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Wheat and Grain Sorghum Yields as Influenced by Long-term Tillage and Nitrogen Fertilizer Application

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Authors' contributions

This work was carried out in collaboration between all authors. Author CAT designed the study, managed and collected all the data. Author AKO performed all the statistical analysis and wrote the manuscript. Author PWS helped with editing and reviewing the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Tillage, choice of crops in a rotation, and fertilizer management affect crop yields. Limited information exist on long-term interaction effects of tillage and nitrogen (N) fertilizer management on grain yield and precipitation use efficiency (PUE) in intensified cereal-based cropping systems. A study was initiated at the Kansas State University Agricultural Research Center-Hays in 1975 to investigate the effect of tillage intensity [conventional tillage (CT), reduced tillage (RT) and No-till (NT)] and N fertilizer rates (0, 22, 45 and 67 kg N ha^{-1}) on wheat and grain sorghum yields. Grain yields and PUE for both wheat and grain sorghum were significantly (P< 0.0001) affected by year × N application rate × tillage interaction. Across all N rates and tillage practices, grain yields and PUE were greater in years of higher precipitation compared to years when precipitation amounts were below the long-term average. Wheat and sorghum yields for RT plots were equal or greater than CT in most years at each N rate. Grain yields and PUE in the NT plots were lower than CT and RT at lower N rates. However, at the highest N rate, grain yields were not different among the tillage systems. Regardless of tillage practice, grain yield increased with increasing N fertilizer application rate. Based on our findings, higher N application rates (> 67 kg N ha^{-1}) may be required to maximize both wheat and grain sorghum yields with any of the tillage systems.

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Keywords: Conventional tillage; dryland systems; no-tillage; precipitation use efficiency.

1. INTRODUCTION

Winter wheat (*Triticum aestivum* L.) and grain sorghum (*Sorghum bicolor L.*) are the predominant crops grown in dryland cropping systems in the central and northern Great Plains regions of the USA. For instance in 2012, over 3.7 million hectares of wheat was grown in Kansas, representing 18.6% of the total winter wheat harvested area in U.S.A (http://www.nass.usda.gov/Statistics_by_State/Kansas/Publications/Crops/Production/2013/cropjan.pdf). Soil moisture availability and N management are some of the major limitations to crop production in dryland cropping systems in the central Great Plains. Crop yields in dryland cropping systems are directly related to available soil moisture at planting and in-season precipitation amounts received [1]. Due to water limitations, crop-fallow has been the traditional dryland cropping system in the Great Plains region [2]. However, the use of conventional tillage (CT) operations for weed control during the fallow period has resulted in insufficient crop residue return to the soil, depletion of soil organic matter (SOM), declining soil fertility, soil erosion and inefficient water storage [3-5].

In recent years, adoption of reduced tillage (RT) and no-till (NT) practices have led to increased moisture storage and allowed crop intensification in most of the Great Plains. Tillage and crop intensification will influence soil water availability, nutrient demand and cycling within the soil profile due to different rooting patterns and nutrient requirements of various crops involved in the rotation. Precipitation storage efficiency in a NT wheat-fallow system was 35% compared to 20% in a CT wheat-fallow cropping system [6]. Economically, intensive cropping combined with RT has been shown to be more profitable compared to wheat-fallow systems in the Great Plains [7,8].

Nutrient requirements of intensified cropping systems are more complicated than a crop-fallow system. For instance, significant NO_3-N accumulates in the soil profile during the fallow period in a crop-fallow system and may be available to the succeeding crop. In contrast, the shortened fallow period due to continuous cropping may reduce N mineralization and availability to crops in rotation [9]. In addition, high residue return to the soil in intensified cropping systems can increase the risk of N loss through NH_3 volatilization. Nitrogen immobilization by soil microbes when N is surface applied can also reduce N availability to crops.

Nitrogen fertilizer is the most limiting nutrient to crop yields and the most expensive input cost in crop production. Globally, nitrogen use efficiency (NUE) of cereal crop production is about 33% [10]. Increasing N application rates results in a reduction in NUE in cereal crops. For instance, NUE in a NT winter wheat- grain sorghum-fallow (W-S-F) cropping system varied from 86, 69, 56 and 45% for 28, 56, 84, and 112 kg N ha^{-1}, respectively [11]. Rising fertilizer costs, low NUE and environmental concerns provide the impetus for developing N management strategies that improve crop yields and reduce N losses to the environment. Because of the high rainfall variability in the Great Plains, long-term field data is required to predict optimal N rates for various crop production systems to avoid environmental risk associated with excessive N application. Moreover, since the magnitude of crop yield response to applied N fertilizer depends on available soil moisture, information on the long-term influence of tillage and N fertility management on grain yield and precipitation use efficiency (PUE) in the central Great Plains is needed to document the performance of these intensive cropping systems. The objectives of this paper are to i) determine long-term effects of tillage and N fertilizer application on grain yield, and ii) investigate PUE after 29-yr of tillage and N fertilizer management in a wheat-sorghum-fallow cropping system in west-central Kansas.

2. MATERIALS AND METHODS

2.1 Experimental Set-up

This long-term experiment was initiated in the fall of 1965 on a Harney silt loam soil (fine, montmorillonite, mesic Typic Agriustoll) at the Kansas State University Agricultural Research Station in Hays (38º86′ N, 99º27′ W, and 609 m elevation) to evaluate the effect of tillage intensity on crop yield under a W-S-F rotation. The three tillage practices were CT, RT, and NT in a randomized complete block design with four replications. Each phase of the crop rotation was present in each year of the study. The experiment was modified in 1975 to include N application rates in a split-plot arrangement. The original tillage treatments (CT, RT, and NT) were assigned to the main plots and the sub-plot factor was four N rates (0, 22, 45 and 67 kg N ha^{-1}). Plot sizes were 20.4 m × 30.5 m for the tillage plots, and 3.4 m × 30.5 m for the N application rate treatments. There was a 3.5 m wide border between tillage treatments.

Thompson and Whitney [12] describe further details on tillage operations and weed management. Briefly, weed control and seedbed preparation during the fallow phase of the crop rotation in the CT plots were done by disking and plowing with residue-incorporating implements (disk, and mulch treader) to about 15 cm depth. Similarly, the RT plots were tilled with residue-saving implements such as V-blade and sweeps to about 15 cm depth. Approximately 3 to 4 tillage operations were performed from harvest to planting in the CT and RT plots. Only herbicides were used for weed control in the NT plots. Appropriate herbicides were used to control weeds in the fallow periods and during wheat and sorghum crops phases across tillage practices. Weed control in grain sorghum were done with a pre-mixture of 25.3% of [alachlor, 2-chloro-2’,6’-diethyl-N-(methoxymethyl) acetanilide] and 15.3% of [atrazine, 2-chloro-4-(ethylamino)-6-(isopropylamino) s-triazine]. Two to four applications of glyphosate [isopropylamine salt of *N*-(phosphonomethyl) glycine] were applied as needed in the fallow period prior to winter wheat planting.

Grain sorghum hybrids and winter wheat cultivars varied over the study period. However, sorghum hybrids and winter wheat cultivars were selected based on Kansas Agricultural Experiment Stations yield performance trials. Average seeding rate for grain sorghum and winter wheat over the study were 108,000 plants ha^{-1} and 65 kg ha^{-1}, respectively. Winter wheat was usually planted in late fall between September 15 through October 15, and sorghum planting was done in the spring (Mid-May through the third week in June).

The N fertilizer source used over the study period was ammonium nitrate that was broadcasted in the fall prior to wheat planting. Nitrogen application for grain sorghum plots were also done in the fall. Because soil test levels for available phosphorus and exchangeable potassium were medium to high over the study period, N was the only fertilizer applied. Grain yields were determined by harvesting 1.5 m × 30.5 m area of each plot with a plot combine. Daily and yearly precipitation data were recorded at the nearby weather station ~ 2.4 km from the study site. Precipitation use efficiency for each tillage and N rate treatment was computed by dividing grain yields (kg ha^{-1}) by annual precipitation (cm) as described by Varvel [13].

2.2 Statistical Analysis

Data for the 28-yr (grain sorghum) and 29-yr (wheat) were analyzed statistical for ANOVA using the PROC MIXED procedure of SAS [14]. Tillage, N rate and year were considered as fixed effects and replicates and their interactions were considered as random effects. The LSMEANS procedure and associated PDIFF were used for mean comparisons. Interaction and treatment effects were considered significant when F test P values were ≤ 0.05. In addition, regression analyses were conducted with the ProcReg procedure in SAS to determine the relationship between grain yield and N application rates.

3. RESULTS AND DISCUSSION

Annual precipitation amounts varied significantly over the study period (Fig. 1). The long-term (146-yr) average precipitation at the study site was 579 mm. In general, the 1993 and 1996 growing seasons recorded the highest precipitation of 965 and 807 mm, respectively. The driest year was 1988, with total annual precipitation of 363 mm (Fig. 1). In 15-yr of the 29-yr study, the amount of precipitation received was equal or above the long-term average. In dryland situations, the high variability in precipitation amounts received may cause crop yield variations.

Year × N application rate × tillage interaction significantly (P< 0.0001) affected wheat and grain sorghum yields. The three-way interaction occurred due to the varied amounts of precipitation received over the 29-yr study period. Across all N rates and tillage practices, wheat grain yields were significantly greater in years of higher precipitation compared to years when precipitation amounts were below the long-term average (Figs. 1 & 2). This observation was expected because crop yields in the semi-arid Great Plains are highly dependent on available soil moisture [1]. Regardless of tillage practice, grain yield increased significantly with increasing N fertilizer application rates. The magnitude of N response for each tillage practice was particularly greater in wet years (Fig. 2).

Wheat yields for RT plots were equal or greater than CT in most years at each N rate. Winter wheat yields under NT were significantly lower than CT and RT. The difference was more pronounced in wetter years and at lower N application rates (Fig. 2). These results agree with López-Bellido and López-Bellido [15] who reported greater wheat grain production in CT than NT systems. In a 12-yr study, Halvorson et al. [16] found spring wheat yields with RT were similar to CT in most years, but NT grain yields were lower than CT. Grain sorghum yields showed similar response as wheat. Though not consistent, NT yields were generally lower than CT and RT, especially at lower N application rates (Fig. 3). The lower wheat and sorghum grain yields with NT may be to due poor plant stands (caused by drier soil conditions at planting), increased weed competition due to poor weed control, and reduced N availability to wheat and sorghum crops caused by N immobilization from crop residue. The lack of adequate weed control in conservation tillage systems has been reported to reduce winter wheat yields compared to moldboard-plowed systems [17]. In our present study, poor control of invasive grass species tumblegrass [*Schedonnardus paniculltus* (Nutt.) Trel] and windmillgrass (*Chloris verticillata* Nutt.) in the NT plots compared to the CT and RT can cause significant yield reductions in the NT system.

Since the significant year × tillage × N interactions were due to variation in precipitation amounts over the study period, we examined the influence of the main effects of tillage and N rate on crop yield and PUE.

The two- and three-way interaction with year does not convey any important agronomic information compared to the impacts of N fertilizer application on grain yield stability in each of the tillage practices over the study period. Averaged across years, grain yield for wheat and sorghum were significantly affected by tillage and N application (Fig. 4a). At lower N rates, wheat grain yields were greater with CT and RT than with NT. However, at 67 kg N ha^{-1}, there were no yield differences among tillage systems. Similarly, at 0 and 22 kg N ha^{-1}, grain sorghum yields with NT were lower than CT and RT, but at 45 kg N ha^{-1}, grain yields were similar with NT and CT systems. At the highest N rate (67 kg N ha^{-1}); sorghum yields were similar for all tillage systems (Fig. 4b). Locke and Hons [18] reported greater grain sorghum yields with CT than NT at low N rates (0 and 50 kg N ha^{-1}), but no yield differences between the two tillage practices at higher N rates (100 and 150 kg N ha^{-1}). Similar responseswere found in barley. Grain yields of barley were found to be significantly lower under NT that CT when N rates were between 0 to 33 kg N ha^{-1}, but at higher N rates (67 or 100 kg N ha^{-1}) NT produced equal or greater yields than CT [19].

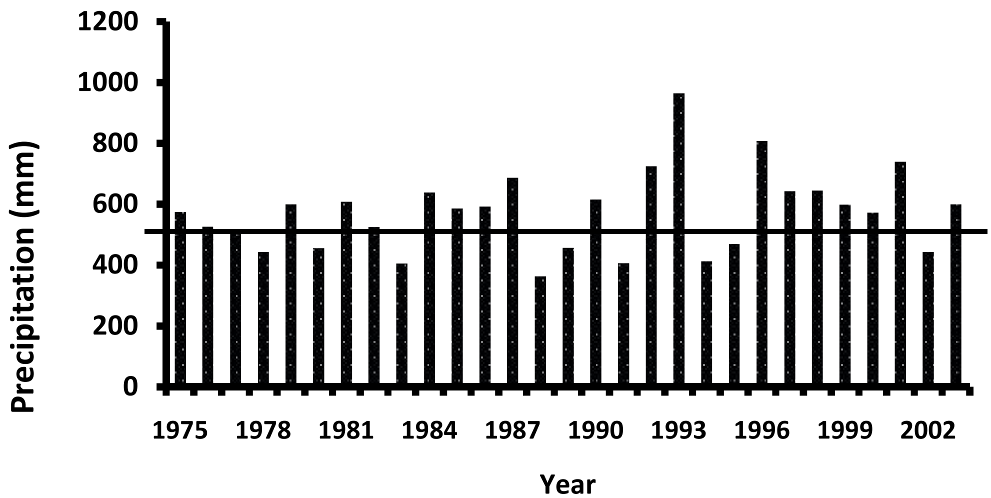


Fig. 1. Precipitation amounts received at Kansas State University Agricultural Research Center in Hays, KS from 1975 to 2003. Inserted line indicates 146-yr average annual precipitation (579 mm) at the study site

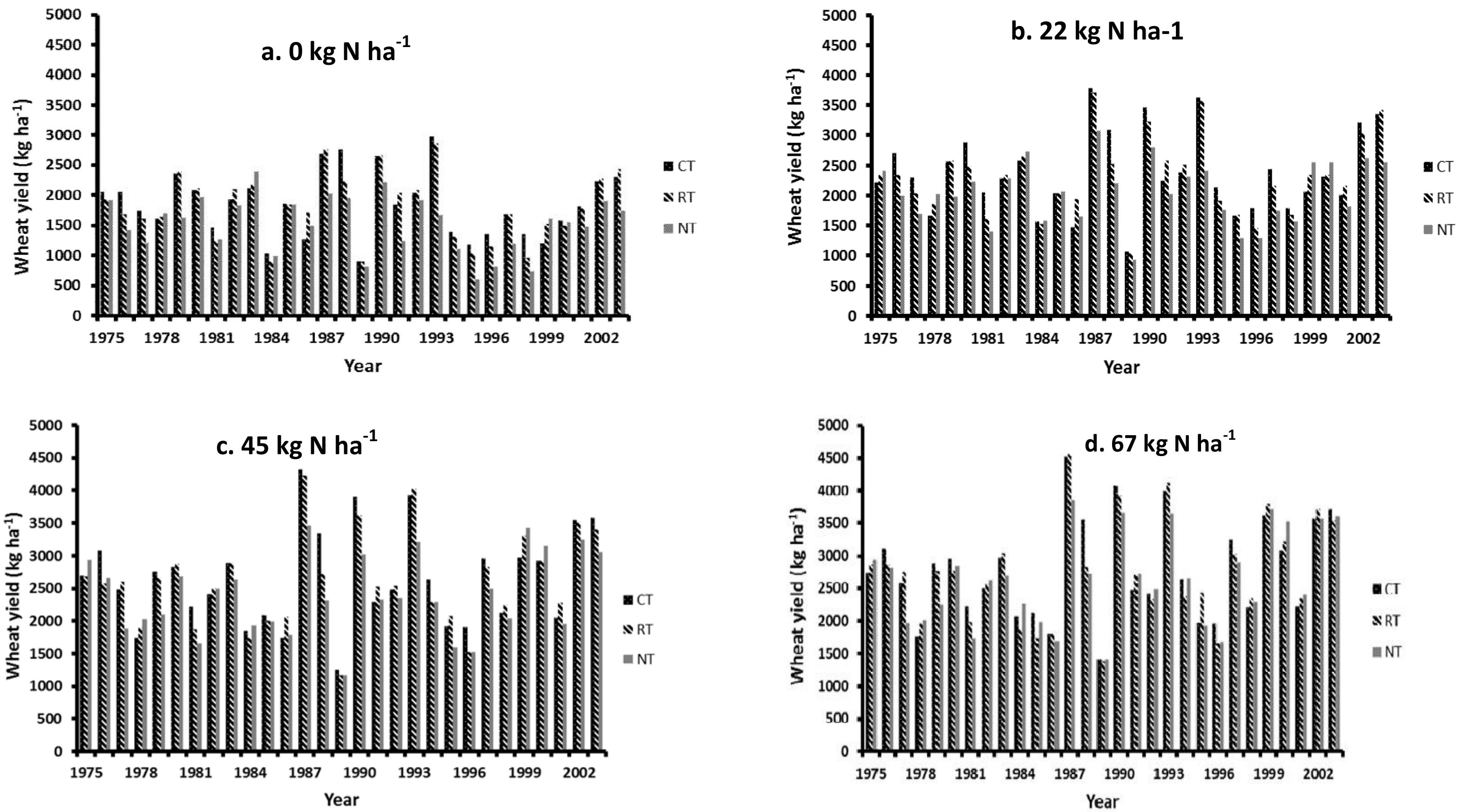


Fig. 2. Winter wheat grain yield as affacted by tillage and nitrogen fertilizer application over 29-yr study period. Means are averaged over four replication (n = 4). CT, Conventional tillage; RT, Reduced tillage; NT, No-till. N rate are 0, 22, 45 and 67 kg N ha^{-1}

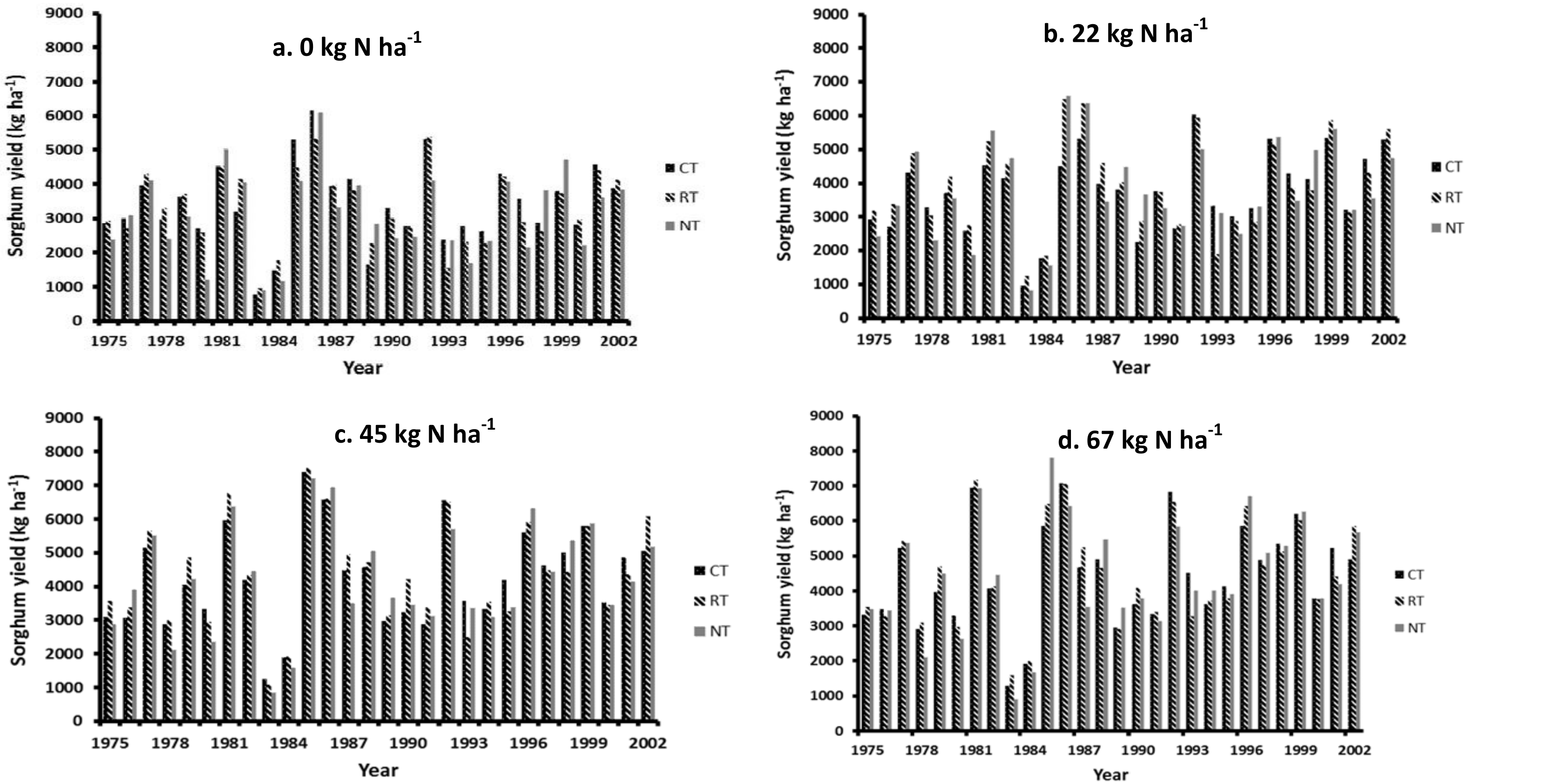


Fig. 3. Sorghum grain yield as affected by tillage and nitrogen fertilizer application over 28-yr study period. Means are averaged over four replication (n = 4). CT, conventional tillage; RT, reduced tillage; NT, No-till. N rate are 0, 22, 45 and 67 kg N ha^{-1}

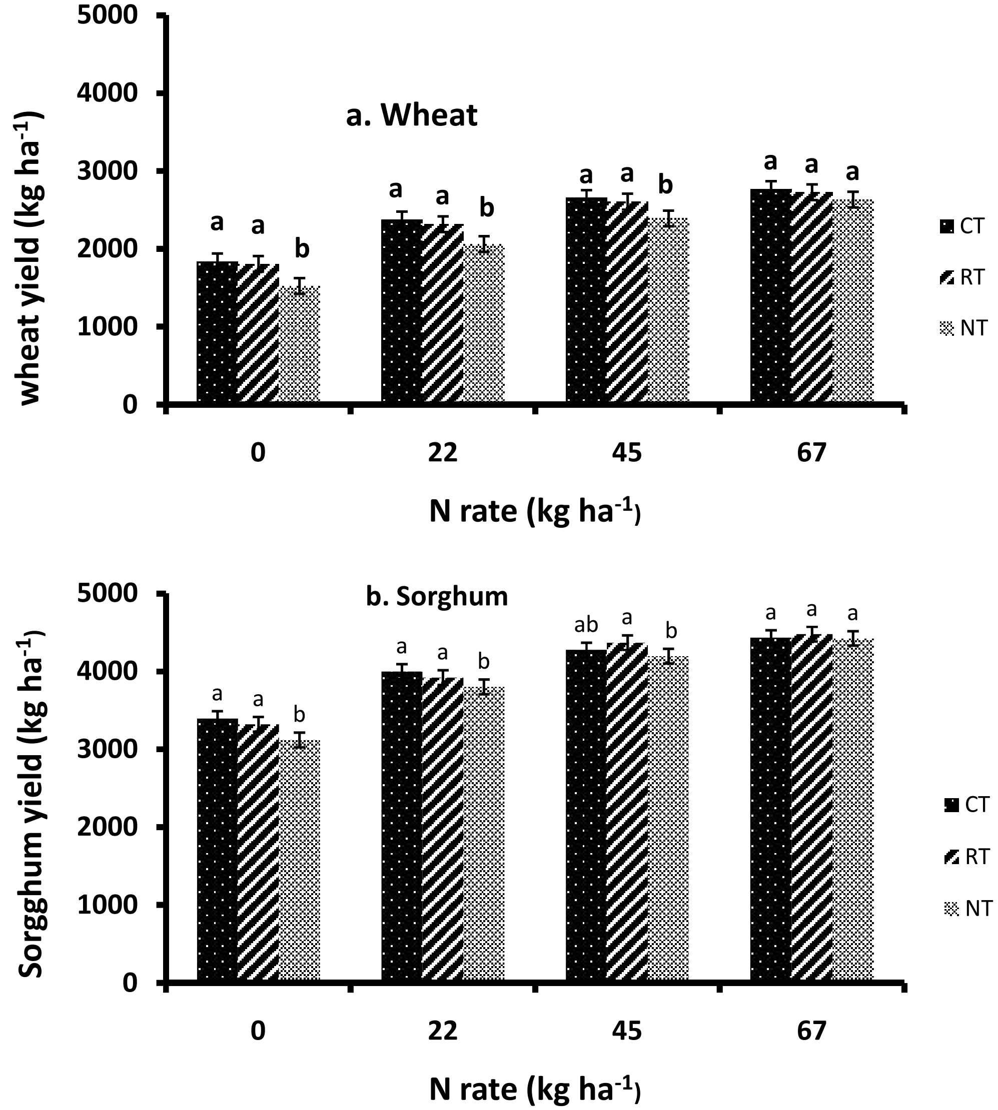


Fig. 4. Tillage and nitrogen application effects on (a) winter wheat and (b) sorghum grain yields over the study period. Data are averaged across years (29-yr for wheat and 28-yr for sorghum) and four replicates. Error bars represent one standard error of the mean. Means followed by the same letter (s) within N rate are not significantly (*P*> 0.05) different

Surface application of N fertilizer to no-till systems with higher residue cover increases the chances of N immobilization [9,19]. Reduced grain yields under NT at low N rates (0 to 45 kg ha^{-1} in this study) may be due to immobilization of the applied N by soil microorganisms. Increasing N application rate to 67 kg N ha^{-1} may have reduced the effects of N immobilization by providing adequate N for both crops. This implies additional N fertilizer application may be required to compensate for N immobilization to avoid wheat and sorghum yield depressions when grown under NT systems.

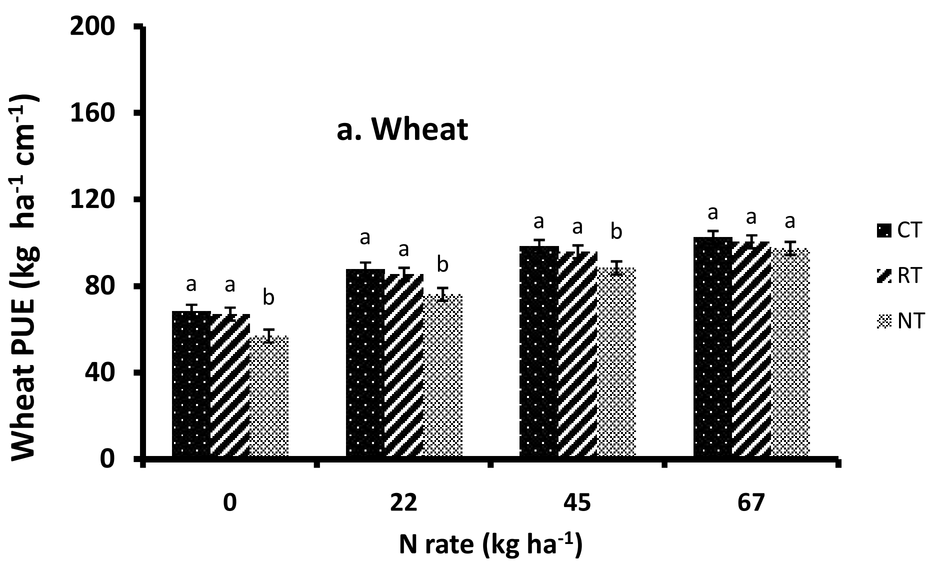
Regression analysis showing winter wheat and sorghum yields as a function of N application rates over the study period in shown in Table 1. Regardless of tillage practice, grain yields increased with N fertilizer application but the amount of N required to achieving maximum yields varied for the tillage systems. The N rate required to maximize wheat grain production was approximately 66, 70 and 87 kg N ha^{-1} with CT, RT and NT, respectively. Grain sorghum yields with CT and RT systems were maximized at 68 kg N ha^{-1} N, but 75 kg N ha^{-1}was needed to maximize yields in NT (Table 1). Nitrogen application of 84 kg ha^{-1} was identified as sufficient N amount to maximize wheat yields in NT wheat-corn-fallow and W-S-F cropping systems in Colorado [11,20]. Based on the regression analysis, NT systems required 21 kg ha^{-1} more N to maximize wheat yields compared to CT (Table 1). This finding agrees with those of Staggenborg et al. [21], who showed that winter wheat planted after grain sorghum required addition of 21 kg ha^{-1} N to maximize grain yields compared to wheat following soybean. The authors attributed this to N immobilization from the higher sorghum residue. Though ammonium nitrate was the N fertilizer source in our long-term study, potential N immobilization occurring in the NT plots can reduce N availability to wheat and grain sorghum thereby causing yield reductions.

When averaged across tillage system, winter wheat grain production over the 29-yr growing seasons was 1725, 2253, 2551, and 2710 kg ha^{-1} for the 0, 22, 45 and 67 kg N ha^{-1}, respectively. Similarly, grain sorghum yields were 3278 kg ha^{-1} for the control (0 kg N ha^{-1}), 3907, 4280 and 4444 kg ha^{-1} for the 22, 45, and 67 kg N ha^{-1}, respectively. The significantly higher yields of the 67 N ha^{-1} rate compared to the lower N rates suggest the highest N rate used in this study was not adequate to optimize either wheat or grain sorghum yields.

Table 1. Regression equations for winter wheat and grain sorghum yields as a function of nitrogen application average of the study period

Tillage	†Equation: $y = a + bx + cx^2$					
	a	b	c	R^2	Maximum yield	N rate required to achieve maximum yield
					kg ha^{-1}	
Winter wheat						
Conventional tillage	1846.3	27.8	-0.21	0.99	2766	66.2
Reduced tillage	1810.4	26.7	-0.19	0.99	2748	70.3
No-tillage	1531.4	26.2	-0.15	0.99	2676	87.3
Grain Sorghum						
Conventional tillage	3405.0	30.1	-0.22	0.99	4435	68.4
Reduced tillage	3310.7	34.0	-0.25	0.99	4467	68.0
No-tillage	4466.7	34.4	-0.23	0.99	4412	74.8

† y = grain yield, kg ha^{-1}; x = N rate, kg ha^{-1}



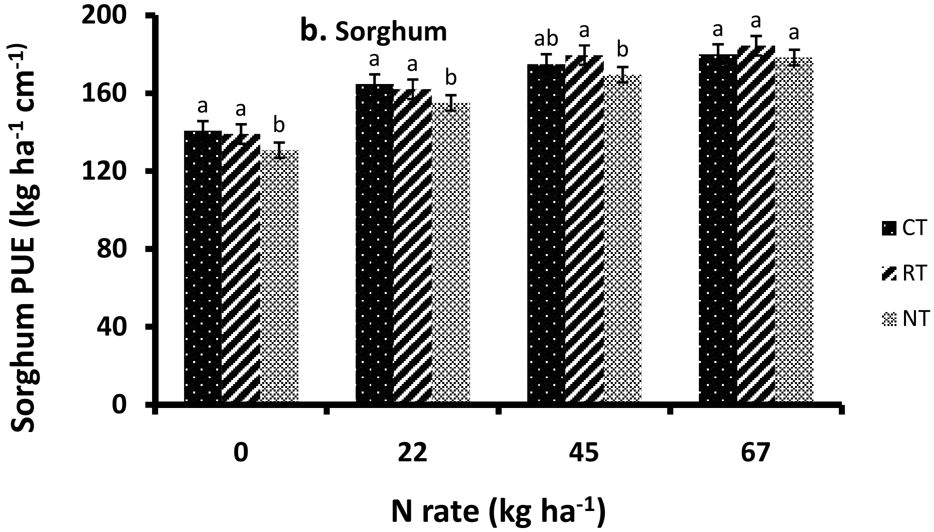


Fig. 5. Tillage and nitrogen application effects on (a) winter wheat and (b) sorghum precipitation use efficiency. Data are averaged across years (29-yr for wheat and 28-yr for sorghum) and four replicates. Error bars represent one standard error of the mean. Means followed by the same letter (s) within N rate are not significantly (*P*> 0.05) different

Precipitation use efficiency was significantly affected by year × N rate × tillage interaction. In addition, all main effects and their interaction were significant (*P*< 0.0001). The PUE for wheat and grain sorghum were greater in years with higher precipitation and greater grain yields. Increasing N rates resulted in significantly greater PUE for each tillage system compared to no N fertilizer application. Averaged across the 29-yr, PUE for CT wheat was 68 kg ha^{-1} cm^{-1} when no N fertilizer was applied and 102 kg ha^{-1} cm^{-1} when N was applied at 67 kg N ha^{-1}. Similarly, grain sorghum PUE under the CT system ranged from 141 kg ha^{-1} cm^{-1} for the control to 180 kg ha^{-1} cm^{-1} when was 60 kg N ha^{-1} applied (Fig. 5 above). At lower N rates, PUE under CT and RT systems were always greater than NT. However, at 67 kg N ha^{-1}, PUE were similar in all tillage systems for both wheat and grain sorghum (Fig. 5).

4. CONCLUSION

The results of this long-term study showed that tillage and N fertilizer application interacts to affect wheat and grain sorghum yields. In most years, grain yields for RT plots were equal or greater than CT at each N rate. Grain yields and PUE with NT were significantly lower than CT and RT particularly when N application rates were low. However, yields were not different among the tillage treatments at the highest N rate. Growers adopting NT practices may need to apply additional N fertilizer (~ 20 kg N ha^{-1}) to improve grain yields and PUE. The significantly greater yields and PUE at 67 kg N ha^{-1} compared to the lower N rates suggests that higher N application rates (> 67 kg N ha^{-1} in the current study) may be required to maximize both wheat and grain sorghum yields with any of the tillage systems.

CONSENT

It is not applicable.

ETHICAL APPROVAL

It is not applicable.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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