No-Till Diversified Cropping Systems for Efficient Allocation of Precipitation in the Southern Great Plains

Andres Patrignani,* Chad B. Godsey, and Tyson E. Ochsner

Core Ideas
- Precipitation allocation increased from 45 to 85% when using diversified crop rotations.
- Shifting timing of fallow periods increased growing season precipitation allocation.
- Diversified crop rotations exhibited lower total water losses during fallow periods than continuous wheat rotations.

ABSTRACT
Conventional till continuous winter wheat (*Triticum aestivum* L.) is a common cropping system in the portion of the Southern Great Plains (Kansas, Oklahoma, and Texas) with >600 mm annual precipitation. This cropping system contributes to soil erosion and uses resources such as precipitation, land, and time inefficiently. Therefore, new cropping strategies are needed. The objective of this research was to determine how no-till diversified cropping systems affect precipitation allocation and precipitation storage efficiency relative to conventional till continuous wheat. Five crop rotations of varied diversity were studied including the following crops: winter wheat, corn (*Zea mays* L.), sunflower (*Helianthus annuus* L.), grain sorghum (*Sorghum bicolor* L. Moench.), and soybean (*Glycine max* (L.) Merr.). The experimental design was a randomized complete block in two location and 2 yr. Soil water content (SWC) to a 2-m depth was measured weekly with a neutron probe. Regardless of the cropping system, nearly 80% of precipitation during fallow periods was lost. Eighty-five percent of the annual precipitation was received during the crop growing seasons in the diversified cropping systems compared with 48% in continuous wheat. Fallow periods were inefficient regardless of cropping intensification and shifting fallow periods from summer to winter months resulted in more efficient use of precipitation in the diversified cropping systems.

Abbreviations: CN, corn; CTIC, Conservation Technology Information Center; CTW, continuous conventional till winter wheat; GS, grain sorghum; LCB, Lake Carl Blackwell; NASS, National Agricultural Statistics Service; NTW, continuous no-till winter wheat; PAW, plant-available water; PSE, precipitation storage efficiency; SB, soybean; SF, sunflower; SPSI, System Precipitation Storage Index; SWC, soil water content; W, winter wheat; W/GS-SF, winter wheat/grain sorghum-sunflower-full-season soybean; W/SF-GS, winter wheat/sunflower-full-season grain sorghum.

Winter wheat (*Triticum aestivum* L.) is the dominant crop in the rainfed agricultural systems of the Southern Great Plains (Kansas, Oklahoma, and Texas) (USDA, 2010). This predominance is not only a consequence of favorable environmental conditions for high yield potential (Greb et al., 1979; Lollato and Edwards, 2015), but also a result of limited crop alternatives. The Southern Great Plains can generally be divided in two regions. The first region is characterized by <600 mm annual precipitation where the predominant rainfed cropping system is wheat–fallow (wheat every other year, with fallow period length of ~14 mo) and a second region with >600 mm of annual precipitation where wheat-based cropping systems are characterized by much shorter fallow periods, which can range from a few weeks to about 5 mo, depending on the crop sequence. In the portion of the Southern Great Plains with >600 mm of annual precipitation, the wheat growing season for grain-only purposes usually starts in early October and extends to the middle of June.

In both regions, the summer fallow periods have been regarded as a strategy to store precipitation in the soil profile for the subsequent wheat growing season. However, fallow precipitation storage efficiency (PSE), defined as the percentage of precipitation during the fallow periods that is stored in the soil profile, is typically low (Haas et al., 1974). For the region of the Southern Great Plains that receives >600 mm of annual precipitation, a study done by Mathews and Army (1960) showed that continuous wheat cropping systems had...
an 11-yr mean PSE of 17% at Woodward, OK. However, such data are rare for this higher precipitation region of the Southern Great Plains. On the other hand, an extensive number of studies have been conducted in soil water storage and water use in northern and central regions of the Great Plains with <600 mm annual precipitation (Farahani et al., 1998b; Jones and Popham, 1997; McGee et al., 1997; Nielsen et al., 2005; Peterson et al., 1996; Smika, 1990; Tanaka and Anderson, 1997). For instance, Jones and Popham (1997) observed a 10-yr mean PSE of 17% during fallow periods in continuous wheat systems in the Texas Panhandle, with no significant differences in fallow PSE between stubble–mulch and no-till. The available data indicate that a majority of precipitation during fallow periods is lost, regardless of whether continuous wheat is under conventional or no-till management. However, conventional tillage and no-till are not equal from the view point of soil and water conservation.

Conventional tillage contributes to water and wind erosion, loss of aggregate stability, degradation of surface hydraulic properties (Dao, 1993), reduction of soil fertility, and requires time consuming field operations. Erosion is a major concern in the Southern Great Plains where the cropland is characterized by fragile soils (Berg et al., 1988; Smith et al., 1991), and where the adoption of conservation tillage still remains low (CTIC, 2008). No-till has the distinct advantage of leaving the soil surface in a less erodible condition (Lal, 1997; Van Pelt et al., 2017), which can help mitigate water and wind erosion in this region. Low fallow PSE and vulnerability to soil erosion are significant disadvantages of conventional till winter wheat monoculture in the Southern Great Plains. In fact, Jones and Popham (1997) classified continuous wheat as the most inefficient cropping system for the portion of the Southern Great Plains with <600 mm annual precipitation. The same authors proposed that crop selection and sequence are significant factors to develop cropping systems that can reach greater precipitation use efficiency. In response to a similar problem with wheat–fallow cropping systems in the Central Great Plains, Peterson et al. (1996) suggested that decreasing fallow length and increasing crop diversity represents a feasible strategy to increase precipitation use efficiency. Similarly, Ochsner et al. (2010) suggested that cropping systems need to be subjected to biological intensification to become more sustainable.

Consequently, new strategies to better use annual precipitation in the Southern Great Plains should be focused on including crops to use precipitation that occurs during summer fallow periods (i.e., summer periods with no crops) instead of attempting to improve fallow PSE. (Farahani et al., 1998b; Jones et al., 1994). Our objective was to quantify how no-till diversified cropping systems affect precipitation allocation and precipitation storage efficiency relative to conventional till continuous wheat in the Southern Great Plain region with >600 mm annual precipitation.

### MATERIALS AND METHODS

#### Study Location and Experimental Design

Experiment locations were established in July 2009 at the Oklahoma State University North Central Research Station at Lahoma, OK (36.3898 N, 98.1076 W); and on the Lake Carl Blackwell Research Station (LCB) (36.1463 N, 97.2866 W) near Stillwater, OK. Locations were 112 km away from each other. The landscape at Lahoma was flat (<1% slope), whereas at LCB the plots spanned a side slope (Replication 1 and 2, 2–3% slope) and toe slope (Replication 3, <1% slope). Signs of water erosion were evident in Replication 1 and 2 at LCB during the experiment. Soil physical and chemical properties of the sites are summarized in Table 1. The experimental site at Lahoma has been under no-till management since 2006 and LCB has been under no-till since 2009.

The experimental design was a randomized complete block at both locations with four and three replications at Lahoma and LCB, respectively. Plot dimensions were 9.1 × 9.1 m at Lahoma and 6.1 × 7.6 m at LCB. The crops used in this experiment were: hard red winter wheat, corn (*Zea mays* L.), sunflower (*Helianthus annuus* L.), grain sorghum (*Sorghum bicolor* L. Moench.), and soybean (*Glycine max* L. Merr.). The treatments (Fig. 1) were continuous conventional till winter wheat (CTW), continuous no-till winter wheat (NTW), and the 2-yr cropping systems: winter wheat–double crop grain sorghum–full-season soybean (W/Gs-SB), winter wheat–double crop soybean–full-season corn (W/SB-CN), and winter wheat–double corn.
crop sunflower—full-season grain sorghum (W/SF-GS). For clarity, the abbreviated notation of the 2-yr cropping systems is as follows: wheat/summer double crop—full-season crop. In this study, double crops are summer crops planted immediately following winter wheat harvest, such that two crops are harvested from the same land in 1 yr. In this case, the fallow period is short and ranges from a single day to a few weeks. In this study, a full-season crop is a summer crop planted at or near the optimal date following a long winter fallow period.

Crop Management

All crops were managed following current best management practices. Crops planting and harvesting dates, seed rate, and variety/hybrids are presented in Table 2. For conventional till wheat tillage during fallow periods was done using a disc within 30 d following harvest (<15% residue coverage) and chisel or cultivator to prepare the seedbed for planting.

Winter wheat was planted using an experimental plot planter at a 17.8-cm (7-inch) row spacing, whereas summer crops were planted at a 30-inch row spacing. Winter wheat was fertilized at seeding with 22 kg N ha−1 as urea. At tiller stage (2.0 Zadoks growth stages) (Zadoks et al., 1974), urea was broadcast at a rate of 112 kg N ha−1 to ensure that N was not limiting. Full-season corn was fertilized at planting with ammonium polysulfate (10–34–0) at rate of 6.6 kg N ha−1 and 4 kg P ha−1, and broadcast with 110 kg N ha−1 as urea in the stage of V5 (Ritchie et al., 1982). Full-season and double crop sunflower, as well as full-season and double crop grain sorghum, were fertilized applying the same rates and sources as in corn. Soybean was inoculated with Bradyrhizobium japonicum in the seed furrow at planting. Additionally, at LCB 1.75 Mg ha−1 of calcium carbonate (CaCO3) was applied to correct the pH. Growing degree days were calculated for winter wheat using a base temperature of 0°C.

Weed control in winter wheat was accomplished by using glyphosate [N-(phosphonomethyl) glycine] as pre-emergence herbicide applied at 1.13 kg ha−1 in solution with 193 L ha−1 of water, 2.5 kg ha−1 of ammonium sulfate, and 1 L ha−1 crop oil concentrate (Paraffin base petroleum oil). Post-emergent herbicides such as 2,4-D amine (dimethylamine salt of 2,4-D-dichlorophenoxyacetic acid) at 1.1 kg ha−1, and Banvel [dimethylamine salt of dicamba (3,6-dichloro-0-anisic acid)] at 0.53 kg ha−1 were also used. Corn and soybean wheat control was achieved by using glyphosate as pre- and post-emergence herbicide using same herbicide rates and additive concentrations as in wheat. In sunflower, sulfentrazone at 0.6 kg ha−1 and pendimethalin [N-(1-ethylpropy)-3,4-dimethyl-2,6-dinitrobenzenamine] at 1.2 kg ha−1 were used as pre-emergence herbicides. In sorghum, a commercial mixture of atrazine at 1.2 ha−1 and metolachlor at 0.62 kg ha−1 was applied as pre-emergent herbicide.

Crop yield was determined when crops achieved physiological maturity by harvesting the central rows of each plot with a plot combine (width 1.83 m, Wintersteiger, Ried, Austria).

Soil Water Content

Soil water content was measured weekly from April to November, and every 20 d during the winter period using a neutron probe device (CPN, model 503 DR). To facilitate neutron probe access, galvanized metal tubes of 3.8 cm inner diameter were installed in the experimental plots. These tubes were installed to 2-m depth into the soil. Extra tubes were installed to calibrate the neutron probe in both wet and dry soil conditions. Readings started at 10 cm below ground level, and were spaced by 20 cm (10, 30, 50, 70, 90, 110, 130, 150, 170, and 190 cm.). The neutron probe device was placed on a stand according to Evett et al. (2003) to obtain accurate depth control.

Soil cores from each depth were taken at both Lahoma and LCB between September and October of 2009. Soil cores were used to determine soil texture by the hydrometer method (Gavlak et al., 2005) at each location. Soil water retention at −1500 and −33 kPa was determined by the pressure plate and Tempe cell method (Dane and Hopmans 2002).

Precipitation Allocation

Precipitation allocation was defined as the percentage of precipitation during the 2-yr study that was received during the growing season. Precipitation storage efficiency was calculated at the cropping system level using the system precipitation storage index (SPSI) proposed by Farahani et al. (1998a). This index combines the PSE of all fallow periods for a given cropping system into a single value. The SPSI was determined by the following equation:

$$\text{SPSI} (%) = \frac{P_S - E_S}{P_S}$$

where $P_S$ is precipitation during all fallow periods of a given cropping system and $E_S$ is all the losses (combined drainage, runoff, and
evaporative losses) during all fallow periods of the same cropping system. Fallow losses were approximated by subtracting the amount of precipitation stored in the soil profile from the total fallow precipitation. In other words, we assumed that the precipitation that was not stored in the soil profile during the fallow period was lost due to one or a combination of drainage, runoff, and evaporation. Precipitation data were obtained from the nearest Oklahoma Mesonet station (McPherson et al., 2007) that was within a radius of 800 m from the experimental plots.

**Statistical Analysis**

Crop yields, precipitation storage efficiency, and fallow losses were analyzed in SAS 9.2 (SAS Institute, Cary, NC) using PROC MIXED, treating replication as a random variable, and using cropping system as fixed variable in the model. Paired-comparison Student t tests were used to analyze differences in plant-available water (PAW) between double crop sunflower and conventional till continuous wheat fallow period.

Precipitation allocation, precipitation storage efficiency, and crop productivity are presented at the cropping system level. In addition, comparisons of specific time periods within the 2-yr cropping systems were made to provide more information about common questions related to crop choice and sequence. These specific comparisons are: (i) crop yield and productivity of continuous wheat systems and diversified cropping systems; (ii) PAW depletion between a double crop and a conventional till continuous wheat summer fallow period, and (iii) winter wheat grain yield either following a traditional fallow period or following a full-season crop.

**RESULTS AND DISCUSSION**

**Growing Season Precipitation Allocation**

Total growing season length across 2 yr for all cropping systems and locations ranged from 431 to 523 d (Table 3). The shortest diversified cropping system growing season at Lahoma, W/SF-GS, was shorter than the growing season for continuous wheat at the same location. Furthermore, all diversified cropping systems at LCB resulted in shorter growing season length than continuous wheat at Lahoma. Therefore, diversified cropping systems did not use the land resource more intensively per unit of time than continuous wheat. This is because winter wheat has a long growing season, and the substitution of one wheat crop in the diversified cropping systems by a summer full-season crop and a double crop ends in a similar total growing season length at the cropping system level. However, important differences were observed in precipitation allocation between cropping systems.

Precipitation allocation of diversified cropping systems ranged from 70 to 85% for both locations, while precipitation allocation of continuous wheat cropping systems ranged from 42 to 48% (Table 3). This means that diversified cropping systems received more precipitation during the growing season compared with continuous wheat. Therefore, precipitation that was susceptible to be lost during summer fallow periods in continuous wheat cropping systems can potentially be available for a summer crop in diversified cropping systems. Higher values for precipitation allocation in diversified cropping systems at Lahoma compared to LCB were caused by higher precipitation values than the 30-yr average in August 2009 (123% higher) and July 2010 (139% higher) (Table 4).

Considering both locations, total precipitation during the growing seasons of diversified cropping systems over 2 yr ranged from 1129 to 1310 mm, whereas precipitation in continuous wheat ranged from 743 to 774 mm (Table 3). Since growing season length for all cropping systems was similar, diversified cropping systems resulted in higher precipitation per day of growing season. Precipitation per day of growing season ranged from 2.4 to 2.7 mm d\(^{-1}\) in diversified cropping systems and from 1.5 to 1.8 mm d\(^{-1}\) in continuous wheat systems (Table 3).

**Precipitation Storage Efficiency**

System precipitation storage index values ranged from −0.13 to 0.22 at LCB, and from 0.17 to 0.42 at Lahoma (Fig. 2). Grouping SPSI by cropping systems, average values for continuous wheat (no-till and conventional till) resulted in −0.10 at LCB and 0.31 at Lahoma, whereas diversified cropping systems had 0.14 and 0.30 at LCB and Lahoma, respectively.

At LCB, the diversified cropping systems W/SF-GS and W/GS-SB had the highest SPSI. Continuous wheat cropping systems, both in conventional and no-till management, had negative SPSI, with no significant differences between them. Negative values mean that not only an amount of water equal to the precipitation during the fallow period was lost, but also a portion of the water previously stored in the soil profile. We hypothesize that SPSI values were low at LCB, partly as a result of runoff, which was evident after precipitation events. It seems plausible that water loss due to runoff combined with high reference evapotranspiration caused continuous wheat cropping systems to end the fallow period with a soil profile drier than at its starting point, and therefore, the negative SPSI value. Although diversified cropping systems had greater SPSI than continuous wheat at this location, it is not certain that the no-till caused this difference by preventing runoff. In the Southern Great Plains, there is not strong evidence that no-till reduces runoff. In fact, several authors (Berg **Table 3. Growing season length, precipitation during growing season, and precipitation allocation (PA) for five cropping systems at Lahoma and Lake Carl Blackwell (LCB), OK.**

| Crop† | Lahoma | | Lahoma | | Lahoma | | Lahoma | | Lahoma |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|
|       | Growing season | Precipitation in GS | PA | Growing season | Precipitation in GS | PA |
|       | d | mm | mm d\(^{-1}\) | d | mm | mm d\(^{-1}\) |
| W/SF-GS | 473 | 1129 | 2.4 | 0.73 | 479 | 1286 | 2.7 | 0.70 |
| W/GS-SB | 523 | 1310 | 2.5 | 0.85 | 479 | 1286 | 2.7 | 0.70 |
| W/SF-CN | 520 | 1262 | 2.4 | 0.82 | 479 | 1286 | 2.7 | 0.70 |
| CTW (2-yr)‡ | 482 | 743 | 1.5 | 0.48 | 431 | 774 | 1.8 | 0.42 |
| NTW (2-yr)‡ | 482 | 743 | 1.5 | 0.48 | 431 | 774 | 1.8 | 0.42 |
| 2-yr total | 1538 | 1835 |

† Double crops are grain sorghum (GS), soybean (SB), and sunflower (SF). Full-season crops are soybean (SB), corn (CN), grain sorghum (GS), and winter wheat (W).

‡ CTW, conventional till continuous wheat; NTW, no-till continuous wheat.
et al., 1988; Jones et al., 1994; Sharpley and Smith, 1994) have found that no-till had similar or slightly higher annual runoff values compared with conventional tillage.

At Lahoma, W/SF-GS and NTW had the highest SPSI, and SPSI values were more homogeneous than at LCB. The diversified cropping system W/SF-GS had the highest SPSI at both locations. We hypothesize that the adaptability of sunflower and grain sorghum to environments with frequent water deficits (Inuyama et al., 1976) and high temperatures was an important contributing factor. These crops’ adaptability to these environments promotes steady production of crop biomass resulting in a substantial residue that was returned to the soil and covered the ground surface. No-till systems rely on the constant contribution of crop residues to the soil surface, especially in environments with high decomposition rates. Differences in residue production were significant at LCB, where soybean and corn showed poor performance and did not contribute a large amount of crop residue. In fact, measurements of crop residue on the soil surface in April 2010 at LCB showed that the treatment W/SF-GS had 110 and 470% more residue than W/SB-CN and W/GS-SB, respectively. It is worth noting that SPSI values for continuous wheat systems (both conventional till and no-till) at Lahoma were similar to that of diversified cropping systems because the high-yielding environment allowed for substantial crop residue production that covered most of the soil surface during the summer fallow period in continuous wheat.

Table 4. Monthly precipitation for cropping year 2009–2010, and 2010–2011, as well as 17-yr reference ETo, which was obtained from Mesonet weather stations network. Reference ETo was calculated using the Penman–Monteith method. The 30-yr average precipitation was obtained from Oklahoma climate survey.

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† LCB, Lake Carl Blackwell.
‡ ETo, grass reference evapotranspiration.

Fig. 2. Comparison of precipitation storage efficiency among different cropping systems using the System Precipitation Storage Index (SPSI). Treatments were: continuous conventional till winter wheat (CTW), continuous no-till winter wheat (NTW), winter wheat–double crop grain sorghum–full-season soybean (W/GS-SB), winter wheat–double crop soybean–full-season corn (W/SB-CN), and winter wheat–double crop sunflower–full-season grain sorghum (W/SF-GS). Different letters indicate significant differences within location at p < 0.05. Error bars represent ±1 SD.

Fig. 3. Total fallow period length (white bars) and fallow period water losses (black bars) in mm. Treatments were: continuous conventional till winter wheat (CTW), continuous no-till winter wheat (NTW), winter wheat–double crop grain sorghum–full-season soybean (W/GS-SB), winter wheat–double crop soybean–full-season corn (W/SB-CN), and winter wheat–double crop sunflower–full-season grain sorghum (W/SF-GS). Different letters indicate significant differences within fallow losses at p < 0.05.
On the other hand, the amount of biomass produced by continuous wheat systems at LCB was poor, leaving the soil surface exposed to large evaporative losses during the summer fallow period.

As can be seen in Fig. 3, all cropping systems at both locations had similar fallow period length. Nonetheless, continuous wheat cropping systems showed significantly higher water losses during fallow periods, compared with diversified cropping systems. Losses under continuous wheat were 300 to 400 mm higher across 2 yr. Since there were no large differences in fallow period length between cropping systems, the fundamental change was the timing of the fallow period occurrence. Fallow periods in continuous wheat systems occurred from middle June to middle October (high atmospheric demand), whereas diversified cropping systems had most of the fallow period concentrated from late October to early April (low atmospheric demand). For this reason, precipitation during summer fallow periods was more vulnerable to evaporation. Changing the occurrence of the fallow periods from summer to winter may be a key strategy to achieve more efficient use of precipitation in regions with >600 mm annual precipitation and high evapotranspiration demand during the summer.

### Crop Yields and Productivity

Crop yields at Lahoma were generally higher compared with crop yields at LCB (Table 5). The experiment site at Lahoma has higher yield potential than LCB due to better soil quality (slope <1%, higher soil organic C, higher P and K content, and deeper soil profile). As expected, summer full-season crops had higher yields than double crops. For instance, grain sorghum and soybean, when grown as double crops, resulted in yields approximately half of the respective full-season crop at each location (Table 5). The summer full-season crops can be planted earlier than double crops, and therefore, critical crop stages have a greater probability of occurring before the often severe water deficits, high temperatures, and low relative humidity of July and August.

Double crop sunflower showed grain yields similar to the state average at Lahoma and yields 40% lower than the state average at LCB. The rest of the double crops, which were soybean and grain sorghum, had yields lower than the state average at both locations. It is important to note that state averages include both full-season and double crops (USDA, 2010).

Summer full-season grain sorghum at Lahoma had higher yields than state average for 2010 (3200 kg ha⁻¹). At LCB, grain sorghum was below the state average, but again, the yield reduction compared with the state average was the least among all full-season crops. Grain sorghum yields were similar to those observed by Jones and Popham (1997) in a continuous no-till sorghum in the Texas panhandle and similar to yields obtained under no-till conditions by Unger and Wiese (1979) in dryland conditions in Bushland, TX.

Corn yields were considerably below the state average of 8100 kg ha⁻¹ (which includes rainfed and irrigated corn cropland) at both locations. Corn yields were strongly affected by above-optimum temperatures, which caused reduced pollination, to the extent that many ears contained no kernels. This is in agreement with Cicchino et al. (2010), who reported that heat stress in late vegetative stages and the silking-pollination period strongly affects the kernels set of corn ears.

Wheat yields ranged from 1820 to 4450 kg ha⁻¹ at Lahoma and from 1020 to 1690 kg ha⁻¹ at LCB. Wheat yields were generally lower at Lahoma in 2009–2010, in part because early growing season precipitation was only 34 mm from planting until 1 January. In contrast, wheat in 2010–2011 was sown in early October and received 94 mm from planting until 1 January. Therefore, in early stages, wheat during 2010–2011 had 176% more precipitation than wheat in 2009–2010. Afterward, wheat in 2009–2010 had equal or even higher precipitation amount than wheat in 2010–2011, but most likely that was too late for the crop to compensate with more and heavier kernels per head. At LCB, planting dates were similar in both years (early November). At this location precipitation during vegetative stages was similar in both years. However, during the wheat growing season of 2010–2011, winter wheat did not receive significant amounts of precipitation from middle March to late April, the time of the year where wheat is in reproductive stages. A water deficit in this stage may reduce maximum achievable grain yield.

### Summer Double Crop vs. Summer Fallow

The continuous wheat cropping systems had a summer fallow period between growing seasons. In contrast, in the diversified cropping systems, a summer double crop was planted soon after the winter wheat growing season ended. The soil water dynamics between double crop sunflower and CTW summer fallow at Lahoma in 2009 (Fig. 4) illustrate the depletion of root-zone PAW, which reaches maximum depletion values as the crop approaches maturity. This soil water depletion implies that summer precipitation and prior soil water storage were used by evapotranspiration during the crop cycle.

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† Double crops are grain sorghum (GS), soybean (SB), sunflower (SF). Full-season crops are soybean (SB), corn (CN), grain sorghum (GS) and winter wheat (W). Conventional till continuous wheat (CTW), and no-till continuous wheat (NTW).

‡ Significant differences are only shown for wheat 2010–2011 at Lahoma, and wheat 2009–2010 at LCB.

§ Means followed by same letter are significantly different at P < 0.05.
However, the soil profile in which double crop sunflower was grown was recharged in the fall, and PAW was not significantly different from that under CTW at the first neutron probe reading after wheat planting, meaning that summer double crops constitute a feasible alternative for efficiently using summer precipitation in some years.

**Winter Wheat after Summer Full-Season Crop or Fallow Period**

In traditional continuous wheat cropping systems, wheat follows a summer fallow period. In the diversified cropping systems used in this experiment, winter wheat followed summer full-season crops such as grain sorghum, corn, or soybean. No significant differences in winter wheat grain yield were found when growing wheat either after a fallow period or a full-season crop at LCB (Table 5). However, significant differences in wheat grain yield were observed at Lahoma, with lower wheat yields after summer full-season soybean. Winter wheat grain yield after summer full-season crops has previously been reported to be lower than after fallow periods (Sanford et al., 1973). In that study, wheat growth and yield were lower when planted after grain sorghum than after summer fallow due to N immobilization, which led to N stress of the wheat crop (Sanford et al., 1973). However, in our experiment, sufficient N was applied to avoid N deficiency, and the low C/N ratio of soybean residue made immobilization unlikely. Therefore, differences in wheat yield may have been a consequence of a greater soil water deficit caused by full-season soybean, which could negatively affect the subsequent wheat grain yield.

**Limitations of the Study**

A key limitation of this study is that it contains data for 2 yr at two locations, meaning that for the diversified cropping systems the crop rotation cycle was completed only one time. A second limitation is that not all phases of the crop rotation are present every year at each location, which prevented us from comparing summer full-season and summer double crops of the same rotation during the same year at each location. Nevertheless, our results allowed us to detect clear differences in precipitation allocation and PSE between continuous wheat systems and diversified cropping systems; this can be useful to investigators studying similar cropping systems in the US Great Plains or other similar regions of the world.

**CONCLUSIONS**

Growing season precipitation allocation was increased from 45% under continuous wheat to 85% under diversified cropping systems in the region of the Southern Great Plains with >600 mm annual precipitation. This increase in precipitation allocation using diversified cropping systems was not a result of increasing the growing season length or shortening the fallow periods, but rather a consequence of shifting the timing of the fallow periods. Summer fallow periods that are common practice in continuous wheat were shifted to winter fallow under diversified cropping systems. Even though fallow periods had similar length and precipitation storage efficiencies at the cropping system level, total water losses during winter fallow periods of diversified cropping systems were markedly lower than the water losses in summer fallow periods of continuous wheat. Diversified cropping systems appear to be a feasible alternative to increase crop productivity per unit of land and time through more efficient allocation of precipitation in the >600 mm annual precipitation portion of the Southern Great Plains.

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