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Crop rotation and tillage impact yield performance of soybean, sorghum, and wheat

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Abstract

The benefits of no-till to crop yield depend on environment and crop sequence; thus, understanding their interactions is a long-term process. This 44-year field experiment examined grain yield, yield stability, and adaptability of continuous winter wheat (*Triticum aestivum* L.) (Ct-WT), continuous soybean [*Glycine max* (L.) *Merrill*] (Ct-SY), continuous grain sorghum [*Sorghum bicolor* (L.) *Moench*] (Ct-GS), soybean–winter wheat rotation (SY-WT), and soybean-grain sorghum rotation (SY-GS) under three tillage systems (NT, no-tillage; RT, reduced tillage; CT, conventional tillage) near Ashland Bottoms, KS. The temporal variation across the studied years allowed us to evaluate treatments under low- and high-yielding environments. Crop rotation consistently outyielded continuous cropping, and the advantage was enhanced when integrated with NT. Yield stability decreased under NT continuous cropping in most systems. Wheat was adaptable to low- and high-yielding environments with similar grain yield and yield stability among treatments, except for NT Ct-WT, which had the lowest yield stability and grain yield (2.5 vs. 3.5 Mg ha^{-1}). Soybean grain yield was greater under rotation than Ct-SY (2.7 vs. 2.0 Mg ha^{-1}) and under NT than RT and CT (2.6 vs. 2.4 Mg ha^{-1}), with similar yield stability. Soybean grown after wheat was more adaptable to low-yielding environments and grown after sorghum to high-yielding environments. Sorghum in NT SY-GS was adaptable to low- and high-yielding environments and had the greatest yield (6.2 Mg ha^{-1}) and yield stability. This long-term study demonstrated the advantages of crop rotation combined with NT on grain yield, yield stability, and crop adaptability.

Abbreviations: CT, conventional tillage; Ct-GS, continuous grain sorghum; Ct-SY, continuous soybean; Ct-WT, continuous winter wheat; NT, no-tillage; PA, precipitation allocation; PUE, precipitation use efficiency; RT, reduced tillage; SOC, soil organic carbon.; SY-GS, soybean–grain sorghum rotation; SY-WT, soybean–winter wheat rotation.

1 | INTRODUCTION

Increasing agricultural production while simultaneously meeting sustainability and conservation goals is a challenge that farmers and researchers face to meet the projected food demand for a growing population (Cohen, 2002). Adopting practices that are considered part of a "conservation agriculture" system may help meet this goal while protecting natural resources (Giller et al., 2015). However, recent evidence suggests that individual practices within conservation agriculture may not always result in improved crop yield (Pittelkow et al., 2015). Thus, there is a need to quantify under which conditions certain conservation agriculture practices may benefit the system through improved crop yield or yield stability.

Conservation agriculture is a system characterized by practices including crop rotation, minimal soil disturbance (i.e., no-tillage [NT] or reduced-tillage [RT] systems), and permanent soil cover, as described by Hobbs et al. (2008). Several studies showed the beneficial impacts of crop rotation on the environment (e.g., increased biodiversity and carbon sequestration; Bowles et al., 2020; Leteinturier et al., 2006; Piorr, 2003; West & Post, 2002); soil health (Abreu et al., 2011; Karlen et al., 2006); and disease, weed, and pest suppression (Liebman & Dyck, 1993; Thenail et al., 2009). Recent evidence also suggests that crop rotation and diversification can increase agricultural resilience under extreme growing conditions (Bowles et al., 2020). At issue here is an increasing trend toward monocropping in the first decade of the 2000s in the central United States (Plourde et al., 2013), primarily led by economics and allowed by genetic advances (i.e., pesticide- and insect-resistant crops, drought-tolerant crops) and agricultural intensification (i.e., accessibility to resources such as pesticides, fertilizers, and irrigation), resulting in the deliberate application of pesticides, synthetic fertilizers, and water to maintain high yields. The increasing monocropping area was recently evidenced by a survey suggesting that as many as 51% of winter wheat (*Triticum aestivum* L.) fields in central Kansas are monoculture (Jaenisch et al., 2021).

Conventional-tillage (CT) has been used in agriculture for fertilizer incorporation, weed control, and seedbed preparation. However, CT negatively impacts soil quality by lowering water-stable aggregation, soil organic carbon (SOC), soil microbial biomass, and soil nutrient availability, and increasing soil loss (i.e., erosion) (Jackson et al., 2003; Karlen et al., 2013; Lollato et al., 2012; Van Eerd et al., 2014). Thus, agriculture has shifted toward NT systems (Derpsch et al., 2010). Soil and water conservation are essential to sustain productivity, and the residue present on the soil surface plays an essential role in reaching this objective. Long-term conservation agriculture through NT and increased soil residue cover can increase water infiltration rate (Bissett & O'Leary, 1996; Bombino et al., 2019) and enhance precipitation storage by up to 35% as biomass residue increases (Nielsen et al., 2005).

Core Ideas

- Crop rotations outyielded continuous cropping, with a greater advantage in no-till systems.
- Yield performance and stability of no-till decreased under continuous cropping.
- Soybeans following wheat or sorghum outyielded continuous crop in low- and high-yield environments, respectively.
- Continuous no-till wheat had the greatest yield penalty among the three crops evaluated.
- Soil organic carbon increased over time with no-till but did not change with conventional tillage.

Therefore, adopting NT practices in water-limited environments can positively impact crop yields by enhancing soil water conservation in dryland cropping systems (e.g., Farooq et al., 2011; Pittelkow et al., 2015; Rusinamhodzi et al., 2011; Schlegel et al., 2019a).

In water-limited environments where dryland cropping systems are adopted, the efficient use of water is essential for crop production. Precipitation use efficiency (PUE; crop yield per unit of growing season precipitation) is directly affected by crop sequence due to the length and timing of crop presence in the field and the precipitation received during this period, and also by the tillage system owing to its effects on crop yield and soil moisture retention (G. A. Peterson & Westfall, 2004; G. A. Peterson et al., 1996). Managing PUE can be the key to a dryland cropping system's success. However, PUE is a function of crop yield and growing season precipitation; thus, the concept of precipitation allocation (PA; the ratio of precipitation received during the growing season over the total precipitation during the entire crop rotation cycle) can complement the analysis of PUE in rainfed agriculture (Patrignani et al., 2019; G. A. Peterson & Westfall, 2004). Crop sequence directly affects PA, and cropping systems with shorter fallow periods and greater diversity and intensity can enhance PUE and PA (Patrignani et al., 2019; G. A. Peterson et al., 1996).

Despite the benefits of NT to different aspects of the production system, research has also shown drawbacks depending on environmental conditions and cropping system management (Giller et al., 2015). The lack of yield improvement in the first few years after NT adoption is often attributed to a "transitional period" (Derpsch et al., 2010) in which some benefits of NT—such as soil organic matter accumulation—have not yet been fully realized (e.g., Abreu et al., 2011; Paustian et al., 1997). Additionally, in a meta-analysis evaluating the long-term effect of conservation agriculture on maize (*Zea mays* L.) grain yield, Rusinamhodzi et al. (2011) found that cover mulch led to waterlogging and decreased yield in areas with an annual rainfall greater than 1000 mm. Many literature reviews have also shown that high amounts of residue on the soil left by NT could reduce crop yields due to a decreased soil temperature at planting in colder climates, increase time for crop establishment, and slower crop development (Kravchenko & Thelen, 2007; Ogle et al., 2012). In addition, a shift in the weed population, mostly from broadleaves to grass weeds, and an increase in disease and insect pressure that survive in crop residue and soil are typical in NT systems (Giller et al., 2015; Thenail et al., 2009). All these factors can lead to yield reductions in some environments even though the concepts of conservation agriculture have been thoroughly communicated and encouraged worldwide (Giller et al., 2015).

One way to verify the long-term potential of conservation agriculture is through yield stability analysis in long-term studies (e.g., Raun et al., 1993; Silva et al., 2021). Yield stability refers to the ability of a crop to change its performance as environmental conditions change (Becker & Leon, 1988; Tollenaar & Lee, 2002), and it can be either a positive trait (e.g., a more stable system that sustains acceptable yield levels under below optimal conditions such as drought, improving a system's sustainability) or a negative trait (e.g., a more stable system that does not capitalize on above optimal conditions when these occur, detrimental to the sustainability of a system). The latter is usually captured by adaptability analysis that describes under which environmental conditions (e.g., high- vs. low-yielding environments) a given crop management or genotype was more adaptable (Finlay & Wilkinson, 1963). Yield stability analysis is usually performed for different genotypes (Eberhart & Russell, 1966) but can also be applied to evaluate the performance and predictability of cropping systems or fertilizer management strategies (Gaudin et al., 2015; Grover et al., 2009; Heinrich et al., 1983; Raun et al., 1993; Stelluti et al., 2007; St. Luce et al., 2020; Xu et al., 2019). Analysis of yield stability can reflect the aforementioned positive and negative effects of rotation and tillage practices, helping to evaluate the long-term effect of cropping systems on crop yield. Yield stability is a simple way to explain treatment × environment interactions (Stelluti et al., 2007) but requires a relatively large number of environments, either through long-term experiments (thus, temporal variation in environments) or through experimental replication at different locations (thus, regional variation in environments).

Long-term studies can help to understand the effects of different tillage systems and their interaction with crop rotation across years, also potentially highlighting the role of crop yield stability to system's sustainability. Thus, our main objective was to compare the grain yield of winter wheat, soybean [*Glycine max* (L.) Merrill], and grain sorghum [*Sorghum bicolor* (L.) Moench]—three important crops in the central United States—as impacted by the interaction of crop rotation and tillage systems. Specifically, we were interested in the yield response to crop rotation and tillage systems in low- and high-yielding years, crop adaptability to different temporal environments, crop yield stability, PUE, and PA. Our secondary objective was to compare SOC changes among different tillage practices at different periods.

2 | MATERIALS AND METHODS

2.1 | Long-term experiment and data source

Data used in the current study have been partially explored in previous studies (Doyle et al., 2004; Fabrizzi et al., 2007; Godsey et al., 2007; McVay et al., 2006; D. E. Peterson, 1981; D. Peterson & Roozeboom, 2007; Yin et al., 2010) which described the experimental setup in detail. The focus of these studies was primarily on soil health (i.e., physical, chemical, and biological properties)—which differs from our objectives—and, in some instances, on crop yield. The most recent study that included crop yield resulting from the same field experiment was published in 2007; thus, we added another 11 years of grain yield data to previous reports.

2.2 | Site description

This research was conducted from 1974 to 2018 (44 years) at the Kansas State University Agronomy Farm near Ashland Bottoms (Riley County; 39°07′ N, 96°37′ W), KS. Most of the experimental area was located on a Muir silt loam (fine-silty, mixed, mesic Cumulic Haplustoll), with a small portion located on a Reading silt loam (fine, mixed, mesic Typic Arguidoll). We note, however, chemical and physical proprieties (i.e., soil pH, cation exchange capacity, and particle size) of both soils were not significantly different (Doyle et al., 2004), and thus we would not expect the different soil series to influence the outcome of the analyses. The experiment was established under rainfed conditions with average annual precipitation from 1974 through 2018 of 850 mm, ranging from 460 to 1100 mm. This range is similar to that experienced across different geographies in the state of Kansas (Lollato et al., 2017; Lollato, Bavia, et al., 2020). Daily maximum and minimum air temperature and 24-h precipitation were taken from the daily Global Historical Climatology Network (Menne et al., 2012) from 1974 to 2018.

2.3 | Experimental design, treatments description, and general study management

The experiment was arranged as a split-plot design with four replications where crop sequence was the whole plot and tillage practices the subplots. Winter wheat, soybean, and grain sorghum were arranged in five crop sequences combined with three tillage systems. The crop sequences were continuous winter wheat (Ct-WT), continuous soybean (Ct-SY), continuous grain sorghum (Ct-GS), soybean–winter wheat rotation (SY-WT), and soybean–grain sorghum rotation (SY-GS). Crop rotations × tillage practices were duplicated in the experiment, so each crop was harvested yearly to eliminate the potential confounding effect of annual variation on crop yield.

The cycle length for each crop sequence was considered the number of years that involved one growing season for each crop present in the rotation, so all the crop sequences were 2-year cycles. For SY-WT rotation, wheat was sown as soon as soybean was harvested, and soybean was planted in the year following wheat harvest. All crop sequences had a winter-fallow period (7 months), except Ct-WT, which had a summer fallow period (4 months), and SY-WT with a winter- and spring-fallow period (10 months). The intensity rate reflects the product between the number of crops grown in a crop rotation cycle and the respective crop's score (USDA pre-defined score based on crop water demand) divided by the unit of land area (USDA-NRCS, 2013). The diversity rate is the frequency of appearance of a given crop type (grass, broadleaf, summer/winter crops, etc.) in the crop rotation length (USDA-NRCS, 2013). The intensity rate for all crop sequences was 2, except for Ct-WT which was 1. The diversity rate for SY-WT and SY-GS rotation was 0.5, for Ct-WT it was −0.5, and for Ct-SY and Ct-GS it was −1.0.

The tillage systems consisted of NT, RT, and CT. In the NT treatment, crops were planted directly into the residue of the previous crops, fertilizer was not incorporated, and weed control was exclusively chemical. In RT plots, the soil was disked one to two times in the spring, and the field was field-cultivated before each crop planting to incorporate broadcast fertilizer, control weeds, and prepare the seedbed for planting. The CT plots were similar to RT plots but with an average of two extra tillage operations during the fall after crop harvest. Tillage for RT and CT treatments also varied year-to-year as needed depending upon environmental conditions. The only exception was for wheat in the SY-WT rotation in which both RT and CT consisted of one tillage before wheat sowing due to the short period between soybean harvest and the sowing of the subsequent wheat. Thus, the difference between RT SY-WT and CT SY-WT treatments is that there were only one to two extra tillage practices before soybean.

Subplots containing each combination of crop sequence and tillage were 6.1 m wide and 18.3 m long. Wheat was sown at 90 kg ha^{-1} in 20-cm row spacing. Sorghum was planted at 162,500 seeds ha^{-1}, and soybean was planted at 312,500 seeds ha^{-1}, both in 76-cm row spacing. Varieties and hybrids changed during the study so that modern genotypes with good disease and insect tolerance were always adopted in combination with recommended seed treatments. Despite changes in the genotypes along the 44 years of the study, each treatment had the same variety/hybrid planted within any given year so that all treatments evaluated the same genotype, eliminating the confounding effect of genotype on treatment performance. Herbicide application varied year-to-year depending on weed population and new technologies that became available over the years. Foliar fungicides or insecticides were not applied during any time of the experiment. Fertilizers were applied according to university fertilizer reports recommendations based on soil test analysis, except for nitrogen and phosphorus. The same amount of fertilizer (112 kg N ha^{-1} year^{-1} and 11.5 kg P ha^{-1} year^{-1} of urea-diammonium phosphate mixture) was broadcast before each crop planting to reduce the impact of different amounts of nitrogen and phosphorus applied in the crop sequences (Godsey et al., 2007). This would not be a typical farmer practice for soybean; however, uniform, adequate fertilizer applications were implemented at the beginning of the experiment to eliminate fertility as a limiting variable for the evaluated systems. Wheat yields were based on a 1.83-m swath harvested from the center of each plot. Soybean and sorghum yields were harvested from each plot's fifth and sixth rows representing a 1.52-m swath width.

2.4 | Statistical analysis

Mean crop grain yield in each treatment was calculated as the grain yield average across replications. Mixed model analysis of variance (ANOVA) was performed to compare the treatment effect on crop yield using PROC GLIMMIX procedure on SAS 9.4 software (SAS Institute), with crop sequence and tillage system as fixed effects and years as random effect. These analyses were performed across the 44 years of the study but also independently for high-yielding years (i.e., annual crop's mean yield greater than 66th percentile) and low-yielding years (i.e., annual crop's mean yield below 33rd percentile) for each crop.

2.5 | Crop adaptability and yield stability

Yield stability and adaptability analyses were performed as the linear regression of annual mean yield for each treatment against the environmental index (i.e., annual crop's mean yield of each treatment minus crop's grand mean yield across all years-treatments), as described by Eberhart and Russell (1966). While adaptability and stability analyses were initially created to investigate the interaction between crop genotype and environment, these indices can also be applied to evaluate different agronomic treatments (Piepho, 1998; Reckling et al., 2021) as widely done in the literature (Gaudin et al., 2015; Grover et al., 2009; St. Luce et al., 2020; Xu et al., 2019). The adaptability of each treatment in different yielding environments can be described by the slope of the regression (α), so $\alpha > 1$ reflects adaptability in high-yielding environments, $\alpha = 1$ indicates broad adaptability, and $\alpha < 1$ reflects adaptability in low-yielding environments. Meanwhile, a stable crop sequence and/or tillage system attains a treatment-environment coefficient of determination of the regression close to one (i.e., $r^2 = 1$). The intercept (β) reflects the average grain yield of the treatment. Regression analysis for adaptability and stability was performed using the REG procedure on SAS 9.4 software. Paired-comparison Student *t*-tests were used to analyze differences in α and β coefficients between treatments within the same crop, and $\alpha \neq 1$ was evaluated by the confidence interval of 95%. Because genotypes varied over the years for the three crops in this study, we checked for potential time trends in genotype-specific stability and adaptability by first clustering our data into periods based on when genotypes were modified for each crop over the years. Second, we performed the individual linear regression analyses as described above for each period and crop's respective treatments (following ANOVA's significant effects). The resulting slopes for each treatment-by-period combination were plotted against time and compared for significant differences (Figures S1–S3). Since only 6 of 180 slope comparisons were significantly different over the years (for comparisons within crops across time periods), we are confident to proceed with the analysis using the overall yield of 44 years. Finally, we calculated cumulative yields as a function of crop cycle to determine the production advantage of a given tillage-rotation combination across the entire study period. Both of these analyses respected the ANOVA results across the 44 years of study.

2.6 | Precipitation use efficiency and allocation

Growing season was defined as the months of mid-October to mid-June for wheat and mid-May to mid-October for soybean and sorghum. The ratio of total grain yield of a specific treatment (kg ha^{-1}) and the precipitation (mm) during growing season of all crops in the treatment defined PUE. The ratio of rainfall each treatment received during the growing season of all crops in the rotation over the total precipitation during the entire rotation cycle defined PA. Student *t*-tests were used to define differences in PA and PUE between treatments. In this study, the significance level of a given hypothesis test is set at 0.05

2.7 | Soil organic carbon

The means for SOC from previous studies of the same experiment (Doyle et al., 2004; D. E. Peterson, 1981; Sarto, data not published, 2018) were retrieved to evaluate the changes in SOC over the years for NT, RT, and CT across the five crop sequences at the 0–5 cm depth.

3 | RESULTS

3.1 | Environmental conditions

Wheat growing season precipitation ranged from 225 to 727 mm, with an average of 460 mm (Figure S4). During the summer-crop growing season, precipitation ranged from 270 to 920 mm, with an average of 470 mm. The mean minimum temperature ranged from −0.1 to 4.8˚C for wheat and 14.5 to 18.3˚C for summer crops during their respective growing seasons. Meanwhile, mean maximum temperature ranged from 11.6 to 18.3˚C for wheat and 27.5 to 30.1˚C for summer crops. No significant relationship between crop yield and precipitation was detected for any crops in the study (data not shown).

3.2 | Grain yield, crop adaptability, and yield stability

3.2.1 | Winter wheat

Grain yield ranged from 0.1 to 6.9 Mg ha^{-1} across treatments and years. The crop sequence × tillage interaction significantly impacted yield across the 44 years evaluated and in low-yielding years (Table 1, Figure 1). In these two groupings, NT Ct-WT yielded as much as 35% less than the remaining treatments (2.5 vs. 3.2–3.4 Mg ha^{-1}). In high-yielding years, both main effects of crop sequence and tillage system were significant (Table 1, Figure 1), with CT yielding similarly to RT, but both yielding more than NT (4.6, 4.6, and 4.1 Mg ha^{-1}, respectively). Additionally, wheat in rotation with soybean yielded more than Ct-WT (4.6 vs. 4.3 Mg ha^{-1}, respectively) (Table 1, Figure 1).

Crop adaptability and yield stability analysis are depicted in Figure 2A. Wheat had a slope equal to one for all crop sequence × tillage combinations, suggesting broad adaptability across environments irrespective of crop sequence or tillage system. The lowest yield stability occurred for NT Ct-WT compared to all other treatments ($r^2 = 0.71$ vs. $r^2 > 0.81$). Tillage (i.e., RT and CT) slightly improved yield stability in Ct-WT. The low stability of NT Ct-WT was even more

TABLE 1 Analysis of variance (ANOVA) of winter wheat, soybean, and grain sorghum under different tillage systems (T) and crop sequences (CS) in high-yielding years (HY), low-yielding years (LY), and across 44 years from a long-term study (1974–2018) near Ashland Bottoms, KS, USA

	HY (n = 14)[a]			LY (n = 14)			Across 44 years (n = 44)		
Factor	Winter wheat	Soybean	Grain sorghum	Winter wheat	Soybean	Grain sorghum	Winter wheat	Soybean	Grain sorghum
	p-value[b]								
T	0.0027	0.4186	0.7526	0.0040	0.0079	0.0178	<0.0001	<0.0001	0.1071
CS	0.0245	<0.0001	<0.0001	0.2928	<0.0001	0.2753	0.0004	<0.0001	<0.0001
T × CS	0.0873	0.9310	0.3280	0.0012	0.7747	0.0135	<0.0001	0.2399	0.0088

[a]High-yielding years represent crop's mean yield greater than 66th percentile, and low-yielding years represent crop's mean yield less than 33rd percentile.
[b]F values significant at $p < 0.05$.

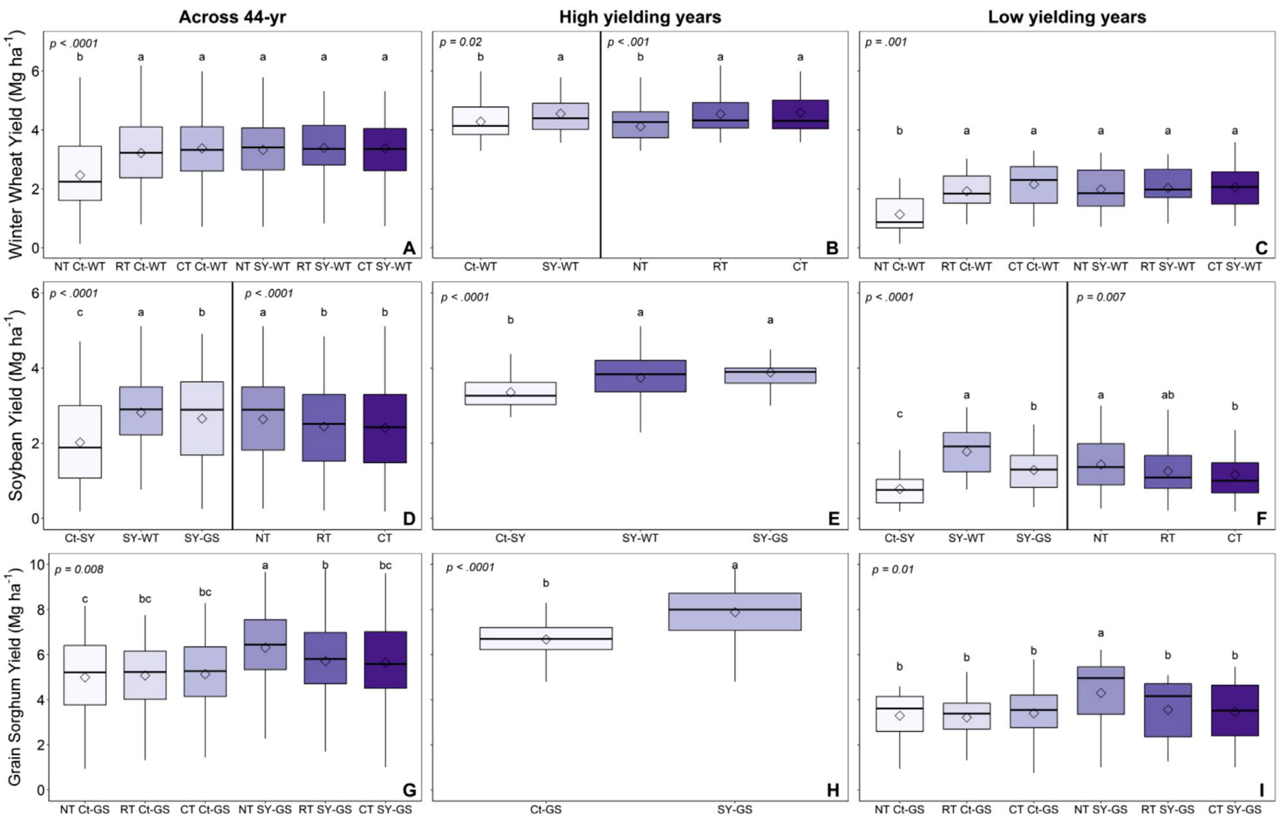

FIGURE 1 Grain yield of (A–C) winter wheat, (D–F) soybean, and (G–I) grain sorghum under five crop sequences (Ct-WT, continuous winter wheat; Ct-SY, continuous soybean; Ct-GS, continuous grain sorghum; SY-WT, soybean–winter wheat rotation; SY-GS, soybean–grain sorghum rotation) and three tillage systems (NT, no-tillage; RT, reduced tillage; CT, conventional tillage) (A,D,G) across a 44-year study and (B,E,H) in high-yielding years and (C) low-yielding years among the 44-year study (1974–2018) near Ashland Bottoms, KS. High-yielding years represent crop's mean yield greater than 66th percentile, and low-yielding years represent crop's mean yield less than 33rd percentile over the 44-year study. Boxplots with the same letter are not statistically different according to Honest Significant Difference test (F values significant at $p < 0.05$), and only the significant effects for each crop are shown.

apparent when comparing the intercept of the equations, as the intercept for RT and CT was significantly greater than NT ($\beta = 3.21$ and 3.37 vs. 2.46 Mg ha^{-1}, respectively), indicating greater overall mean yields for RT and CT. When wheat was rotated with soybeans, there was low variation about the fitted line and the slope was close to one, suggesting that SY-WT had wide adaptability and greater stability across different environments, regardless of tillage. The intercept of SY-WT was consistently greater than for Ct-WT, except for CT Ct-WT, which outyielded all the other treatments. The cumulative yield analysis for wheat (Figure 3A) showed NT Ct-WT only accumulated 105 Mg ha^{-1} across the

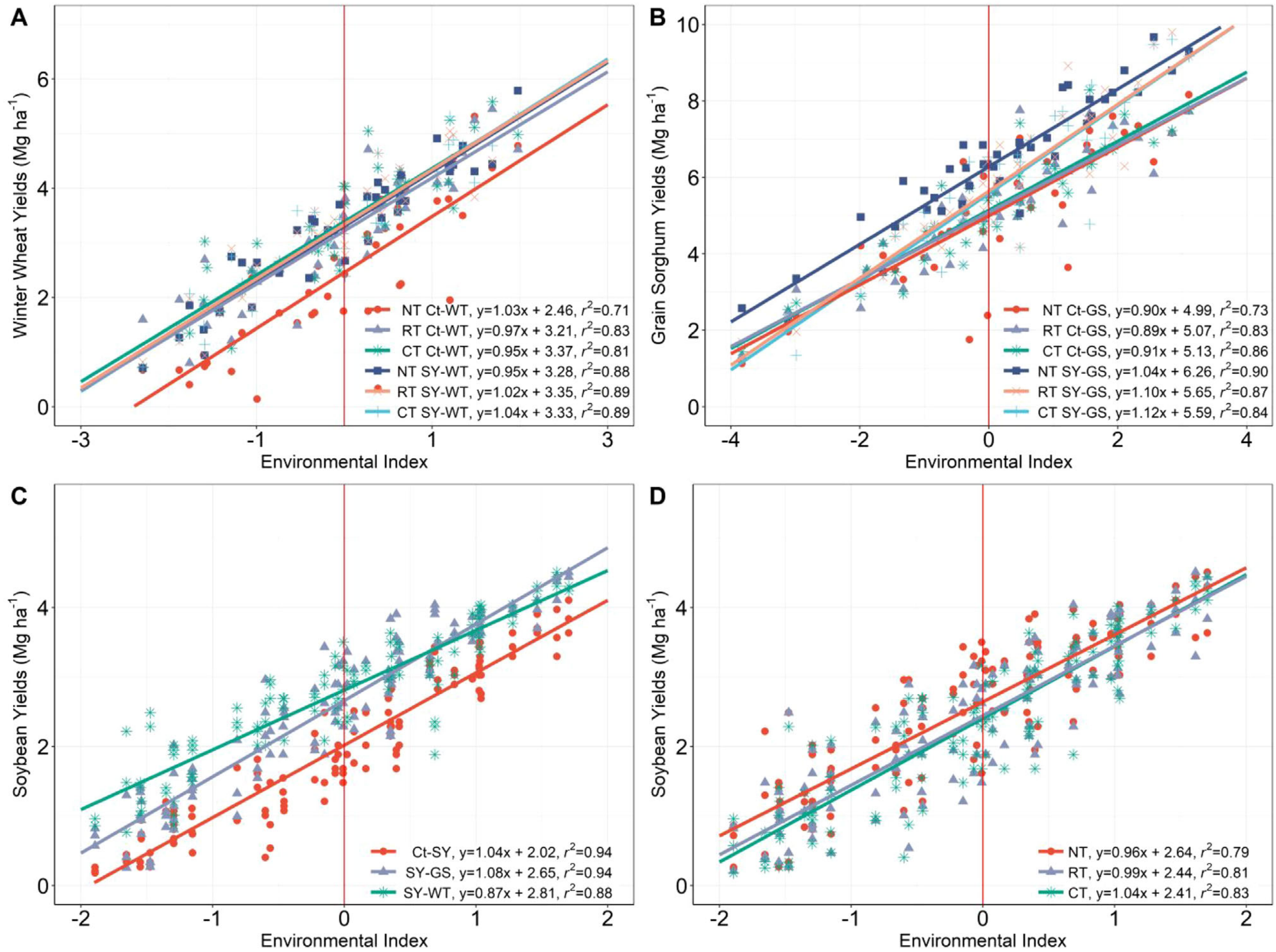

FIGURE 2 Linear regression relationship between crop yield and the environmental index for yield of (A) winter wheat, (B) grain sorghum, and (C,D) soybean under different tillage systems (NT, no-tillage, RT, reduced tillage; CT, conventional tillage) and crop sequences (Ct-WT, continuous winter wheat; Ct-SY, continuous soybean; Ct-GS, continuous grain sorghum; SY-WT, soybean–winter wheat rotation; and SY-GS, soybean–grain sorghum rotation) in a 44-year study (1974–2018) near Ashland Bottoms, KS

44 years, while all the other treatments accumulated around 140 Mg ha^{-1}.

3.2.2 | Soybean

Grain yield ranged from 0.2 to 5.1 Mg ha^{-1} across treatments and years. The main effects of tillage system and crop sequence were significant across the 44 years and in low-yielding years, whereas only crop sequence was significant in high-yielding years (Table 1, Figure 1). Across the 44 years, NT yielded more than RT and CT, but the last two did not differ (2.6 vs. c.a. 2.4 Mg ha^{-1}, respectively). Results were similar in low-yielding years, except RT did not differ from NT or CT. Soybean yields were significantly greater for SY-WT, followed by SY-GS, and Ct-SY (2.8, 2.6, and 2.0 Mg ha^{-1}, respectively), reflecting a yield increase of 16%–27% when soybean was in a rotation with either sorghum or wheat. For high-yielding years, soybean yield in rotation with either wheat or sorghum (SY-WT and SY-GS) did not differ, but both were greater than Ct-SY.

Crop adaptability and yield stability analysis for soybean yields are depicted in Figure 2C,D. Crop sequence (Figure 2C) and tillage system (Figure 2D) analyses were performed separately due to the lack of significant interaction in the ANOVA across the 44 years (Table 1). Regarding crop sequences, Ct-SY showed a slope equal to one and low variation about the fitted line (i.e., r^2 close to one), suggesting monocropping soybean had broad adaptability and high stability over time. However, we note the Ct-SY treatment did not exploit high-yielding environments, which agreed with our ANOVA results for high-yielding years. This can also be noted by a significantly lower intercept for Ct-SY than SY-WT and SY-GS ($\beta = 2.02$ vs. 2.66 and 2.82 Mg ha^{-1}, respectively), suggesting lower overall yield levels. Soybean after wheat showed a slope significantly less than one, while SY-GS showed a slope significantly greater than one, and both slopes differed. This result indicates that SY-WT was better adapted to

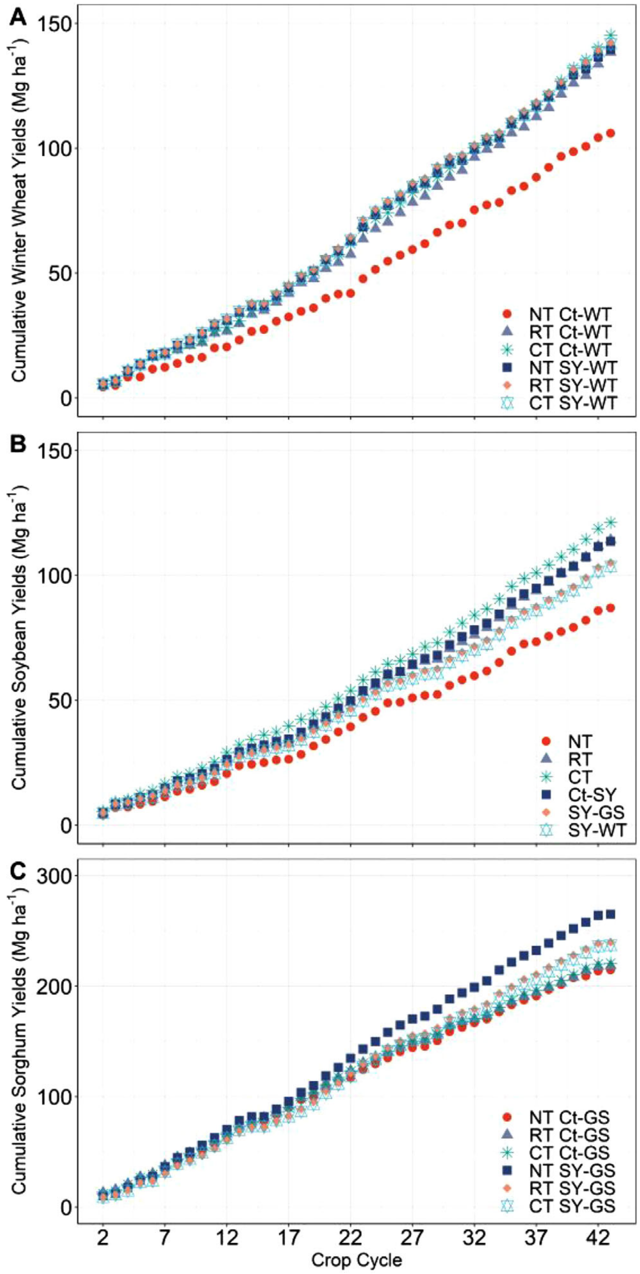

FIGURE 3 Cumulative yield analysis for (A) winter wheat, (B) grain sorghum, and (C) soybean under three tillage systems (NT, no-tillage; RT, reduced tillage; CT, conventional tillage) and five crop sequences (Ct-WT, continuous winter wheat; Ct-GS, continuous grain sorghum; Ct-SY, continuous soybean; SY-WT, soybean–winter wheat rotation; SY-GS, soybean–grain sorghum rotation) in a 44-year study (1974–2018) near Ashland Bottoms, KS

low-yielding environments, whereas SY-GS had better adaptability to high-yielding environments. Both rotations showed low variation about the fitted line, indicating that their yields were stable across years. Regarding the tillage system, soybean yields were broadly adaptable ($\alpha = 1$) and stable ($r^2 = 1$) across environments under the three tillage systems. The cumulative yield analysis (Figure 3B) showed SY-WT rotation had the greatest yield accumulated over the years (120 Mg ha^{-1}), followed by SY-GS (115 Mg ha^{-1}), while Ct-SY had the lowest yield accumulated in the 44th year (87 Mg ha^{-1}). The NT system had the greatest yield accumulated compared to RT and CT (115 vs. c.a. 105 Mg ha^{-1}, respectively).

3.2.3 | Grain sorghum

Grain yield of sorghum ranged from 0.6 to 9.8 Mg ha^{-1} across treatments and environments during the 44-year study period. The crop sequence × tillage interaction significantly affected yield across the 44 years of the study and in low-yielding years (Table 1). In both cases, NT SY-GS treatment had the highest yield compared to all other treatments (6.3 and 4.2 Mg ha^{-1} across the 44 years and in low-yielding years, respectively). Sorghum mean yields were greater in SY-GS rotation than Ct-GS, regardless of the tillage system, and were enhanced with less intensive tillage practices. In high-yielding years, the crop sequence main effect was significant (Table 1) in which SY-GS had significantly greater yield than Ct-GS.

Crop adaptability and yield stability analysis are depicted in Figure 2B. For Ct-GS and SY-GS, slopes did not differ statistically from one, meaning sorghum grain yields are widely adaptable across different environments in both crop sequences. Sorghum grain yield stability was the greatest for the NT SY-GS treatment, having the least variation about the fitted line (greatest r^2), followed by RT and CT. The lowest yield stability across environments occurred for NT Ct-GS. The cumulative yield analysis (Figure 3C) showed that SY-GS had greater yield accumulation over the years compared to Ct-GS across tillage systems (215–220 vs. 237–265 Mg ha^{-1}), and the advantage was more apparent when associated with NT system (265 Mg ha^{-1}).

3.3 | Precipitation use efficiency and precipitation allocation

More intense crop rotations increased PA (Figure 4A). Precipitation allocation over the 44 years was significantly lower for Ct-WT (51 ± 1%, summer-fallow, intensity rate 1.0) than for rotations involving one or two summer crops such as Ct-SY, Ct-GS, SY-GS (PA = 63 ± 1%, winter-fallow, intensity rate 2.0), and SY-WT (65%, winter- and spring-fallow, intensity rate 2.0). Precipitation allocation ranged from 39% to 64% for Ct-WT, 49% to 75% for SY-WT, and 49% to 74% for crop sequences involving two consecutive years of summer crops.

Precipitation use efficiency for soybean was greater for NT than CT within all crop sequences, and NT was greater than RT in Ct-SY and SY-GS rotation (Figure 4B). Overall,

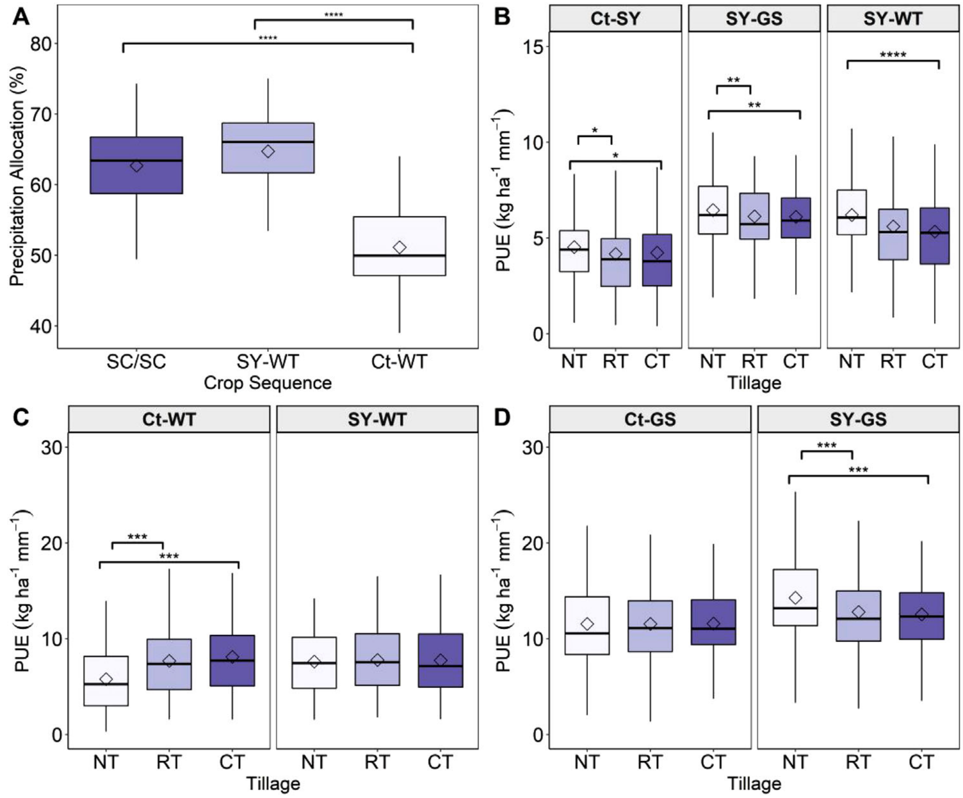

FIGURE 4 (A) Precipitation allocation in three cropping systems (SC/SC, two consecutive summer crops; SY-WT, soybean–winter wheat rotation; and Ct-WT, continuous winter wheat) and precipitation use efficiency of (B) soybean, (C) winter wheat, and (D) grain sorghum in different cropping sequences (Ct-SY, continuous soybean; SY-GS, soybean–grain sorghum rotation; Ct-GS, continuous grain sorghum) under three tillage systems (NT, no-tillage; RT, reduced tillage; CT, conventional tillage) in a 44-year study (1974–2018) near Ashland Bottoms, KS. *Significant at $p = 0.05$; **significant at $p = 0.01$; ***significant at $p = 0.001$

rotational crop sequences showed greater PUE than continuous cropping in soybean and sorghum (Figure 4B,D). Wheat had similar PUE among all treatments, except NT Ct-WT had the lowest PUE (5.7 vs. >7.5 kg ha^{-1} mm^{-1}). No significant differences in PUE were observed for wheat in the SY-WT rotation, regardless of the tillage system (c.a. 7.5 kg ha^{-1} mm^{-1}). Sorghum had similar PUE among all treatments, except NT SY-GS was greater than RT and CT within SY-GS (14.3 kg ha^{-1} mm^{-1} for NT vs. 12.6 kg ha^{-1} mm^{-1} for RT and CT).

3.4 | Soil organic carbon

Figure 5 depicts SOC concentration in the three tillage systems in 1981, 2004, and 2018 at the 0–5 cm depth. The first SOC data were published 7 years after the experiment was established (D. E. Peterson, 1981). In this case, all tillage treatments had similar SOC, with a slight advantage for NT systems (15 g kg^{-1} for NT vs. 14.5 g kg^{-1} for RT and 14.0 g kg^{-1} for CT). Over the years, it was evident that NT practices enhanced SOC (+7 g kg^{-1}), followed by lower increase in RT (+2 g kg^{-1}) and no increase in CT. However, SOC did not vary at deeper depths (data not shown).

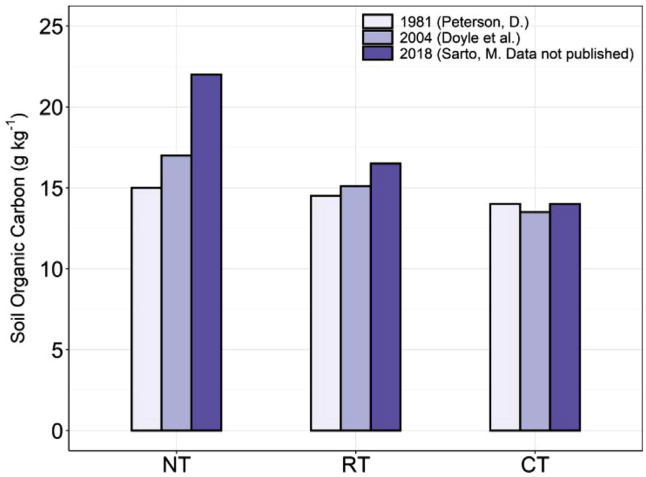

FIGURE 5 Soil organic carbon at 0–5 cm depth as affected by tillage system (NT, no-tillage; RT, reduced tillage; CT, conventional tillage) in 1981, 2004, and 2018 retrieved from a 44-year crop sequence and tillage system study (1974–2018) in Ashland Bottoms, KS

4 | DISCUSSION

The benefits of rotational cropping compared to monocropping on crop yield and soil health are well reported in the literature (Bowles et al., 2020; Edwards et al., 1988; Letein-turier et al., 2006; Liu et al., 2020; Piorr, 2003), but few studies showed if the benefits were consistent in the long term (Bowles et al., 2020; Congreves et al., 2015; Renwick et al., 2021), which here were explored within a stability context. Our study revealed the yield benefits of rotational cropping for soybean and sorghum across an extended period, which was enhanced when associated with NT. Meanwhile, wheat showed little response to crop sequence or tillage, except for reduced yields when continuously cropped under NT. It was also evident that long-term NT increased SOC at the 0–5 cm depth with no variation at deeper soil layers, aligning with existing literature (Al-Kaisi et al., 2015; Baker et al., 2007; Lollato et al., 2012; Luo et al., 2010). Finally, an original contribution of the current study is the cumulative analysis of yield for each crop over the 44-year study period, which is informative as it highlights how minor differences in annual crop yields can accumulate and impact the long-term crop production at the farm level (Figure 3).

4.1 | Winter wheat

The literature reports inconsistent and sometimes nonsignificant wheat yield response to rotation and tillage (Baumhardt & Jones, 2002; Lollato, Ruiz, et al., 2019; Lund et al., 1993; Schlegel et al., 2019a). Our study has original contributions to help clarify these relationships using a dataset with 44 continuous years of yield data. Grain yield of NT Ct-WT was lower and less stable than CT Ct-WT, but the CT benefit was absent when a soybean rotation was implemented. Thus, we suggest that the benefits of CT compared to NT for wheat are exclusive to mono-cropping, and crop rotations under NT bring benefits to offset the need for CT adoption. These findings are supported by long-term variety trial (Munaro et al., 2020) and grower-reported data (Lollato, Ruiz, et al., 2019) analyses in the region. The low yield and yield stability observed for NT Ct-WT may be potentially attributed to (i) a decrease in soil pH due to the composition of wheat residue (Godsey et al., 2007; Schroder et al., 2011), (ii) greater weed infestation over time due to lack of herbicide rotation (Murphy & Lemerle, 2006; Young et al., 2013), (iii) increased incidence of soilborne (Angus et al., 2015; Smith et al., 2004) and necrotrophic pathogens (near Carignano et al., 2008; Hesston, 1992) which can survive in wheat residue, and (iv) lack of benefits in soil water storage of NT compared to CT when NT is adopted on continuous wheat (Patrignani et al., 2012).

Partial data from the current study published in Godsey et al. (2007) suggested that Ct-WT and NT plots had significantly lower pH than all other treatments, and consequently, aluminum toxicity may have limited wheat yield in this treatment (Lollato et al., 2013; Lollato, Ochsner, et al., 2019). In a different experiment, Wright and Hons (2005) observed a higher C/N ratio and lower turnover rates in wheat residues than sorghum and soybean residues, which may have also decreased soil pH. From a weed control perspective, a major concern of downy brome (*Bromus tectorum* L.) infestation in NT Ct-WT was previously reported for the current study (D. Peterson & Roozeboom, 2007). Wheat yield losses are often correlated with greater weed density, especially grassy weeds (Hume et al., 1991; Pollard et al., 1982; Sarani et al., 2014; Swanton et al., 1993). In an 18-year rotation study, Ruisi et al. (2015) observed that continuous wheat increased weed seedbank density and decreased weed diversity compared to wheat in rotation with other crops. Likewise, in a 10-year tillage study, Campiglia et al. (2018) reported an increase in perennial weed population on minimal tillage compared to CT system in organic wheat under crop rotation. In both studies, weed control options for wheat became very limited when NT was not associated with crop rotation along with chemical weed control. In terms of crop rotation, Bushong et al. (2012) reported a c.a. 12% greater yield of wheat grown succeeding a brassica crop rather than a wheat crop in the US Great Plains, with yield gains of similar magnitude due to crop rotation originating from other wheat growing regions (Arshad et al., 2002; Kirkegaard & Ryan, 2014; Kirkegaard et al., 2008; Krupinsky et al., 2006; Miller et al., 2003; Smiley et al., 2014). Beyond the better control of troublesome grass weed species (Bushong et al., 2012), the yield benefit was also attributed to a lesser incidence of some soilborne pathogens common in cereal monoculture systems (Angus et al., 2015; Smith et al., 2004). Finally, while the benefits of NT to wheat in semi-arid regions are well reported due to its better soil water storage (Giller et al., 2015; Pittelkow et al., 2015), recent evidence suggests that both NT and CT result in similar soil water storage at sowing when crop rotation is not adopted (Patrignani et al., 2012), offsetting some of these expected benefits. Our results showed that, when water is not a limitation (i.e., high-yielding years), the long-term benefits of NT were also offset, but the benefits of crop rotation still prevailed for wheat. Wheat was adaptable in both low- and high-yielding environments regardless crop sequence or tillage system, likely due to more conservative use of water throughout the crop's cycle (Lobet et al., 2014) and deep root systems (Manschadi et al., 2010; Sciarresi et al., 2019), which is essential in low-yielding environments. The adaptability in high-yielding environments demonstrates the crop's ability to explore environmental sources such as water. We note in passing that although the crop was adaptable to high seasonal weather variabilities such as precipitation and temperature, management practices that maximize wheat yield under NT may differ from those under CT (Jaenisch et al., 2019; Munaro et al., 2020), suggesting that careful re-evaluation of management adoption is needed for growers transitioning from one tillage system to another.

4.2 | Soybean

In rotation with another crop, soybean yields were significantly greater than monocropping across a wide range of environments in the current study. However, these benefits depend on environmental-yielding conditions because soybean yields after wheat were more adaptable to low-yielding environments, and soybean yields after sorghum were more adaptable to high-yielding environments. Similar results were found by Schlegel et al. (2019a) in a low-yielding semi-arid environment (455 mm annual precipitation) in which soybean yields were greater when following wheat rather than after another summer crop such as maize. The authors suggested that the benefit was due to greater off-season soil water accumulation at soybean planting, which likely explains our soybean adaptability results in low-yielding environments following wheat rather than sorghum.

Higher average yield and yield stability of soybean under rotation and NT are likely due to improvements in soil's physical, biological, and chemical properties (Doyle et al., 2004; Fabrizzi et al., 2007; Godsey et al., 2007; McVay et al., 2006; Yin et al., 2010). Studying SOC storage in the same plots reported in the current study, Fabrizzi et al. (2007) reported that Ct-SY had the lowest and most negative change in SOC, which reduced SOC over the years. The authors assigned this effect to soybean's residue composition, which has a low C:N ratio and higher turnover rates. Meanwhile, previous reports derived from the current study suggested that crop sequences that included wheat and sorghum had higher levels of SOC and water holding capacity, which can be explained by the greater above-ground biomass produced, higher C:N ratio, and more fibrous roots (hence influencing soil structure) of these two crops (Fabrizzi et al., 2007; Godsey et al., 2007; McVay et al., 2006). Additional reasons for the improved soybean yield in rotation may include the greater residue cover remaining after the cereal phase of the rotation, which can help control summer weeds due to shading (Crutchfield et al., 1986; Liebl et al., 1992; Weisberger et al., 2019) and improve soil moisture retention (Schlegel et al., 2019b).

4.3 | Grain sorghum

Sorghum grain yields were also enhanced under rotation with soybeans and decreased tillage intensity. When focusing on the tillage aspect, the greater yield for NT SY-GS than RT and CT was likely due to sorghum residue conservation, enhancing SOC over the years (Godsey et al., 2007). Although NT Ct-GS would also conserve a considerable amount of residue, low yield stability over the years observed for NT Ct-GS possibly explains the lower yields in Ct-GS compared to SY-GS rotation. The low yield stability for Ct-GS may be associated with weed pressure over the years resulted from lack of crop diversity (hence, lack of pesticide rotation) and lack of mechanical weed control, which are the two keys to weed herbicide resistance development (Hicks et al., 2018). Shyam et al. (2020) reported for the first time the evolution of six-way herbicide resistance (ALS-, PS II-, HPPD-, PPO-, EPSPS-inhibitor herbicides, and synthetic auxins) in a single plant of Palmer amaranth (*Amaranthus palmeri* S. Watson) in the Ct-GS plots in the current study, which confirms the lack of pesticide diversity and potential for development of herbicide resistance in weed populations in monoculture cropping.

Sorghum was more adaptable in low-yielding environments when planted continuously, possibly due to high residue produced, which contributes to better soil water conservation (Baumhardt et al., 2012), and deep roots, which enable the crop to reach deeper underground water (Assefa et al., 2010). When rotating with soybean, sorghum was more adaptable in high-yielding environments if tillage was applied, probably due to the lack of soil water conservation, thus requiring the crop to rely on in-season precipitation. However, when tillage was absent, NT SY-GS had wide adaptability in both environments and high stability and greater overall yield than all other treatments (Figure 2B).

4.4 | Precipitation allocation and precipitation use efficiency

Precipitation allocation intervals were proportional to the rainfall distribution for the region, which is mainly concentrated during the spring and summer (Rahmani et al., 2014). Thus, crop sequences with winter fallow periods such as Ct-GS, Ct-SY, SY-GS, and SY-WT had significantly greater PA than those with summer fallow periods. This suggests that although crop sequence seems to be important when considering PA, the nature of the crop (e.g., summer crop vs. winter crop) plays a more critical role in determining the PA as affected by the timing that the fallow period happens. In agreement, Patrignani et al. (2019) also observed greater PA in diversified cropping systems due to shifting fallow periods from summer to winter. The PUE values observed in this study differ from those previously published in the literature (Patrignani et al., 2019; G. A. Peterson & Westfall, 2004; G. A. Peterson et al., 1996) mainly because of the nature of the PUE calculation, which uses grain yield and rainfall data only. Thus, any difference in treatments, crop management, variety selection, and soil type will directly affect crop yield; different locations will also affect precipitation regime and, thus, PUE values. Expectedly, PUE was proportional to crop yield, as previously reported in the literature in which tillage or crop rotation affected PUE only when crop yield differed (Jones & Popham, 1997; Schlegel et al., 1999). The result also agrees with Schlegel et al. (1999), who suggested that NT sorghum had greater PUE than CT due to greater sorghum yields in the NT system.

4.5 | Limitations of the current study

One limitation of this study relates to an issue commonly experienced in long-term agricultural studies, which is the modification of varieties and hybrids over time to accommodate modern genetics. While the change in varieties is common in long-term experiments (e.g., Lollato, Figueiredo, et al., 2019; Raun et al., 1993), it creates a data structure in which variety/hybrid is nested within a year, not allowing to clearly distinguish and eliminate the interaction effects of genetic × management. Because the majority (i.e., five out of six) of the adaptability indices pairwise comparisons that differed significantly year-to-year were related to wheat (Figures S1–S3), we will focus on this crop for the purpose of this discussion. For example, the years of 1997 and 2013 were considered high-yielding environments for winter wheat because the annual mean yield for the crop in each of these years was in the upper third, regardless of management or genotype. Should the same wheat variety used in 2013 have been used in 1997, perhaps the yield in that environment would have been higher—provided that the assumption that modern varieties have greater yield potential is true. However, in the specific case of wheat, we note that the genetic gains in this region are lower than in other US regions (Lollato, Roozeboom, et al., 2020), and more importantly, rates in yield gain have not maintained historical rates in the last 30 years (Maeoka et al., 2020), perhaps justifying the few differences (5 of 60 comparisons for wheat, 6 of 180 comparisons for the three crops) in adaptability among varieties tested in the different time periods (Figures S1–S3).

5 | CONCLUSIONS

Results of this 44-year experiment highlight the long-term benefits of crop rotation and NT even in simpler crop rotations, such as those evaluated in the current study. Overall, our study showed that crops grown in rotation (cereal–legume) outyielded continuous cropping in most instances, and the advantage was greater when associated with NT. In low-yielding years, crop rotation and NT showed significant advantages in crop yield over monocropping and when soil was tilled for soybean and sorghum. The two summer crops also showed greater grain yield, yield stability, and crop adaptability to a wide range of environments in rotation rather than continuous cropping, regardless of the tillage system. Wheat grain yield slightly varied among treatments but showed the lowest yield under NT monocropping, evidenced by the lower yield stability, suggesting that NT is unsuitable for continuous wheat production. Although NT is environmentally friendly, the negative impact from continuous cropping appears to be greater when combined with NT than for other tillage systems. Our study demonstrated that cropping systems slightly affected PA in simplified crop sequences (one to two crops in 2 years). Crop sequences and tillage system impacted PUE only when crop grain yield was affected by the system as well. From a practical perspective, our results suggested that (i) farmers should consider using diversified cropping systems to enhance crop grain yield and long-term yield stability, (ii) NT should be adopted in combination with appropriate crop sequences (i.e., crop rotation), and (iii) the adaptability of a crop in a specific yielding environment (i.e., low- or high-yielding environment) depends on the crop sequence adopted based on the nature of the crop (i.e., summer crop vs cool season crops).

AUTHOR CONTRIBUTIONS

Luana M. Simão: Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; resources; supervision; writing – review & editing. **Dallas Peterson**: Data curation; writing – review & editing. **Kraig L. Roozeboom**: Funding acquisition; investigation; writing – review & editing. **Charles W. Rice**: Formal analysis; writing – review & editing. **Xiaomao Lin**: Data curation; writing – review & editing. **Juan Du**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; visualization; writing – review & editing. **Romulo P. Lollato**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; visualization; writing – review & writing.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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