6
WUE (grain), bushels per acre per inch of ET	6.79	6.65

†Adapted from: Howell, 1998.

Crop Selection and Management

Crops differ in total amount of water use and in their pattern of water use (Table 10, page 22). For example, sorghum requires less water to produce the first bushel of grain, but corn produces more grain for each additional unit of water after the threshold requirement has been met.

Within a crop, threshold and seasonal water use differ depending on the length of the growing season for specific varieties or hybrids. For example, a short-season corn hybrid produces a smaller plant, reaches maturity sooner, and uses less total water than a full-season hybrid (Table 11). Similar differences in growth and water use with short-season compared to full-season cultivars occur for other crops as well.

Timing of water use and water availability also come into play. Typically, corn is planted earlier than sorghum or soybeans, shifting key periods of water use earlier in the growing season. Most grain crops are highly sensitive to water deficits at and around the time of pollination. Figure 24 illustrates that corn pollination typically takes place when expected precipitation and temperatures are slightly more favorable than when sorghum pollination occurs at Manhattan, Kan.

Planting date can be manipulated to shift silking and pollination to a different part of the growing season. Figure 25 shows that corn silking can take place anywhere from mid-June to mid-August, depending on when the corn was planted. Planting a month later does not result in a similar delay in silking because corn develops faster when temperatures are higher. Later-planted corn (Figure 26) is exposed to higher temperatures, especially early in its development, reducing the number of days required to reach silking and eventually maturity. The range in silking dates for each planting date reflects the influence of hybrid maturity. Typically, hybrids rated from 100 to 118 days in relative maturity will silk within 3 to 14 days of each other depending on location and growing conditions.

Increasing Crop Intensity

Increasing crop intensity means that less of the growing season occurs without a growing crop, increasing transpiration relative to evaporation. Rotations that include only winter annuals or only summer annuals typically use water relatively inefficiently. Increasing crop diversity by rotating summer and winter annuals can effectively increase cropping intensity. Annual duration of fallow months in common western Kansas crop rotations averages 7.5 months in wheat-fallow, 7 months in wheat-summer crop-fallow, or 6 months in wheat/forage sorghum (double crop)-summer crop-fallow.

Annual duration of fallow months in common western Kansas crop rotations averages 7.5 months in wheat-fallow, 7 months in wheat-summer crop-fallow, or 6 months in wheat-summer crop-pea. Inserting a double crop or cover crop between wheat harvest and corn planting in this rotation decreases the average time without a crop each year to about 4.5 months. Continuous wheat is relatively crop intensive, with about 3 months without a crop each year. Unfortunately, the 3 months without a crop often have significant rainfall that is subject to runoff or evaporation.

In areas with sufficient rainfall, double cropping after winter wheat harvest can be an effective way to decrease time in fallow. Soybeans historically have been a typical choice, but corn, sorghum, sunflowers, summer-annual forages, and other crops have been grown successfully in this situation. Double-crop yields are highly dependent on rainfall amount and distribution, but are often only 50 percent or less of full-season yields for these crops when successful. Forage crops can produce some usable product with relatively

Figure 24. *Timing of pollination for corn planted April 13 to 23 and sorghum planted May 11 to 24, 2004 to 2008. Normal daily precipitation and maximum temperatures 1970 – 2000 at Manhattan, Kan.*

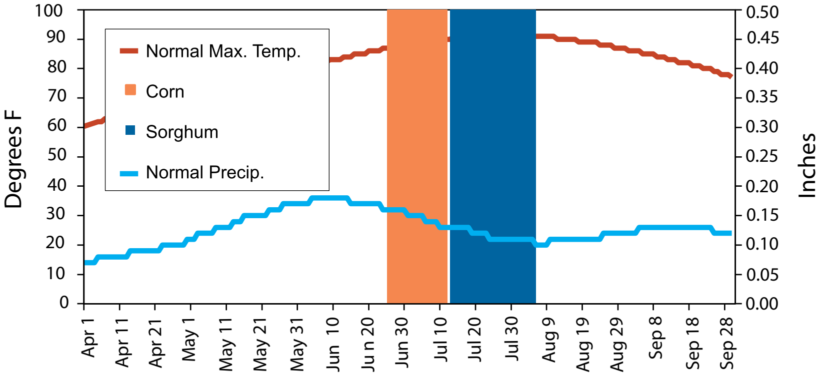


Figure 25. *Timing of corn pollination for different planting dates 2004 to 2008 and 1970-2000 Normal daily precipitation and maximum temperatures at Hutchinson, Kan.*

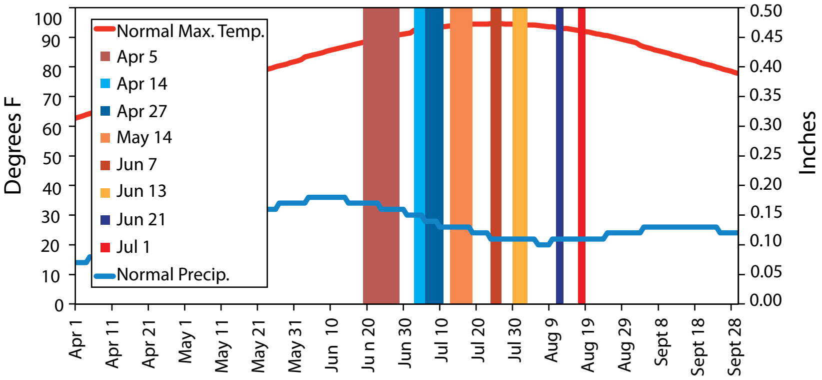
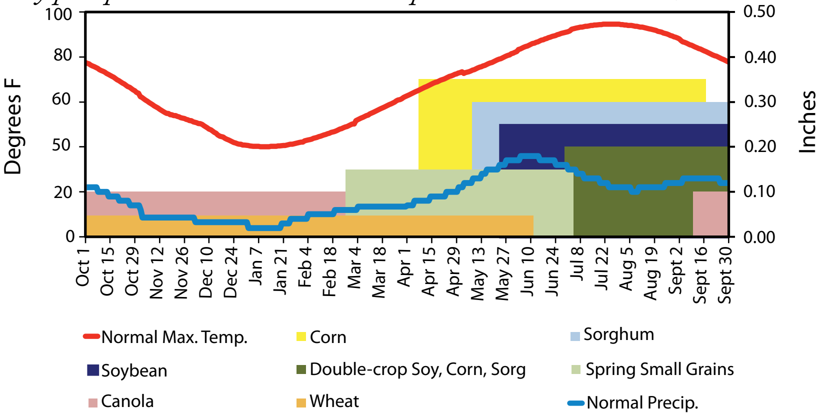


Figure 26. *Growing seasons for several crops and 1970-2000 normal daily precipitation and maximum temperatures at Hutchinson, Kan.*



little plant-available water compared to grain crops. Most grain crops can be harvested as forage if in-season precipitation does not support adequate grain yield. Whenever possible, select a double crop that adds diversity to the rotation. For example, insert a broadleaf or legume between wheat and a summer grass crop.

Cover Crops

Cover crops do not produce a marketable product, but they benefit rotations by increasing organic matter, maintaining surface residue, reducing nitrate leaching, reducing soil erosion, suppressing weeds, and adding diversity to crop sequences. Cover crops or mixtures with carbon to nitrogen ratios (C:N) greater than 25:1 generally increase longevity of residue and may tie up available nitrogen, making it less available to the next crop. Cover crops or mixtures with C:N ratios less than 25:1 generally cycle nitrogen more quickly. Nitrogen in these residues is relatively more available, and a sizable fraction may be released in time to be used by a following summer annual crop or may speed the breakdown of accumulated low-nitrogen residues from previous crops such as wheat, corn, or sorghum.

Figure 27. *Average sorghum yield response to preceding cover crop and nitrogen fertilizer over six years at Hesston, Kan.*

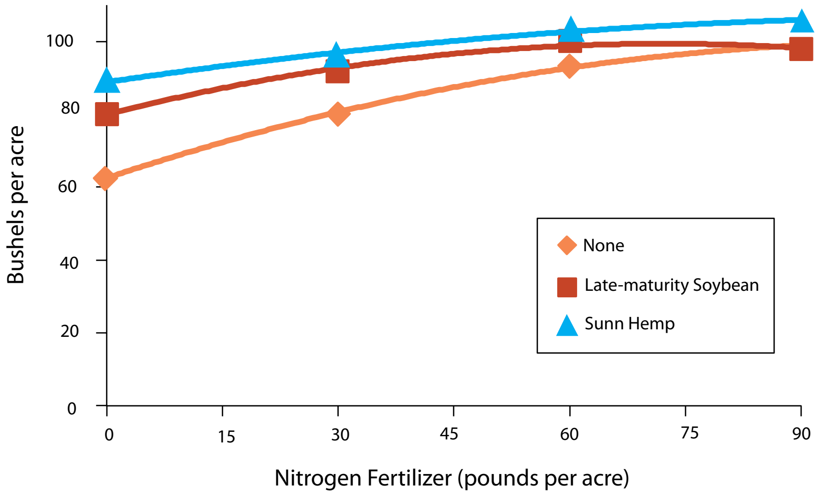
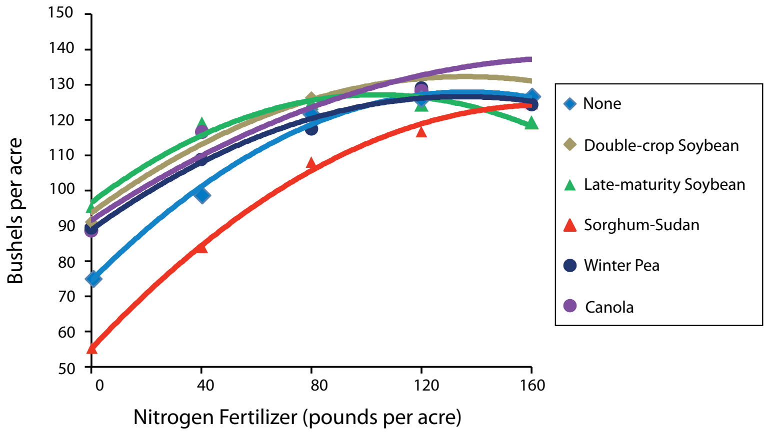


Figure 28. *Average sorghum yield response to preceding cover crop and nitrogen fertilizer over two years at Manhattan, Kan.*



Research with cover crops conducted at Kansas State University demonstrated the influence of cover crops in different rotations. Figure 27 shows the influence of late-maturity soybeans and sunn hemp in a wheat-sorghum rotation at Hesston, Kan. A late-maturing soybean cover crop increased grain sorghum yields with 60 pounds per acre or less of nitrogen fertilizer, but generally had no yield benefit compared to no cover crop when nitrogen rate increased to 90 pounds per acre. Sunn hemp resulted in greater sorghum yields at all nitrogen rates, although the yield benefit was less with more fertilizer nitrogen. When averaged over nitrogen application rates, the long-term grain sorghum yield benefits from late-maturing soybean and sunn hemp cover crops amounted to 8.8 and 14.9 bushels per acre, respectively.

Sorghum response to cover crops in a wheat-sorghum-soybean rotation at Manhattan, Kan., was similar (Figure 28). With less than 80 pounds per acre of fertilizer nitrogen, sorghum planted after double-crop soybeans or cover crops with C:N ratios less than 25:1 (late-maturity soybeans, winter pea, winter canola) yielded more than sorghum after no cover crop. Application of 160 pounds of nitrogen fertilizer per acre was required for sorghum planted after the sorghum-sudangrass cover crop to produce yields comparable to sorghum after other cover crops or after no cover crop. Sorghum-sudangrass produced large amounts of residue with a high C:N ratio that likely immobilized much of the residual and fertilizer nitrogen.

A summary of cover crop characteristics is presented in Table 12 (page 23). Grazing or cutting a cover crop for hay shifts it from being a true cover crop to being a forage crop. Timing of termination of cover crops is important and depends on what crop is being planted next, especially in more water-limited environments.

Annual forages or cover crops were grown in place of fallow in a wheat-fallow no-till cropping system between 2007 and 2012 at Garden City, Kan. (Figure 29). Wheat yields were similar whether the previous crop was harvested for forage or left standing as a cover crop. Wheat yield following the previous crop or fallow was dependent on precipitation during fallow and the growing season. When moisture was limiting and wheat yields following chem-fallow were less than 35 bushels per acre, growing a crop during the fallow period reduced wheat yield. When wheat yields following fallow were greater than 70 bushels per acre, only winter triticale, grain peas, and continuous wheat grown in place of fallow reduced yield. Averaged across all years, wheat yield following continuous wheat was 41 percent less, and following grain peas was 21 percent less compared to wheat-fallow. Wheat-fallow averaged 56 bushels per acre. Cover crops never increased wheat yields. Annual forages and grain peas can increase profitability, but cover crops commonly reduced profitability compared to wheat-fallow.

Crop selection for the next season becomes important after a double crop because the soil profile is often more water-depleted than if the double crop or cover crop had not been grown. A long-term rotation study at Hesston, Kan., demonstrated that sorghum yielded less following sorghum or double-crop sorghum than sorghum after soybeans or double-crop soybeans (Figure 30). Sorghum yields were greatest following wheat without a double crop.

Conclusion

Water use efficiency can be improved by shifting more of the water use from evaporation to transpiration. Increasing crop intensity or selecting crops that grow during parts of the year that are most susceptible to evaporative losses are two ways to accomplish this goal. Even if available growing season length or annual precipitation preclude intensifying grain or oilseed crop production, cover crops can be used to fill some portion of the fallow period, capturing available soil water for soil-building benefits.

Figure 29. *Average wheat yield response to preceding crop or fallow at Garden City, Kan., from 2009 to 2012. The crop rotation was winter wheat-fallow. Means or bars followed with the same lowercase letter are not statistically different at the 0.05 probability level.*

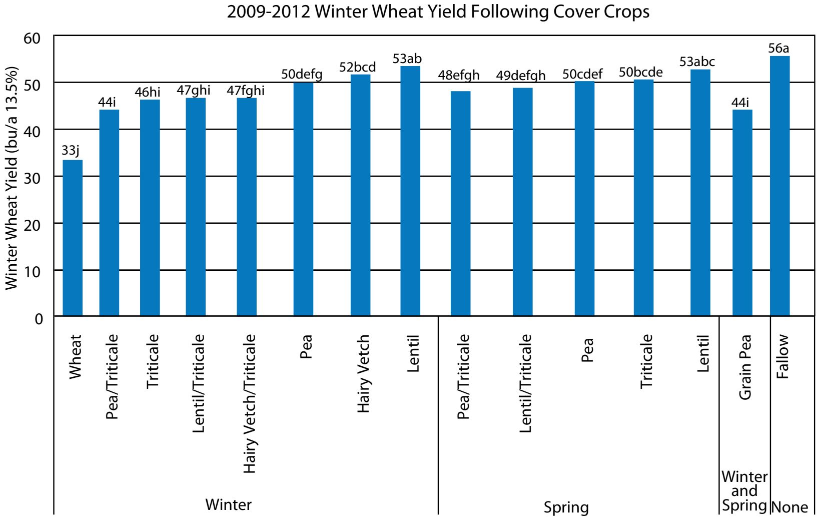


Figure 30. *Average sorghum yield response to preceding crop over 6 years at Hesston, Kan.*

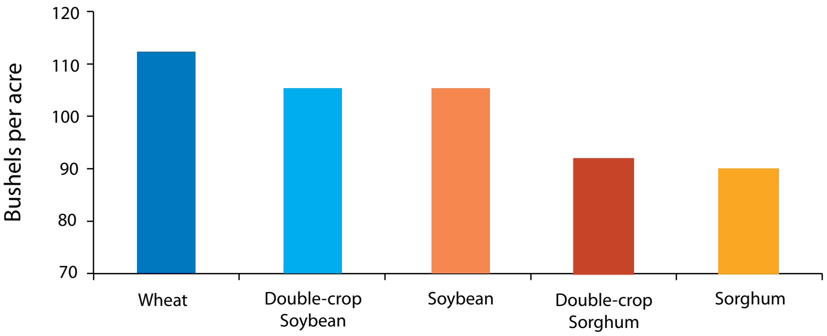


Figure 31. *A growing crop, whether it is for grain or for cover, shifts soil water usage from evaporation to transpiration.*


Presley

Table 10. *Crop characteristics and water use.*

Crop	Season	Season	Double-crop Potential	Water requirement	Threshold ET† (inches)	Water Use Efficiency†† (yield/inch ET)	Seasonal Water Use (inches)	Residue amount/ Water conservation value/ Snow catch potential	C:N Ratio/ Residue Persistence
Broadleaf Crops									
Spring Camelina	Feb/Mar to June/July	Cool-season	Before summer crop	Intermediate	3	147 lb/acre/in	10 - 21	Low	Low
Winter Canola	Sept to June	Cool-season	Before summer crop	Intermediate	4	166 lb/acre/in	18 - 24	Low - Intermediate	Low
Cotton	May/June to Oct/Nov	Warm-season		High	6‡	60 - 100 lb/acre/in	16 - 24	Low	Low
Safflower	Feb/Mar to June/July	Warm-season	Before summer crop	Intermediate	8	205 lb/acre/in	15 - 21	Low - Intermediate	Low - Int.
Soybean	May to Oct	Warm-season	After wheat	High	9‡	330 lb/acre/in	20 - 24	Low	Low
Sunflower	April to Sept	Warm-season	After wheat	Intermediate	5‡	150 lb/acre/in	18 - 22	Low - Intermediate	Low
Grass Crops									
Barley	Feb/Mar to June/July	Cool-season	Before summer crop	Low	5	325 lb/acre/in	13 - 18	Intermediate	Depends on maturity
Corn	Mar/Apr/ May to Aug/ Sept	Warm-season	After wheat	High	11‡	728 lb/acre/in	18 - 25	High	High
Grain sorghum	May/June to Sept/Oct	Warm-season	After wheat	Intermediate	7‡	504 lb/acre/in	13 - 21	High	High
Oats	Feb/Mar to June/July	Cool-season	Before summer crop	Low	5	300 lb/acre/in	13 - 18	Intermediate	Depends on maturity
Pearl millet	June to Sept	Warm-season	After wheat	Intermediate	6	225 lb/acre/in	13 - 21	High	High
Proso millet	June to Aug	Warm-season	After wheat	Low	6	132 lb/acre/in	13 - 18	Intermediate	High
Winter Wheat	Sept/Oct to June/July	Cool-season	After summer crop	Intermediate	10‡	275 lb/acre/in	15 - 24	High	High

† Threshold ET (evapotranspiration) is an estimate of the minimum amount of water use required to produce some harvestable grain.

†† Water use efficiency is defined as yield per inch of ET after the threshold ET requirement has been met.

‡ Water use values from Dr. Loyd Stone, Kansas State University; others are adapted from scientific literature or estimates based on similar crops.

Table 12. *Roles and traits of various cover crops.*

Cover Crop	Quick Growth	Biomass Yield	Forage Potential	Erosion Reduction	Loosen subsoil	Loosen topsoil	Weed Suppression	Tolerances	
								Heat	Drought
					Nonlegumes				
Annual Ryegrass	4	4	4	4	3	4	4	2	2
Barley	5	4	3	4	3	4	4	2	3
Buckwheat	5	3	1	2	2	4	4	3	1
Oats	5	3	5	4	3	4	4	2	2
Pearl Millet	4	4	4	4	3	3	4	5	4
Sorghum sudangrass	5	5	5	4	3	3	5	5	5
Sudangrass	5	5	5	4	3	3	5	5	5
Forage sorghum	4	5	5	4	3	3	5	4	5
Triticale	4	4	5	4	3	4	4	3	3
					Brassicas				
Radish	4	3	2	4	5	3	4	3	2
Rapeseed/Canola	4	4	4	4	4	3	4	2	3
Turnips	4	4	4	4	4	3	4	2	3
					Legumes				
Berseem clover	3	4	3	4	2	4	3	3	3
Cowpea	4	4	5	4	3	4	4	5	4
Forage Soybean	4	4	5	3	3	4	3	5	3
Hairy Vetch	2	3	4	3	3	4	3	3	3
Lablab Bean (Hyacinth Bean)	4	4	3	3	3	4	3	5	4
Sunn hemp	5	5	0	4	4	4	4	5	4
Sweetclover	2	5	3	4	4	4	3	3	4
Pea	4	3	4	3	2	4	2	2	3

0 = not recommended 1 = poor 2 = fair 3 = good 4 = very good 5 = excellent

Adapted from: Managing Cover Crops Profitably. 3rd Edition. 2007. Sustainable Agriculture Network. Beltsville, MD.

5
CHAPTER

Row Spacing and Plant Orientation Effects on Yield and Water Use on Irrigated and Rain-Fed Crops

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Using different row configurations or plant orientations to manage water use can have a positive or negative influence on crop yield depending on environmental conditions and whether the field is irrigated or rain fed.

Table 13. *Water use as affected by tillage and plant population for corn.*

Irrigation Capacity	Average Application Depth	Tillage System	Target Plant Population (1,000 plants per acre)	Water Use (inches)
1 in/4 days	12.5 inches	Conventional	26	24.7
			30	26.0
			34	24.4
		Strip-Till	26	24.6
			30	25.7
			34	24.6
		No-Till	26	22.6
			30	24.4
			34	23.9
1 in/6 days	11.5 inches	Conventional	26	24.7
			30	24.5
			34	24.0
		Strip-Till	26	24.0
			30	24.6
			34	24.2
		No-Till	26	24.7
			30	22.9
			34	24.6
1 in/8 days	10.5 inches	Conventional	26	24.1
			30	23.9
			34	24.4
		Strip-Till	26	23.7
			30	23.0
			34	23.2
		No-Till	26	23.9
			30	24.0
			34	23.3

Row configurations may range from narrow or twin rows on irrigated fields to a skip-row pattern on rain-fed fields. Producers also may use plant orientation, such as higher or lower plant populations along with clump planting on rain-fed fields, to manipulate water use efficiency and potentially increase yield. This chapter discusses how row spacing and plant orientation configurations influence crop yield and water use.

Corn

Corn growth and development, and ultimately yield, are strongly correlated to water availability during the growing season. Ear length determination begins early in plant development and continues throughout the plant's life cycle. Depending on environmental conditions, ear length can be diminished with significant tip dieback occurring at the end of the growing season due to lack of water. Unlike some other crops, corn needs a steady supply of water for it to produce a good crop.

As more cost is associated with water, producers will more closely analyze the cost of adding additional water. Lamm evaluated the effects of plant population on corn yield and water use over a 4-year period, 2004 to 2007, in Colby, Kan. (Lamm et al., 2008). Lamm concluded that on average there was a 16 to 17 bushel per acre increase in corn yield from the lowest population of 26,800 seeds per acre to a high population of 33,315 seeds per acre. To view the interaction of year by plant population by irrigation amount, see Figure 32. In addition, the total water use for a crop-growing season did not vary significantly between corn populations. At most, water use varied 2 inches between populations as detailed in Table 13.

Narrow rows refer to using rows narrower than 30-inch rows. The premise behind using narrow rows is to evenly space plants in the field so a plant is a similar distance from its neighbors (both intra- and inter-row plants). This distribution helps increase yield potential and increase soil area for plants to extract available soil water. There is an advantage to narrow rows in a high-yield environment and no advantage in the mid- to low-yield environments (Table 14) (Staggenborg et al., 2001). There is a reduction in yield when potential is low. The use of narrow rows in irrigated cornfields in western Kansas may increase production, but their use on dryland fields should be discouraged in most situations.

Twin-row corn is another production technique that producers may evaluate to increase corn yields. Twin-row configuration consists of two rows planted 7.5 inches apart with a 22.5-inch gap between the next twin-rows. Staggenborg (2004) found that there was no difference between 30- and 20-inch row corn compared to twin-row corn in dryland corn fields with a yield potential of less than 130 bushels per acre. On the high-yielding irrigated corn plots, there was only a comparison of the 20-inch and twin-row. No differences in yield were observed between the treatments.

On rain-fed fields, corn population recommendations vary widely across the state due to the variation in annual precipitation. Recommendations may range from 16,000 seeds per acre on the Kansas/Colorado border to 30,000 seeds per acre in northeast Kansas. There will be years that allow higher populations to yield extremely well, but the chances of those higher populations doing well decreases as you move west across the state.

At the Harvey County experiment field near Hesston, Kan., Claassen (2008) completed a 4-year study evaluating corn populations of 14,000, 18,000, and 22,000 plants per acre. He found that the 22,000 plants per acre treatment yielded more than the 14,000 plants per acre but there was no significant difference in yield with the 18,000 plants per acre population.

Research evaluating various corn populations and skip-row pattens has been completed in western Kansas. Between 2004 and 2006, 23 field trials were conducted across the central Great Plains to quantify the effect of various skip-row planting patterns and plant populations on grain yield in dryland corn production (Lyon et al., 2008). A quote from the abstract states:

> A significant planting pattern by plant population interaction was observed at only one of 23 trials, suggesting that planting pattern recommendations can be made largely irrespective of plant population. In trials

Figure 32. *Corn yield as influenced by irrigation amount (Lamm et al., 2008).*

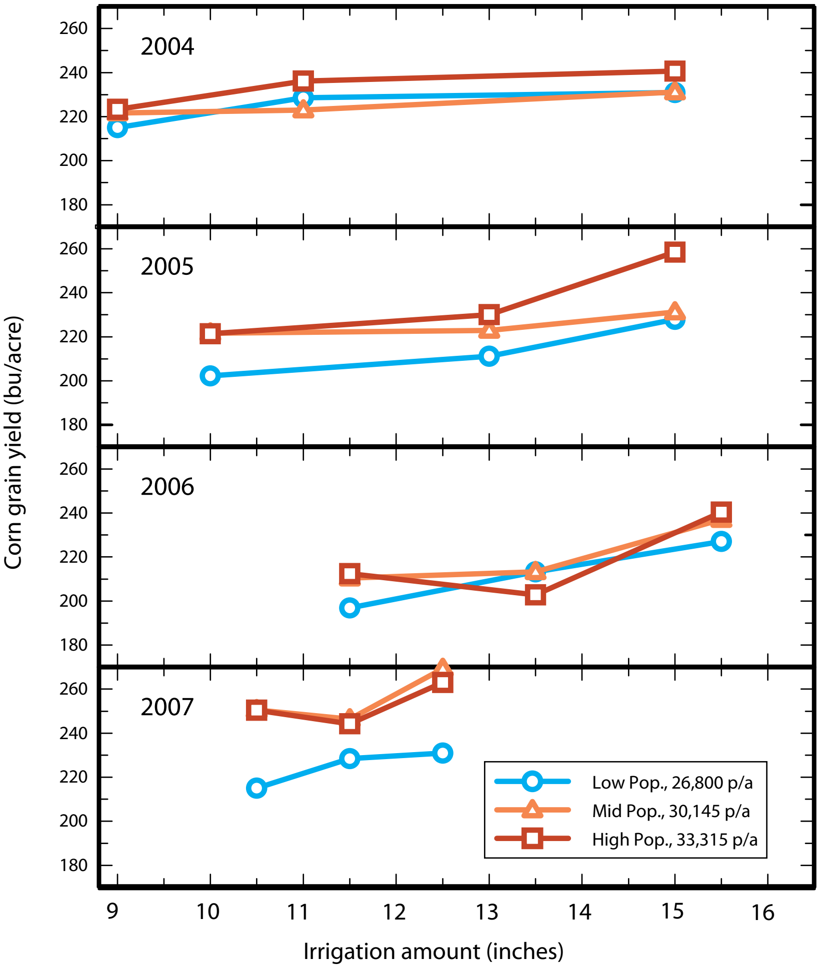


Table 14. *Corn grain yields for three row spacings in 13 environments in Kansas.*

	Yield Potential		
Row Spacing (in)	High >160 bu/a	Medium 160-120 bu/a	Low <120 bu/a
	Grain Yield (bu/a)		
15	202 a*	145 a	39 b
20	191 ab	144 a	41 b
30	182 b	139 a	58 a
Number of Environments	4	7	2

** Results followed by the same letter are not statistically different from other values in the same column.*

where skip-row planting patterns resulted in increased grain yields compared to the standard planting pattern treatment (every row planted using a 30-inch row spacing), the mean grain yield for the standard planting treatment was 44 bushels per acre. In those trials where skip-row planting resulted in decreased grain yield compared to the standard planting pattern, the mean yield was 135 bushels per acre. The plant two rows, skip two rows planting pattern is recommended for risk-averse growers in the central Great Plains where field history or predictions suggest likely grain yields of 75 bushels per acre or less. Planting one row and skipping one row is recommended for growers with moderate risk-aversion and likely yield levels of 100 bushels per acre or less.

Research from Tribune and Colby was included for this analysis. More recent work completed between 2007 and 2009 (Table 15) does not exhibit the same trend where a skip-row pattern can benefit corn yield at lower yield potentials (Olson et al., 2010). There was no difference observed between the every row and plant two/skip two-row pattern. In 2009 at Colby, there was no interaction between crop and skip-row pattern because the growing season was almost ideal for corn production. Corn yielded 161 bushels per acre, and grain sorghum yielded 114 bushels per acre with an LSD ($P \leq 0.05$) of 12 while the skip-row pattern yielded 45 bushels per acre less than planting every row.

Corn yield is directly influenced by water availability. Higher populations can consistently provide high yields under irrigation, and narrow or twin rows also may improve yields. However under a rain-fed management system, corn yield can be highly variable depending upon the environment. Lower plant populations per acre of 16,000 in far western Kansas to 30,000 in eastern Kansas are appropriate. Results from skip-row corn research indicate a yield advantage in Nebraska over conventional row patterns in low-yielding environments (less than 70 to 80 bushels per acre) but the research results in Kansas are highly variable with more results from sites indicating there is no benefit. Farmers need to look at the yield history of a particular field and determine the realistic yield potential for that field before deciding on plant population, narrow rows, or a skip-row pattern.

Soybeans

Soybean yield depends on a number of factors: plants per acre, pods per plant, seeds per pod, and seed weight (Epler and Staggenborg, 2008; Roozeboom, 2010). Seeds per pod and seed weight most often depend on variety but can change depending on soil water levels or other environmental factors. The number of pods per plant is more sensitive to environment and can change more than two fold depending on available space, light, and water resources.

During 2006 and 2007, 26 experiments examining soybean-seeding rates, primarily in central and northeast Kansas, were conducted (Duncan et al., 2008). Five experiments were located on university research sites and 21 were on producers' fields, using their planting and harvesting equipment. Some of the research sites on producers' fields had replicated plots, and some did not. Most were in rotational, no-till cropping systems. Three experiments were irrigated and 23 were rain fed. These studies encompassed a wide range of production practices (row spacings, full-season, double-crop, etc.), environmental

Table 15. *Corn and grain sorghum yield 2007 to 2009.*

Crop	Pattern	Tribune [1]	Garden City[2]	Colby[3]
		Bushels per Acre		
Corn	Every row	66	28	76
	Skip row	65	25	71
Grain sorghum	Every row	80	69	145
	Skip row	62	64	83
LSD (P=0.05)		13.7	6.1	15.0

[1] *Yield from 2007 to 2009.*

[2] *Yield from 2008 and 2009.*

[3] *Yield from 2007 and 2008.*

conditions, and productivity. The average test yield ranged from 12 to 78 bushels per acre.

Yield results from these studies were standardized to percent of the test average to enable comparisons across the wide range of yields. Yields tended to increase in response to increasing population, but only up to a point. After that optimum population level, increasing the number of plants per acre had no effect on yield. Results have been summarized by yield level to determine if the optimal population would change depending on the yield environment.

In low-yield environments, yields plateau at a population of about 70,000 to 80,000 plants per acre, but at those population levels, producers may run the risk of missing out on greater yields if conditions are better than expected. In high-yielding situations, producers need more plants per acre to maximize yields (Table 16). Some of the highest yields (close to 80 bushels per acre) were achieved at an irrigated location in which yields leveled out at a seeding rate of 105,000 seeds per acre (Duncan et al., 2008).

Does row spacing make a difference in soybean yields? Several studies have demonstrated that narrow rows (less than 30-inch spacing) can produce greater yields in high-yield situations (Kelley and Sweeney, 2008), but there is little evidence that more plants per acre are needed to achieve those yields, provided stands are adequate for a high-yield environment (Conley and Shaner, 2007; Grichar, 2007). Studies show that seeding rates must be increased when moving to narrow rows (Staggenborg et al., 1996), but those studies have used a planter for 30-inch rows and a drill for narrower rows (Kelley and Sweeney, 2008). The additional seeds likely were needed to overcome reduced field emergence, not to produce additional plants. Additional seeds can help the plants set pods higher off the ground in some cases, for harvesting ease. Evidence from a recent series of studies suggests that pod height increases little at plant populations greater than 125,000 plants per acre (Roozeboom, 2010).

In low-yield situations (less than 30 bushels per acre), most studies have shown that row spacing has little effect on yields (Conley and Shaner, 2007; Kelley and Sweeney, 2008; Roozeboom, 2010). A few studies have shown a reduction in yield with narrow rows in low-yield environments (Staggenborg, 1996).

Grain Sorghum

Grain sorghum is typically described as a more drought-tolerant crop than corn or soybeans. The grain sorghum plant is able to shut down during dry weather and wait for conditions to improve, while tillering profusely when growing conditions are good in order to take advantage of the environment. A consistent supply of water is not as critical to grain sorghum, but water availability is still important to yield.

Figure 33. *Severe drought stress near flowering greatly reduces soybean yield.*

Shoup

Table 16. *The minimum number of soybean plants needed to maximize yield in various environments.*

Yield Range	Number of Tests	Average Yield (bushels per acre)	Number of Plants Per Acre Needed to Maximize Yield
Less than 30 bushels per acre	6	24	72,000
30 to 40 bushels per acre	7	36	80,000
40 to 50 bushels per acre	6	43	120,000
More than 50 bushels per acre	7	68	105,000

Grain sorghum may have a place for producers on irrigated pivots where well capacity is low. Klocke and Currie (2009) reported that grain sorghum yields were reduced by 8 percent when there was a 72 percent reduction in irrigation from full irrigation, whereas corn had a 20 percent reduction in yield when irrigation was reduced by 50 percent from full irrigation. Plant population on irrigated fields should range between 90,000 to 120,000 plants per acre.

Under dryland conditions, grain sorghum populations vary across the state but due to the ability of the grain sorghum plant to tiller, plant population is not as critical as in some other crops. Recommended planting rates range from 24,000 plants per acre along the Kansas/Colorado border to 70,000 plants per acre in eastern Kansas. Gordon and Staggenborg (1999) reported a 37-bushel-per-acre advantage when increasing the plants per acre from 30,000 to 60,000 plants per acre on 30-inch rows with yields of 98 and 135 bushels per acre, respectively. No further advantage was observed by increasing to 90,000 plants per acre. In addition to plant population, Gordon and Staggenborg also reported no benefit to 15-inch over 30-inch rows when grain sorghum was planted mid-May, but a 29-bushel-per-acre advantage to 15-inch rows compared to 30-inch when grain sorghum was planted in mid-June. Other research by Staggenborg et al. (1999), indicated that 10-inch rows may consistently yield more than 30-inch rows, when yield potential is over 100 bushels per acre, and 30-inch rows may yield more than 20-inch rows when the yield potential is less than 100 bushels per acre (Table 17).

A skip-row configuration is another technique producers may employ to enhance yield. As previously discussed in the corn section, skip-row corn and grain sorghum were evaluated in 2007 to 2009 in Colby, Tribune, and Garden City. No advantage was observed in growing grain sorghum in a plant two/skip two row pattern compared to grain sorghum planted every row (Olson et al., 2010). A disadvantage was recorded when growing conditions were good, with a substantial reduction in yield observed.

Clumped planting of grain sorghum is a technique that may have an opportunity to improve or stabilize grain sorghum yields under dryland conditions. Clump planting is the process in which sorghum seeds are planted together (approximately 4 to 5 seeds) on 30-inch rows. This clumping allows the farmer to have some control over grain sorghum tiller development by decreasing early-season tiller onset. This reduction allows for more soil water to be available to the plant during reproduction. Haag and Schlegel (2009) reported that grain sorghum planted in clumps yielded 58 bushels per acre, whereas 30-inch grain sorghum yielded 51.2 bushels per acre at Tribune, Kan. during a 3-year study, 2006 to 2008. Pidaran et al., (2010) observed that clump planting provided a 7 to 11 percent advantage to 30-inch planted grain sorghum when grain yield was below 96 bushels per acre, but there was a 16 percent disadvantage to clump planting when grain yield was over 143 bushels per acre. Research in recent years evaluating clump planting in the central High Plains was summarized by Pidaran et al., (2011) and can be viewed in Figure 34.

Table 17. *Grain sorghum grain yields for three row spacings in seven environments in Kansas.*

	Location – Years[1]						
Row Spacing	Manhattan[2] 1995	Powhattan[2] 1995	Belleville[2] 1995	Manhattan[2] 1996	Belleville[2] 1996	Manhattan[3] 1997	Wellington[4] 1997
(in)	Grain Yield (bu/a)						
10	137.5	92.1	77.1	122.7	117.9	83.6	77.2
20	115.0	93.4	77.8	119.6	108.8	-----	----
30	115.1	83.8	90.4	113.3	102.5	84.3	79.9
$\text{LSD}^*_{(0.05)}$	- - - - - - - - - - - - - - - 12.2 - - - - - - - - - - - - - - -					NS$^+$	NS$^+$

[1] *Planting dates ranged from May 22 to June 6 across all seven environments.*

[2] *Averaged across three plant populations and two hybrids.* [3] *Averaged across three plant populations.* [4] *Averaged across two hybrids.*

* *LSD Least Significant Difference, used to determine if two means are statistically different.*

\+ *NS — Not significantly different based on the statistical methods used.*

Sunflowers

Sunflowers are considered more drought tolerant than corn or soybeans. Unlike grain sorghum, a sunflower plant has the ability to extract more water from the soil profile due to its large tap root system. During the reproductive stage, however, water availability is important to ensure high yields.

The following information about row spacing and plant population is taken from the *High Plains Sunflower Production Handbook* (Johnson et al., 2009). Available row-crop equipment should dictate row spacing used. Both solid-seeded and row-planted sunflowers have been produced successfully. Currently, 30-inch row spacing is most popular and considered standard. Trials conducted by Colorado State University Extension, however, have found equal sunflower yields with 12-, 15-, and 30-inch row spacings.

Adequate plant population is important for highest possible seed yields. Sunflowers, however, will compensate somewhat for differences in plant populations through adjustments in head size. Higher populations are generally planted for oil-type sunflowers than for confectionary type hybrids. Plant populations for oilseed hybrids grown under dryland conditions should be between 14,000 and 22,000 final plants per acre, adjusting for yield potential. In lower yield environment potentials, plant populations should be lowered slightly. In Nebraska studies, plant populations of 11,000 plants per acre resulted in 1.2-ounce larger heads, 300 more seeds per head, 0.0004 ounce larger seed, and 2 pounds per bushel lower test weight than populations of 20,000 plants per acre. Nebraska yields were similar from 11,000 to 20,000 plants per acre, but higher populations may be helpful in weed competition and soil erosion prevention.

Available water in the soil profile is regarded as the most important criterion for adjusting plant populations within this recommended range. Lower populations are recommended for lower yield potentials (drier soils). Plant populations for dryland oil-type sunflowers should be between 17,000 and 22,000 final plants per acre. Irrigated oil-type sunflower plant population recommendations in Kansas range from 22,000 to 26,000 plants per acre, with western regions requiring lower populations than eastern regions. Confectionary hybrids should be planted between 12,000 (drier soil conditions) and 18,000 (irrigated) final plants per acre. In central and eastern Kansas, irrigated confectionary population recommendations range from 15,000 to 18,000 plants per acre. Higher populations allow faster preharvest drydown as head size will be smaller, but this also can result in smaller seed size. Thinner confectionary stands tend to produce a higher proportion of large seed.

Wheat

Because wheat is a winter annual grass, plant population and row spacing to some extent do not have the same influence on yield as with the summer annual crops. A few abnormally hot days during grain fill in May through early June can quickly depress yield potential. There are differences in recommended seeding rates, with less wheat seeded per acre along the Kansas/Colorado border than in eastern Kansas. Although there may be substantial differences in seed size and thus the seed number per pound, most producers typically plant wheat in pounds per acre and not seeds per acre (Table 18).

Research indicates timing is at least as important, if not more important, to wheat yield than pounds per acre. Planting date and planting rate were evaluated at Colby, Kan. by Olson in 2009 and 2010. As detailed in Figure 35, when wheat was planted in the “typical” time frame of late September to early October in the Colby area, there was little difference in wheat yield between seeding rates. However, when wheat planting was

Figure 34. *Yield advantage of clumped planting is shown for grain sorghum grown in nine environments of the central and southern High Plains. Yield advantage is calculated as the difference in yield between sorghum planted in clumps and sorghum planted with uniform within-row spacing.*

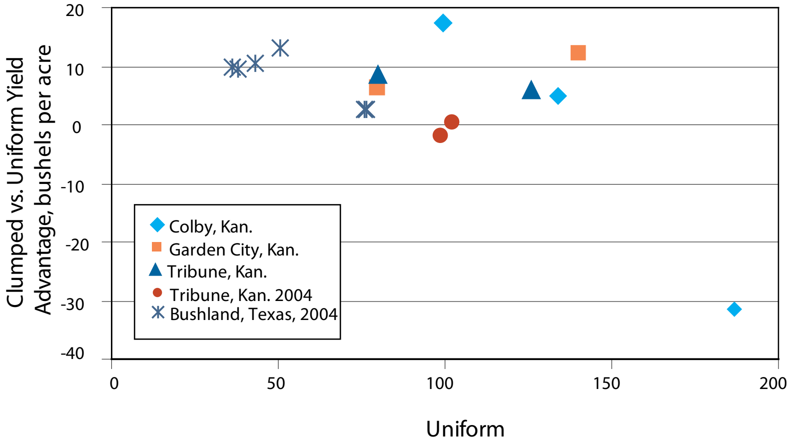


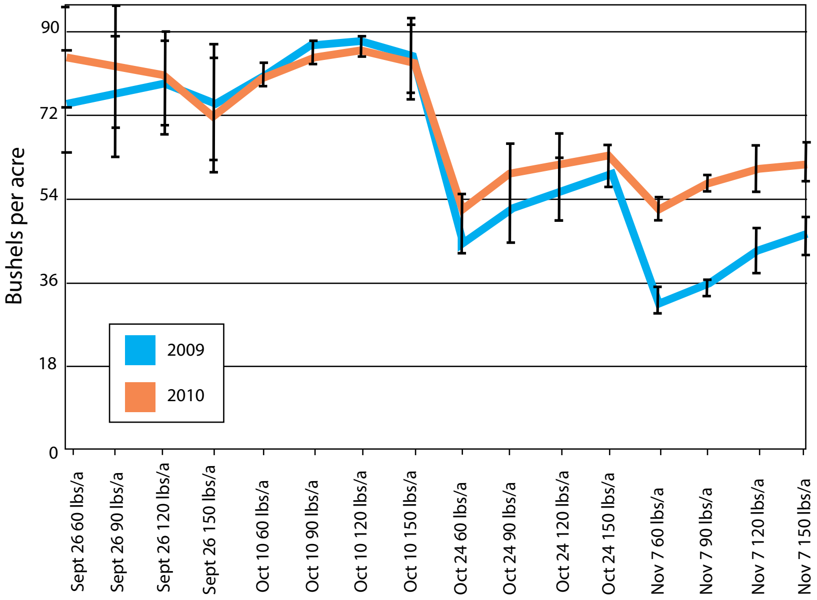
Table 18. *Recommended wheat seeding rates per precipitation zone.*

Precipitation Zone	Pounds per acre
Less than 20 in	50 – 60
20-30 in	60 – 75
More than 30 in	75 – 90
Irrigate	90 – 120
Early planting for grazing	90 – 120

Table 19. *The effect of row spacing on wheat yield at Garden City, Kan. 1988-1990.*

		Row spacing (inches)		
Environment	Variety	5	10	15
Dryland	TAM 107	34.9	35.3	34.4
	Larned	34.5	35.2	33.0
Irrigated	TAM 107	69.9	69.8	67.8
	Larned	47.3	50.6	49.1

Figure 35. *The effect of planting date and planting rate on wheat yield at Colby, Kan.*



delayed until late October to early November, wheat yield was influenced by seeding rate.

The effect of row spacing (Witt, 1991) is presented in Table 19. The results indicate there is no difference between growing wheat on 5-, 10-, and 15-inch row spacings on either dryland or irrigated wheat. However, the top yield of the study was only 70 bushels per acre. As for fields where the yield potential is 80 to 100 bushels per acre, there may be a benefit to narrowing row spacing to between 5 to 10 inches in order to allow for better plant spacing.

In summary, producers need to understand strengths and limitations of the crop they are growing and the environmental conditions the crop will be grown in to determine what plant population and plant orientation will work best to ensure productive and stable crop yields.

Nutrient Management for Efficient Water Use

6
CHAPTER

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Increases in water-use efficiency, both in irrigated and dryland crop production systems, are particularly important in the Great Plains regions of Kansas where irrigation water resources are limited and where rainfall is typically a limiting factor for optimizing crop yield. One of the components of a management system that affects water-use efficiency is soil fertility and optimum nutrient management. The development of the plant root system is exceptionally plastic and strongly influenced by the growth conditions, such as soil fertility. A complete and balanced fertility program helps with root development, increasing the volume of soil that the crop can explore for water and nutrients. Increases in water-use efficiency also can come from improved plant growth.

Nitrogen

Optimum nitrogen fertilization alone can increase water-use efficiency significantly. Nitrogen management improves water-use efficiency primarily through the improvement of crop yield components, such as grain number per unit of land area, that will ultimately increase yields. Fertilized crops (wheat, corn, and sorghum) can extract more soil water from deeper in the profile than nonfertilized crops. The increase in yield will result in increased water-use efficiency (Figure 36). Nitrogen dynamics also influence crop residue levels, which increase water-use efficiency. It is important to consider that overall yield potential and nutrient needs will be determined by the amount of available water during the growing season. Figure 37 indicates that with an increase in nitrogen rate, there is an overall increase in water-use efficiency; however, when water becomes the limiting factor, excess nitrogen fertilizer application can decrease water-use efficiency. For the most efficient use of both nitrogen and water, the supply of one should be adjusted to that of the other. If irrigation is intended for maximum yield, then nitrogen application rate should be adjusted for that yield level.

Figure 36. *Average (1994–96) corn yield, apparent nitrogen uptake in the above-ground biomass, and water use efficiency as related to the total applied nitrogen (preseason amount, starter fertilizer, fertigation, and the naturally occurring nitrogen in the irrigation water). Total applied nitrogen exceeded fertigation applied nitrogen by 30 pounds per acre. (Lamm et al., 1998.)*

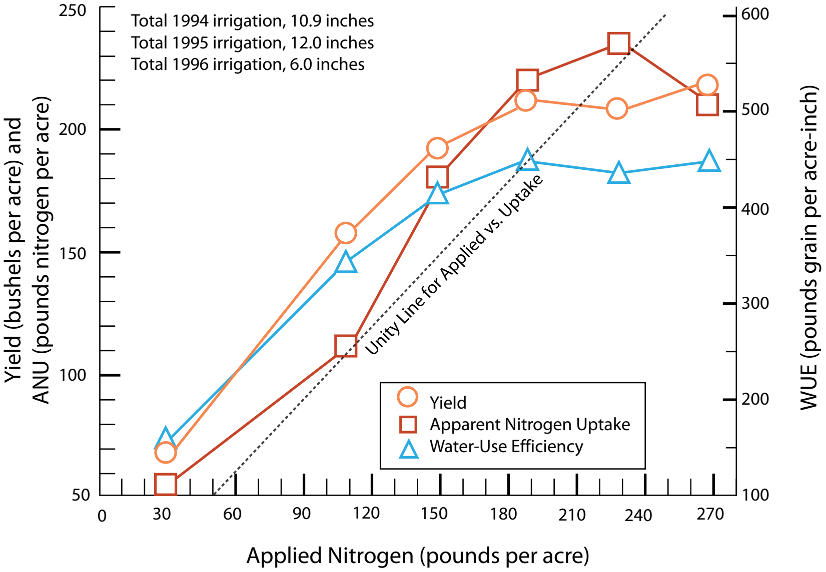
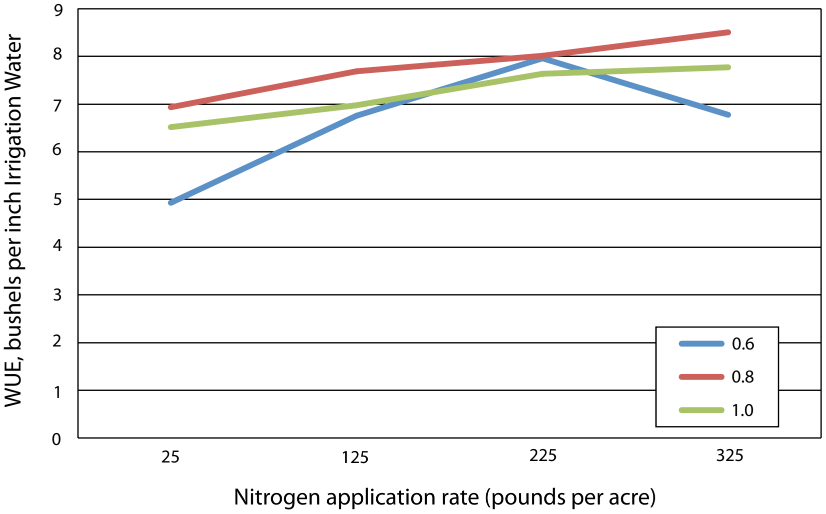


Figure 37. *Effect of irrigation and nitrogen application rate on water-use efficiency in eastern Colorado. Irrigation treatments include 0.6 ET, 0.8 ET, and 1.0 ET (evapotranspiration potential). (Modified from M. Al-Kaisi and X Yin, 2003).*



Phosphorus

Application of phosphorus fertilizer helps improve many crops' tolerance to water deficit. Phosphorus nutrition modifies plant-water relationships in many crops by enhancing root growth. Root activity and proliferation increases with phosphorus fertilization. The fertilization increases root density and rooting depth, expanding the soil volume that roots can explore for water and nutrients. Application of phosphorus, especially in soil with a low phosphorus availability as indicated by soil test (below 20 ppm), will enhance the adaptability to water-deficit stress through the stimulation of root growth. Phosphorus also can increase water-use efficiency in other ways. Optimum phosphorus fertility helps increase shoot dry weight under water deficit conditions, as well as developing an earlier and fuller canopy, which reduces soil water evaporation. Table 20 illustrates that, for a fixed amount of water, there were increases in both alfalfa yields and water-use efficiency with increased phosphorus fertilization rates.

It is also important to consider that even though phosphorus application will be beneficial for root growth, the overall plant response per unit of phosphorus application under water-deficit conditions may not be comparable to conditions with optimum moisture. Phosphorus availability to the plant in water-limited soils may be reduced, which would slow the phosphorus uptake and consequently, the phosphorus metabolism for plant growth. Therefore, a larger amount of phosphorus fertilizer may be required to stimulate root growth in order to alleviate the water deficit. Furthermore, phosphorus placement options may be particularly important when surface soil moisture is limited. Tillage systems, such as no-till, can help enhance surface-applied phosphorus fertilizer by maintaining near-surface moisture and promoting root proliferation.

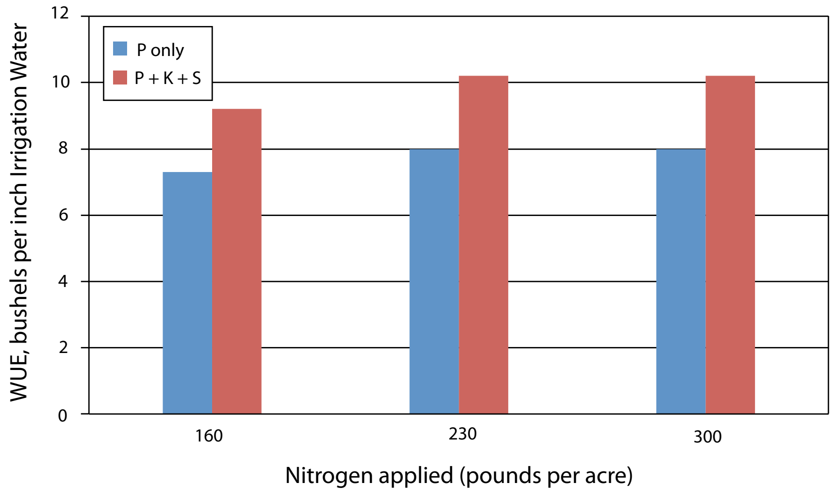
Table 20. *Phosphorus application rates and effect on alfalfa yield and water-use efficiency.*

P_2O_5 (pounds per acre)	Yield (tons per acre)	WUE, (pounds per inch of water)
100	8.3	188
200	9.4	213
400	/[a]	253
600	11.8	267

[a] data not reported

Modified from: Potash & Phosphate Institute. Better Crops, 1999.

Figure 38. *Water-use efficiency of irrigation water as affected by fertility program (B. Gordon, 2000).*



Other Nutrients

Nutrients like nitrogen and phosphorus influence the growth and efficiency of crops, which usually lead to an improvement of dry matter production. This increase in plant growth also will increase total uptake of nutrients such as potassium, as well as secondary and micronutrients. Figure 38 shows the interaction of phosphorus, potassium, and sulfur across various nitrogen levels and the effect on water-use efficiency. The combination of optimum levels of nitrogen and phosphorus alone can potentially increase water use significantly. However, a balanced fertility management, including nutrients such as potassium and sulfur, can further increase water-use efficiency.

Increase in nutrient uptake with fertilizer application can enhance the crop adaptability to drought. This adaptability to the changes in water availability in the soil can ultimately be reflected in yield. Crop productivity is complex and involves genetic and environmental factors; however, nutrient uptake can become a limiting factor when both nutrients and water are deficient.

Controlling Weeds to Conserve Water

7
CHAPTER

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Weeds directly compete with crops for water, light, space, and nutrients. Weeds are potentially responsible for 34 percent of crop losses worldwide (Oerke, 2006). One of the biggest challenges in agriculture is the management of water, widely considered the greatest limiting resource for crops (Lenssen et al., 2007; O'Leary and Connon, 1997; Robbins et al., 1942). This limitation is especially important in the arid environments of the U.S. Great Plains. Weeds are a major competitor for available soil water within crops or during fallow periods (Spitters and Aerts, 1983; Monks and Oliver, 1988). Consequently, proper weed control increases available soil water for crop production.

Plant Factors Affecting Water Use Efficiency

Drought stress has multiple adverse effects on plant growth and development, including loss of leaf turgidity, decreased root absorption of nutrients, and a decrease in the photosynthetic rate of plants (Chapin, 1991). Several factors contribute to the amount of water loss that occurs in water-limiting environments, including weed density, weed species, weed root structure, weed physiology, and duration of weed growth.

Weed density plays a major role in depletion of soil moisture and has significant negative effects on the water-use efficiency of crops. In general, greater weed densities reduce crop yields through water loss and competition for water (Dalley et al., 2006; Banks et al., 1986). In a study evaluating Palmer amaranth competition with irrigated corn, total water use by Palmer amaranth continually increased as densities increased from 0 to 8 plants per meter of corn row (Massinga et al., 2003). Consequently, water use efficiency of corn continued to decrease with increasing Palmer amaranth density resulting in corn yield losses from 11 to 91 percent as density increased from 0.5 to 8 plants per meter, respectively. Although increasing weed density generally decreases soil water, the competitive ability of different weed species at similar densities may not have the same influence on water use. McGiffen et al., 1992, found that while growing with tomatoes, eastern black nightshade significantly reduced soil water, while black nightshade at a density of 1.6 plants per square meter did not reduce soil water.

The ability of a specific weed species to affect crop yield under limited soil water may depend on the plant's physical characteristics, such as rooting structure and depth. The aboveground biomass is not always a good indicator of a plant's ability to extract water from a soil profile. Water extraction pattern of weeds are more closely related to root zone volume of a species rather than the aboveground biomass (Davis et al., 1965). In addition, plants with a deeper rooting system are less affected by drought than plants with shallower rooting systems because they can more readily explore soil profiles for water (Reader et al., 1992; Maganti et al., 2005). For this reason, perennial weeds can be less affected by drought than annual weeds.

The physiology of a weed also plays a role in water use efficiency and thus total water loss from the soil system. In general, C3 plants (i.e., wheat, cheat, mustards) are estimated to be half as water-use efficient as C4 plants (i.e., sorghum, corn, kochia, and shattercane) (Lovelli et al., 2010; Norris, 1996). Plants of the C4 category contain an extra carbon-fixing step in the leaves that allow it to close its stomata during times of limited water supply (Long, 1998). By regulating stomata, plants conserve water internally and continue biomass production under water-limiting environments. The ability of a plant to withstand short periods of drought depends on its ability to regulate stomata closure. For example, corn stomata have a greater ability to remain open and operate at full transpiration at lower water contents than velvetleaf and should have better growth during short periods of drought (Schmidt et al., 2011). Plants that close stomata at higher soil water levels are better adapted to survive prolonged periods of drought. This characteristic, in addition to senescing the oldest leaves to maintain total plant water, can help ensure a plant's ability to produce at least a minimal amount of seed.

Critical Period of Weed Control

An understanding of the timing and growth stage at which weeds should be controlled can help producers control water loss due to weed growth. There are two components to the critical period of weed removal (Swanton and Weise, 1991; Zimdahl, 1988; Weaver, 1984). First is the length of time weed-control efforts must be maintained so no yield loss occurs, or the "Critical Weed Free Period" (Figure 39). Second is the length of time weeds can remain in competition with the crop before they reduce crop growth or yield, or the "Critical Time for Weed Removal." The longer weeds are allowed to persist and use limited resources, such as soil water, the greater crop yield loss that can occur (Dalley et al., 2006; Hall et al., 1992; Hill and Santelmann, 1969; Knake and Slife, 1969; Weaver et al., 1992). This principle was demonstrated in Michigan where optimum corn yields were achieved when weeds were controlled between 4 and 6 inches in height (Dalley et al., 2006). One-time herbicide application at the 2-inch height was too early and allowed a second weed flush that depleted late-season soil water and reduced corn yield. Conversely, weeds controlled at the 9- and 12-inch height allowed too much early-season competition with the corn and also reduced yield.

Figure 39. *Functional approach to determine the critical period for weed control. Adapted from Knezevic et al., 2002.*

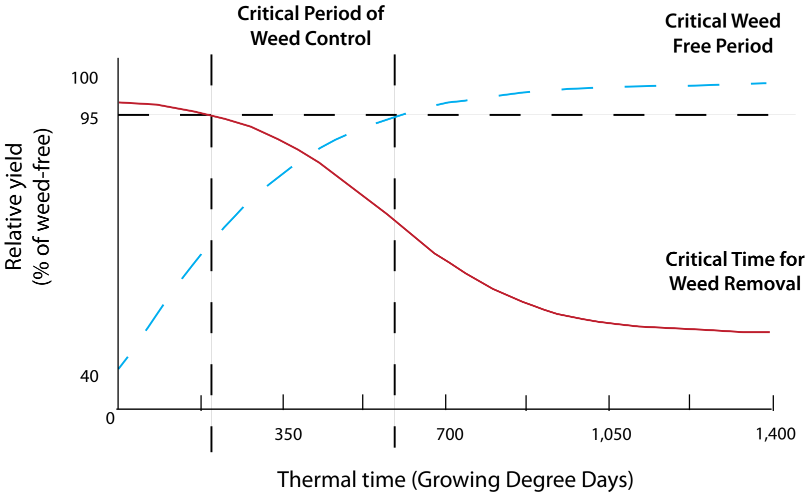
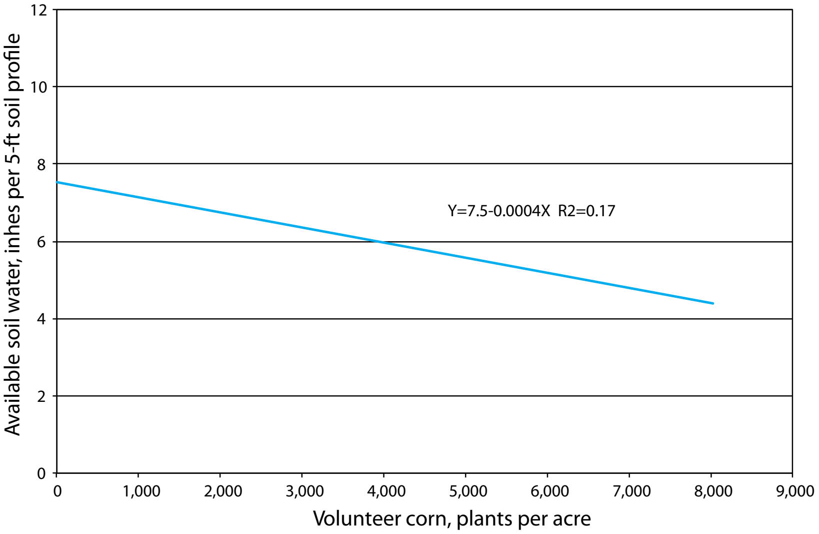


Figure 40. *Weed competition for soil water causes stress to corn plants.*



In semi-arid environments, the critical period of weed control precedes the growing crop during the fallow period. Weeds will deplete soil moisture if allowed to grow during the fallow period, which will result in reduced crop yields when moisture is limiting. Field studies were conducted in western Kansas at Colby, Garden City, and Tribune from 2006 to 2010 to evaluate the impact of volunteer corn on soil moisture storage in fallow and the succeeding winter wheat crop in a wheat-corn-fallow no-till rotation (Holman et al., 2011). Volunteer corn reduced available soil water by 1 inch for every 2,500 plants per acre (Figure 40). When the subsequent wheat crop produced between 35 and 70 bushels per acre, yield was reduced 1 bushel per acre for every 500 volunteer corn plants per acre. When wheat yields were very high (greater than 70 bushels per acre), growing season precipitation was sufficient to overcome the negative impact of volunteer corn during the previous fallow period. On the other hand, when wheat yields were very low (less than 35 bushels per acre), the impact of volunteer corn on wheat yield was not detected because growing season precipitation was too low.

Tillage Systems

Numerous cropping system studies throughout the Great Plains have shown that tillage practices are often major factors for soil water management (Unger et al., 1971). By using herbicides to control weeds, producers reduce the need for tillage, resulting in accumulation of surface crop residues and leading to reduction in soil erosion, increased conservation of water, and increased crop yields (Anderson, 2004; Burnside et al., 1980). When tillage is removed from cropping systems to conserve soil water, producers rely on herbicides to manage weed populations in crop or during the fallow cropping periods (Koskinen and McWhorter, 1986). Fortunately, weed populations are often reduced in no-till systems because of less soil disturbance and more suppression of germination by accumulation of crop residues (Anderson, 2004; Crutchfield et al., 1986). In western Nebraska, the accumulation of more than 6,000 pounds per acre of wheat residue reduced seedling emergence more than 80 percent (Figure 41).

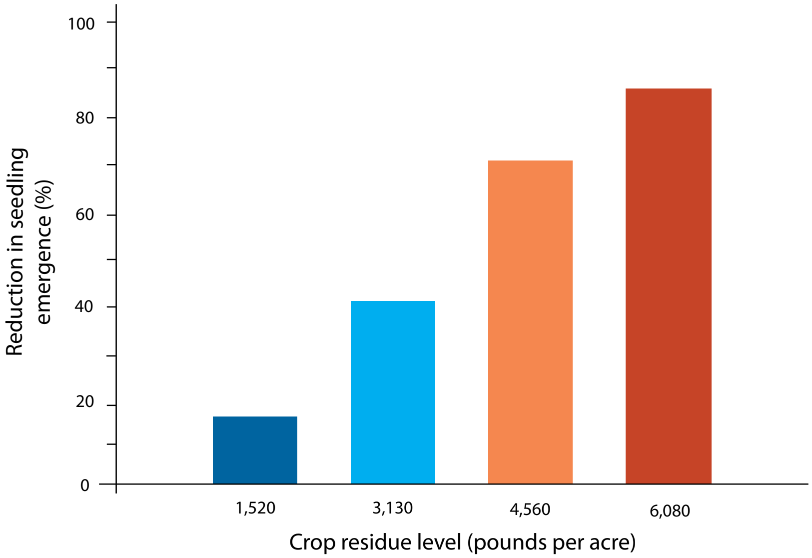
Chemical Weed Control

In minimum-tillage systems, herbicides are an important tool to control weeds and maximize yields. Drier environments that rely on reduced tillage systems to conserve water are often challenging environments in which to achieve effective weed control. Often, there is a relationship between plant water stress and herbicide efficacy. In general, when plants are actively growing, they are more easily controlled with herbicides. Lubbers et al., (2007) found that kochia control with fluroxypyr improved at higher soil water contents. Cool-season grassy species wild oat, downy brome, and jointed goatgrass were controlled more effectively with sulfosulfuron in well-watered soils vs. water-depleted soils (Olson et al., 2000). Velvetleaf control with glyphosate was reduced under drought conditions because water-depleted leaves angled downward, thus reducing herbicide coverage and activity (Zhou et al., 2007).

Increased use of herbicides, particularly herbicides with a similar mechanism of action, in reduced tillage systems are at risk for two possible outcomes: 1) weed population shifts to tolerant weed species and 2) herbicide-resistant weeds. Repeatedly using a specific herbicide often results in a shift in weed populations. In Scottsbluff, Neb., over a 6-year period, repeated use of low rates of glyphosate each spring shifted the weed population to a greater occurrence of common lambsquarters compared to treatments of high rates of glyphosate or using glyphosate every other year (Wilson et al., 2007). In the Great Plains states of Montana, North Dakota, South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, Texas, and New Mexico, 73 combinations of herbicide-resistant weed populations have been reported (Heap, 2011). Herbicide resistance in a weed population may develop from repeated use of low herbicide rates. After using reduced rates of glyphosate in a susceptible population of rigid ryegrass for three generations, the level of resistance in the offspring doubled (Busi and Powles, 2009). Herbicide resistance is not only selected from repeatedly using low herbicide use rates. Resistance also can develop from a single or multiple plant mutation. This is a random natural occurrence but is generally at higher risk of development when an herbicide is repeatedly used for several years.

In cropping systems where tillage is reduced to conserve soil water and herbicides are relied on heavily for weed control, producers should pay special attention to management practices that reduce the risk of developing herbicide-resistant weeds. Producers should implement weed-management strategies such as applying herbicides at labeled use rates, applying herbicide at proper timing, using crop rotations, adjusting crop cultural practices to suppress weeds, and rotating herbicide modes of action (Beckie, 2006).

Figure 41. *Suppression of weed seedlings from accumulation of wheat residue from 2 years at two locations in western Nebraska from March through September. Adapted from Anderson, 2004 and Crutchfield et al., 1986.*



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