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Long-Term Effects of Nitrogen and Tillage on Yields and Nitrogen Use Efficiency in Irrigated Corn

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Abstract: By tonnage, corn (*Zea Mays* L.) is the #1 crop produced globally, and recent research has suggested that no-till (NT) systems can lead to reduced yields of this important crop. Additionally, there is a lack of long-term data about the effects of tillage and N management on cropping systems. Corn is the most nitrogen (N)-fertilized crop in the USA, and N losses to the environment contribute to significant impacts on air and water quality. We conducted long-term studies on conventionally tilled (CT), and conservation tillage systems such as strip tillage (ST) and NT, under different N rates. We found that immediately after conversion to NT, yields from NT were significantly lower than yields from CT (P<0.1), but after five years of NT, the NT yields were 1.5% higher than the CT yields (P<0.1). Initially, the NT yields were lower than the ST (P<0.01), but after seven years of NT, the NT yields were comparable to ST grain yields. Although the total aboveground N uptake with NT immediately after conversion to NT was lower than with CT and ST, these differences were not significant in the long run. The nitrogen use efficiency (NUE) with NT increased over time. The present work highlights the importance of long-term research for determining the cumulative impacts of best management practices such as NT. We found that NT becomes a more viable practice after five or seven years of implementation, demonstrating the high importance of long-term research.

Keywords: nitrogen; no till; tillage; nitrogen use efficiency; yields; corn (*Zea Mays* L.)

1. Introduction

Nitrogen (N) use efficiencies (NUE) in corn have been reported to be around 50%, and there is a need to increase NUE and reduce N losses to the environment [1]. A recently published long-term study found that the N losses from the no-till system ranged from 12 to almost 50% depending on the application rate of the N fertilizer [1]. In a 30-year study using an N balance approach in the Loess Plateau of China, Fu et al. found that over 100% of the applied N fertilizer was taken up and removed with the harvested corn crop [2]. However, another long-term cultivated study in Zhangye, Gansu, China that spanned 22 years and also used an N balance approach, found only 34% of the applied N was being recovered with the harvested fraction and that up to 60% of the applied N fertilizer was being lost to the environment [3]. Iragavarapu and Randall found in an 11-year study conducted on a poorly drained soil in Minnesota that N uptake and removal can be higher with cultivated till (CT) than with no till (NT) [4]. Lower N uptake in NT systems may be due to higher N immobilization and higher denitrification losses with the NT system [5,6]. There is a need to assess the long-term effects of tillage on NUE.

Pittelkow et al. conducted a global metadata analysis and reported that for cereals, implementation of NT creates negative agronomic impacts that contribute to reduced grain yields, with a yield reduction of 2.6% for wheat, and yield reductions of 7.5 and 7.6% for rice and corn,

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respectively [7]. They reported that for corn specifically, the grain yields after incorporation of NT declined during the first two years and continued to decrease with time, except when corn was grown in rainfed, dry climates that decreased initially but over time matched the yields of cultivated systems. They also reported that for corn, N fertilizer is important to ameliorate the negative effects of NT with higher yields at higher N levels. Ogle et al. also conducted a meta-analysis of studies on NT and tillage effects and found that NT yields were lower than yields of cultivated systems, particularly in cooler and/or wetter climatic conditions [8].

Besides these in-depth metadata analyses, there have been studies that have found that NT can increase or maintain corn grain yields in comparison to other tillage systems. Sindelar et al. conducted a 28-year tillage study measuring the effects of tillage (chisel, tandem disk, moldboard plow, NT, ridge-tillage, and subsoil tillage) on grain yields in dryland Nebraska for continuous corn (CC) and corn and soybean rotations [9]. They reported that average corn yields for NT were consistently higher during the last 16 years of the study (1997 to 2013) [9]. Since they conducted a 28-year study and measured a positive response to NT that was consistent for 16 years, at 12 years after establishment of NT, they determined there was a need to conduct long-term studies to identify these trends.

In contrast to findings by Sindelar et al. [9], a 26-year corn-soybean rotation study in Quebec, Canada conducted by Gagnon et al. found that the yield differences between NT and cultivated (moldboard plow) systems were not significantly different the first 10 years, but over time NT yields gradually declined, and during the last eight years, NT yields were lower than those of the cultivated system [10]. Gagnon et al. concluded that at northern latitudes, clay soil was not appropriate for NT, since over the 26-year period the system cultivated by moldboard plow produced 15% higher yields than the NT system [10]. These findings agree with other reports that NT reduces corn grain yields more than other crops, especially in cooler areas, areas with high precipitation, or with poorly drained soils [11–13]. However, in the black soil region of northeast China, Zhang et al. found in a 12-year study that for a rotation of corn and soybean, corn grain yields were higher with NT, and that the lower soil temperatures with NT and ridge tillage did not affect grain yields [14]. These findings agree with other studies that have reported increased grain yields in warm, dry climates or in well-drained soils [15–18]. In contrast, Chen et al. found lower yields in a maize-soybean rotation under NT compared to a maize-soybean rotation under CT in a 2004 to 2010 study in Hailun City, China [19].

Schmer et al. conducted a 10-year study in Nebraska comparing tillage (conventional disk tillage [CT] vs. no till [NT]) with different rates of crop residue (stover) removal in an irrigated, CC system and found higher corn biomass production with the cultivated system than with NT [20]. In Colorado, Halvorson et al. presented the initial results of these studies (2000 to 2004) and found that corn grain yields were 16% higher with the CT than the NT system and that corn residue (stalks and leaves and cobs) yields were similar between the two tillage systems [21]. They found an N fertilizer use efficiency (NFUE) of 43% when averaged over N rates and years for NT and CT systems. They reported a grain N removal of 94 kg N ha^{-1} for the CT, which was higher than the 80 kg N ha^{-1} with NT (averaged over N rates and five years). Similarly, the total N uptake of 141 kg N ha^{-1} with CT was higher than the NT of 131 kg N ha^{-1}.

Using a quadratic regression model, Jantalia and Halvorson reported on the effect of N rates on the yields of the CT plots presented here from 2001 to 2007 plus the 2008 plots that were severely impacted by hail [22]. They found that CT irrigated corn yield and stover increased with N rate and maximized at about 177 kg N ha^{-1}and 185 kg N ha^{-1} of applied N fertilizer, respectively. Using a quadratic equation for the data from 2002 to 2012 (plots split into NT and ST), Stewart et al. found that ST had 8% higher yields compared to NT [23]. Additionally, they determined that the optimum grain yield for NT was achieved with 190 kg N ha^{-1}, while for ST, it was achieved at a similar N rate of 203 kg N ha^{-1}.

Previous results from the global literature about the effects of tillage on corn grain yields and residue production have been conflicting, and there is a continued need for assessments of the long-term effects of tillage systems on yield, especially under sprinkler irrigation in temperate systems

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where there is a lack of long-term data. Recent studies have shown the need for additional long-term studies on these topics [1,7–10,20]. The goals are to a) assess the effects of N fertilizer rates and tillage on recovery of N by the grain, stalks and leaves, and cob compartments; and b) assess total N recovery across different N rates and tillage systems and the removal of N with the harvested grain and the N cycled back to the system. In our review of the published literature, we did not find a long-term study on NT versus cultivated linear-move sprinkler-irrigated continuous corn, nor did we find a long-term study on NT versus ST where the agronomic N use efficiencies, N uptake by aboveground compartments, total uptake and N removal with harvested grain were reported and assessed using a linear-plus-plateau model. There is a need to conduct these long-term studies and to make these data sets available to the scientific community.

2. Materials and Methods

2.1. Site and Management Information

Tillage studies were conducted at the Halvorson long-term research experimental area established in 2000 at Colorado State University's Agricultural Research, Development and Education Center (ARDEC) in Fort Collins, Colorado (40°39′6″ N, 104°59′57″ W, 1535 m above sea level) on a Fort Collins clay loam soil (fine-loamy, mixed, mesic Aridic Haplustalfs) with a 1 to 2% slope. The site's average minimum, mean, and maximum air temperatures; growing degree days (GDD); and precipitation were 10.1 °C, 18.3 °C, 26.6 °C, 1303 GDD and 194.7 mm, respectively for the planting to physiological maturity (R6, black layer) stages during the 2001 to 2017 growing seasons. The averages for these weather variables for the growing seasons of 2001 to 2007, 2006 to 2007, and 2006 to 2017 are presented in the supplemental material (Table S1).

The experimental units used for this tillage and N budget study were from a CC under NT (2000 to 2017) in a randomized block design with six N treatments and three replicates (n=3), 21.9 m wide by 137.2 m long each, that had been managed similarly since 2000. These NT plots were split into NT and ST in east and west sides, respectively, for seven years (2006 to 2012) and then returned to completely NT plots. The NT plots on the east side were monitored continuously from 2000 to 2017 as the NT plots that were never cultivated with ST. A set of plots 45 m away from the NT plots were under cultivation and were monitored under the same management as the NT plots. These plots were the fully cultivated plots (CT) monitored from 2000 to 2008. These cultivated plots were changed to strip tillage plots (ST) in December 2008 and were another site of strip plots under the same management monitored from 2008 to 2017.

Prior to the start of these studies in 2000, the experimental unit's areas were in cultivated corn for seven years. The full cultivation from 2001 to 2008 and the strip plots from 2009 to 2017 were in a completely randomized design with four replicates and different N rates. The N rates per experiment are described in detail in the supplementary materials (see Table S2). Since the initial N rates established in 2000 for NT were 0, 34, 67, 101, 134, and 202 kg N ha^{-1} [21], which were different from the initial N rates established in 2000 with CT of 0, 75, 125, and 200 kg N ha^{-1} [22], we started the analysis for the data presented in the present work in 2001. In 2001 the N rates were changed to 0, 67, 134, and 168 kg N ha^{-1} [22], similar to the 2001 N rates for NT [21]. Additionally, since the N application rate of one of the lower N rate NT plots that initially was receiving 34 kg N ha^{-1} was changed to 246 kg N ha^{-1} in 2007, changed to 202 kg N ha^{-1} in 2009, changed to 0 kg N ha^{-1} in 2013, and returned to 34 kg N ha^{-1} in 2014, only data from 2001 to 2006 and from 2014 to 2017 were used to represent the yields and N uptake at 34 kg N ha^{-1} with NT.

For additional information about the N fertilizer applications, including N rates, see Tables S2 and S3 in the supplementary materials. All planting, fertilization, irrigation, pesticide applications, and harvest actions were kept the same between tillage treatments (Tables S3 and S4). A detailed description of tillage management operations is included in Table S3 as well as the calibration of the instruments used for plant nitrogen analysis. Throughout the study, a Valley® linear-move sprinkler irrigated the corn as needed. Planting was done around end of April and beginning of May, and plant biomass was harvested at R6, which was usually in September. The plant biomass at R6

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(physiological maturity) was divided into stalks, leaves, cobs, and grain. Throughout the present work, we refer to the biomass of the stalks, leaves, and cobs as crop residue since this plant material was collected at physiological maturity. The drydown process occurred in October. Details about pest and weed management are provided in the Table S3. Details of plant, soil, and irrigation sampling and analysis are also shown in Tables S3 and S4.

2.2 Statistical Analysis

Statistical analysis of the harvested grain, crop residue, and N uptake of different crop compartments was performed with a linear-plus-plateau model. Plant crop residue outliers were removed to assess the effects of tillage and N rates on the yields and crop residue production as well as the N uptake dynamics. The 2008 yields were not used to assess changes in corn crop residue production and N uptake since yields were significantly reduced due to a large hailstorm that resulted in heavy damage. Due to crop damage from slugs (order *Pulmonata*), yields from 8 experimental units in the NT study affected in 2009 were ignored. Additionally, due to crop damage from spider mites (family *Tetranychidae*), yields from 2 experimental units in each of the split NT and split ST studies and 1 experimental unit in the ST study in 2011 were removed. For the 2012 data, 6 experimental units in the split NT study, 5 in the split ST study, and 4 in the ST study were also ignored. Also, one experimental unit in the ST study in 2013 with an unusually large yield was ignored. Additionally, the experimental units from 2007 to 2013 where the N application rate was changed from 34 kg N ha^{-1} to 246, 202, and 0 kg N ha^{-1}, were also removed as outliers during 2007 to 2013 (see Table S2 for N rates and tillage methods used for this study).

The linear-plus-plateau model was used to determine differences in yield or N uptake at the plateau ($\boldsymbol{\hat{Y}_p}$), the N fertilizer rate at the plateau ($\boldsymbol{N_p}$), and the intercept of the linear-plus-plateau ($\boldsymbol{\beta_0}$) for the data covering CT and NT from 2001 to 2007; CT, NT, and ST from 2006 to 2007; and NT and ST from 2006 to 2017. Additionally, we conducted a t-test analysis by year and N rate treatment from 2001 to 2007 (CT vs. NT), 2006 to 2007 (CT vs. NT; CT vs. ST; ST vs. NT) and from 2006 to 2017 (ST vs. NT). A detailed description of the linear-plus-plateau model analysis is also included in Table S3.

The harvested grain agronomic N use efficiency ($ANUE_{HG}$) (Eq. 9 in Table S3), the crop residue agronomic N use efficiency ($ANUE_{CR}$) (Eq. 10 in Table S3), the NUE of the harvested grain at the linear-plus-plateau (NUE_{LPPHG}) (Eq. 11 in Table S3), the NUE of the aboveground crop residue N content at the linear-plus-plateau (NUE_{LPPCR}) (Eq. 12 in Table S3), and the NUE of the total aboveground biomass (stalks, leaves, cobs and grain) N content at the linear-plus-plateau (NUE_{LPPTB}) (Eq. 13 in Table S3) were calculated.

3. Results

3.1. Effect of Long-Term Tillage on Grain Yield

When we compared NT and CT data for the 2001 to 2007 period with the linear plus-plateau model, we found that the NT grain yield at the plateau ($HG\hat{Y}_p$) of 9,445 kg ha^{-1} was significantly lower than the $HG\hat{Y}_p$ of CT, which was 9,852 kg ha^{-1} (P<0.01; Figure 1a; Tables 1 and 2). However, in the last two years (2006 to 2007), the NT $HG\hat{Y}_p$ of 9,410 kg ha^{-1} was higher than the CT $HG\hat{Y}_p$ of 9,270 kg ha^{-1} (P<0.05; Figure 1b; Tables 1 and 3). However, during the 2006 to 2007 period, the ST $HG\hat{Y}_p$ of 9,898 kg ha^{-1} was higher than the NT $HG\hat{Y}_p$ of 9,410 kg ha^{-1} and the CT $HG\hat{Y}_p$ of 9,270 kg ha^{-1} (P<0.05; Figure 1b; Tables 1 and 3). The NT $HG\hat{Y}_p$ of 10,067 kg ha^{-1} for the 2006 to 2017 period was higher than the $HG\hat{Y}_p$ of 9,410 kg ha^{-1} for the 2006 to 2007 period, and this relative increase in yields was no different from the $HG\hat{Y}_p$ of 10,328 kg ha^{-1} achieved with ST during the 2006 to 2017 period (Figure 1c and 4; Tables 1 and 4).

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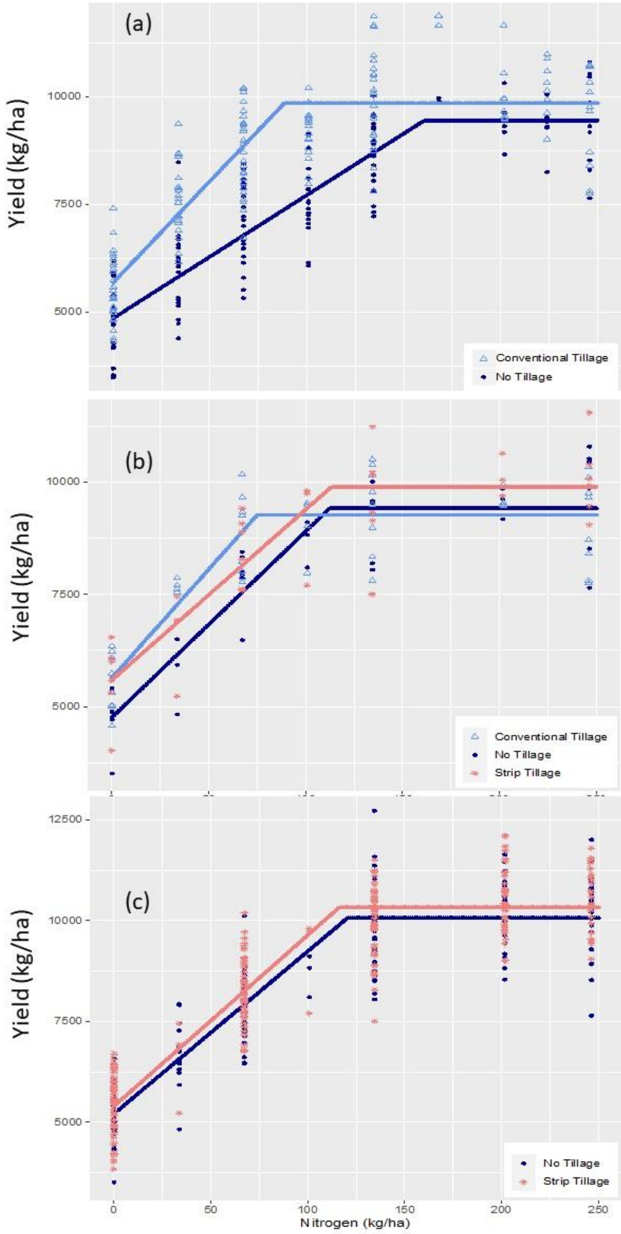

Figure 1. Effect of N fertilizer rates on yields of irrigated corn grain (oven-dried weight) grown on a clay loam soil (fine-loamy, mixed, mesic Aridic Haplustalfs) with a 1 to 2% slope at the Agricultural Research, Development, and Education Center (ARDEC) from 2001 to 2007 under CT and NT systems (a); from 2006 to 2007 under CT, NT, and ST systems (b); and from 2006 to 2017 under ST and NT systems (c). Data fitted with a linear-plus plateau model.

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Table 1. Summary table of growing period and tillage (GPT) for compartment (yield or N content) assessed: yield of harvested grain, crop residue biomass [stalks, leaves and cobs]) yield, N content of harvested grain, N content of crop residue, and total aboveground N content (sum of harvested N with grain and N content in crop residue). The slope (β_1), intercept (β_0), N at plateau (N_p) and predicted plateau ($\hat{Y}_p$) for each modeled compartment (yield or N content) as a function of N fertilizer rate applied in kg N ha^{-1} in irrigated corn grown on a clay loam soil, are shown. The effects of tillage and N rates on harvested grain and crop residue yields, as well as the effects of tillage and N rates on N content of harvested grain, crop residue and total aboveground N content, were assessed with a linear-plus-plateau model or a linear relationship model.

GPT$	Compartment	Model	β_1	β_0	N_p	$\hat{Y}_p$
NT 2001-2007	Harvested Grain	LPPM¶	28.5b***	4,866 b***	161 a***	9,445 b***
CT 2001-2007	Harvested Grain	LPPM¶	47.1a***	5,694 a***	88 b***	9,852 a***
NT 2001-2007	Crop Residue Biomass	LPPM¶	18.0 n.s.	6,163 n.s.	168 n.s.	9,187 n.s.
CT 2001-2007	Crop Residue Biomass	LPPM¶	16.4 n.s.	6,093 n.s.	168 n.s.	8,845 n.s.
NT 2001-2007	Harvested Grain N	LPPM¶	0.43 *b	43 b***	169 a*	115 b***
CT 2001-2007	Harvested Grain N	LPPM¶	0.49 *a	57 a***	150 b*	130 a***
NT 2001-2007	Aboveground Biomass N	LPPM¶	0.64 n.s.	68 b***	173 n.s.	179 b***
CT 2001-2007	Aboveground Biomass N	LPPM¶	0.68 n.s.	81 a***	168 n.s.	196 a***
NT 2001-2007	Crop Residue Biomass N	LPPM¶	0.22 n.s.	25 n.s.	181 n.s.	64 n.s.
CT 2001-2007	Crop Residue Biomass N	LPPM¶	0.23 n.s.	23 n.s.	184 n.s.	64 n.s.
NT 2006-2007	Harvested Grain	LPPM¶	41.5 n.s.	4,762 b**	112 a***	9,410 b**
CT 2006-2007	Harvested Grain	LPPM¶	48.4 n.s.	5,643 a**	75 b***	9,270 c**
ST 2006-2007	Harvested Grain	LPPM¶	38.0 n.s.	5,593 a**	113 a***	9,898 a**
NT 2006-2007	Crop Residue Biomass	LPPM¶	15.9 n.s.	6,101 n.s.	242 a**	9,944 a**
CT 2006-2007	Crop Residue Biomass	LPPM¶	16.6 n.s.	5,659 n.s.	172 ab**	8,500 ab**
ST 2006-2007	Crop Residue Biomass	LPPM¶	17.4 n.s.	6,300 n.s.	113 b**	8,256 b**
NT 2006-2007	Harvested Grain N	LPPM¶	0.60 n.s.	37 b***	101 b**	98 c***
CT 2006-2007	Harvested Grain N	LPPM¶	0.61 n.s.	56 a***	114 b*	125 b***
ST 2006-2007	Harvested Grain N	LPPM¶	0.52 n.s.	57 a***	151 a**	136 a***
NT 2006-2007	Aboveground Biomass N	LPPM¶	0.61 n.s.	70 b*	172 n.s.	175 b*
CT 2006-2007	Aboveground Biomass N	LPPM¶	0.70 n.s.	82 b	157 n.s.	192 ab
ST 2006-2007	Aboveground Biomass N	LPPM¶	0.72 n.s.	82 a*	157 n.s.	195 a*
NT 2006-2007	Crop Residue Biomass N	LR¥	0.20 a***	27 a	246 n.s.	76 a***
CT 2006-2007	Crop Residue Biomass N	LR¥	0.19 a*	23 a	246 n.s.	69 a*
ST 2006-2007	Crop Residue Biomass N	LR¥	0.14 b***	28 a	246 n.s.	62 b***
NT 2006-2017	Harvested Grain	LPPM¶	40.3 n.s.	5,216 n.s.	121 n.s.	10,067 n.s.
ST 2006-2017	Harvested Grain	LPPM¶	42.4 n.s.	5,405 n.s.	116 n.s.	10,328 n.s.
NT 2006-2017	Crop Residue Biomass	LPPM¶	33.3 n.s.	7,514 a***	82 n.s.	10,233 a***
ST 2006-2017	Crop Residue Biomass	LPPM¶	37.5 n.s.	6,161 b***	86 n.s.	9,379 b***
NT 2006-2017	Harvested Grain N	LPPM¶	0.49 n.s.	46 n.s.	156 n.s.	123 n.s.
ST 2006-2017	Harvested Grain N	LPPM¶	0.52 n.s.	48 n.s.	159 n.s.	131 n.s.
NT 2006-2017	Aboveground Biomass N	LPPM¶	0.72 n.s.	78 n.s.	165 n.s.	197 n.s.
ST 2006-2017	Aboveground Biomass N	LPPM¶	0.73 n.s.	76 n.s.	165 n.s.	196 n.s.
NT 2006-2017	Crop Residue Biomass N	LPPM¶	0.23 n.s.	32 a*	186 a	74 a*
ST 2006-2017	Crop Residue Biomass N	LPPM¶	0.21 n.s.	28 b	180 a	65 b

$No till (NT); Cultivated till (CT); Strip till (ST); GTP and compartments with different letters were significantly different; ***, ** and * are significant at P <0.01, P <0.05 and P <0.10, respectively; non-significant (n.s.). ¶Linear-plus-plateau model (LPPM). ¥The linear-plus-plateau model could not be identified as a response function for describing crop residue biomass N versus N. Due to this, a linear regression model was used.

Table 2. Likelihood-ratio test statistics for the estimated linear-plus-plateau model parameters of harvested grain, crop residue biomass, harvested grain N content, crop residue biomass N content, and total aboveground N content responses to N rates for NT and CT comparison from 2001 to 2007.

Parameter Estimate	Grain Response	Biomass Response	Grain N Uptake	Total Aboveground N Uptake	Crop Residue N Uptake
Intercept	14.367***	1.052	18.219***	8.099***	1.554
Slope	10.328***	1.236	3.379*	1.609	1.074
N at Plateau	17.176***	1.019	3.645*	1.171	1.016

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*** Significant at the 0.01 level; ** Significant at the 0.05 level; * Significant at the 0.10 level.

Table 3. Likelihood-ratio test statistics for the estimated linear-plus-plateau model parameters of harvested grain, harvested grain N content, crop residue biomass N content, and total aboveground N content responses to N rates for NT, CT, and ST system comparisons from 2006 to 2007.

Parameter Estimates	Compartment	NT vs. CT	NT vs. ST	CT vs. ST
Intercept	harvested grain	5.892**	4.438**	1.015
Slope	harvested grain	1.809	1.206	2.588
N at Plateau	harvested grain	6.555***	1.005	5.274**
Intercept	Biomass	1.929	1.286	2.503
Slope	Biomass	1.018	1.075	1.011
N at Plateau	Biomass	2.498	7.653***	2.176
Intercept	grain N uptake	7.550***	8.360***	1.054
Slope	grain N uptake	1.001	1.691	1.899
N at Plateau	grain N uptake	1.716	5.206**	3.556*
Intercept	total N uptake	2.678	2.927*	1.001
Slope	total N uptake	1.687	2.185	1.030
N at Plateau	total N uptake	1.404	1.520	1.000

*** Significant at the 0.01 level; ** Significant at the 0.05 level; * Significant at the 0.10 level.

Table 4. Likelihood-ratio test statistics for the estimated linear-plus-plateau model parameters of harvested grain, crop residue biomass, harvested grain N content, crop residue biomass N content, and total aboveground N content responses to N rates for NT and ST comparison from 2006 to 2017.

Parameter Estimate	Grain Response	Biomass Response	Grain N Uptake	Total aboveground N Uptake	Crop Residue N Uptake
Intercept	2.144	12.984***	2.093	1.102	2.821*
Slope	1.331	1.239	1.404	1.001	1.245
N at Plateau	1.256	1.104	1.104	1.005	1.063

*** Significant at the 0.01 level; ** Significant at the 0.05 level; * Significant at the 0.10 level.

3.2. Effect of Long-Term Tillage on Crop Residue

The crop residue production at the plateau (CR$\hat{Y}_p$) from 2001 to 2007 (9,187 kg ha^{-1}) for NT was no different than the 8,845 kg ha^{-1} produced with the CT (Figure 2a; Tables 1 and 2). For the 2006 to 2007 period, the NT CR$\hat{Y}_p$of 9,944 kg ha^{-1} and the CT CR$\hat{Y}_p$ of 8,500 kg ha^{-1} were no different (Figure 2b; Tables 1 and 5). During this period, the NT crop residue of 6,101 kg ha^{-1} at 0 kg N ha^{-1} (CRβ_0) was not different than the ST CRβ_0 production of 6,300 kg ha^{-1} (P<0.05; Figure 2b; Tables 1 and 3). However, the NT CR$\hat{Y}_p$ (9,944 kg ha^{-1}) was higher than the ST CR$\hat{Y}_p$of 8,256 kg ha^{-1} (P<0.05; Figure 2b; Tables 1 and 5). The production of CT CRβ_0 (5,659 kg ha^{-1}) was not different than ST CRβ_0 (6,300 kg ha^{-1}; P<0.05; Figure 2b; Tables 1 and 3). Comparison of NT and ST crop residue production from 2006 to 2017 found that the NT CR$\hat{Y}_p$ of 10,233 kg ha^{-1} was higher than the CR$\hat{Y}_p$with ST (9,379 kg ha^{-1}; P<0.01; Figure 2c; Tables 1 and 4).

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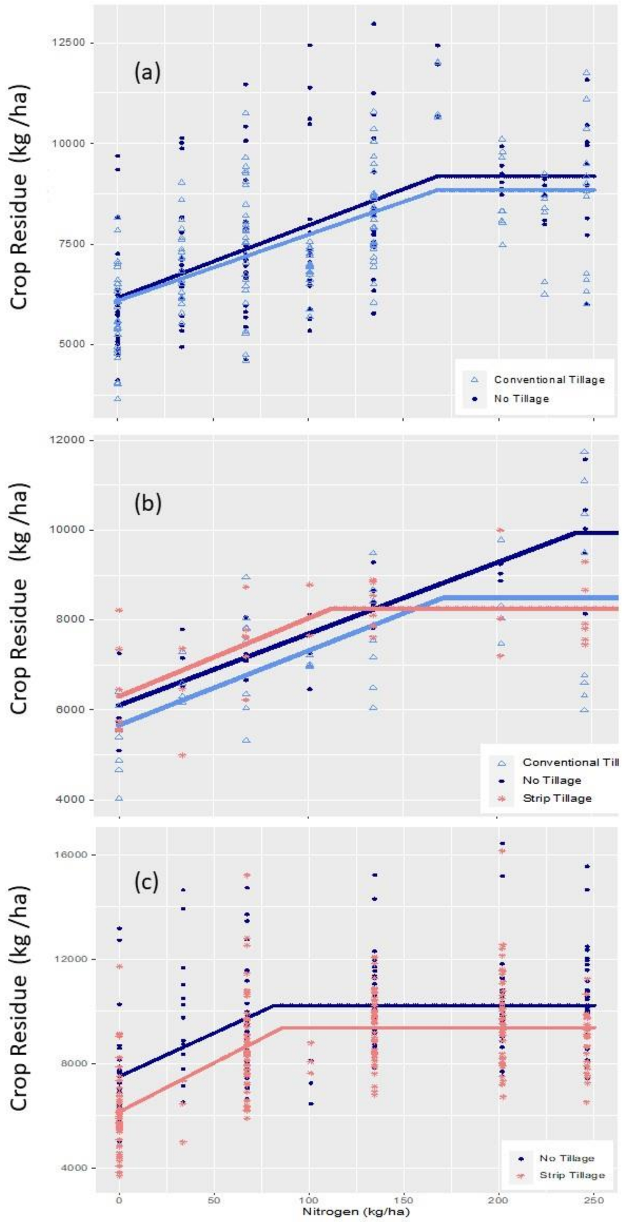

Figure 2. Effect of N fertilizer rates on crop residue biomass (stalks, leaves, and cobs) yields (oven-dried weight) of irrigated corn grain grown on a clay loam soil (fine-loamy, mixed, mesic Aridic Haplustalfs) with a 1 to 2% slope at the Agricultural Research, Development, and Education Center (ARDEC) from 2001 to 2007 under CT and NT systems (a); from 2006 to 2007 under CT, NT, and ST systems (b); and from 2006 to 2017 under ST and NT systems (c). Data fitted with a linear-plus plateau model.

3.3. Effect of Long-Term Tillage on Grain N Uptake

A comparison of NT and CT for the 2001 to 2007 period using the linear-plus-plateau model revealed that the simulated harvested grain N content at the plateau (HGNC$\hat{Y}_p$) for CT was 130 kg N ha^{-1}, which was greater than the HGNC$\hat{Y}_p$ of 115 kg N ha^{-1} with corn grain grown under NT (P<0.01; Figure 3a; Tables 1 and 2). The HGNCβ_0 of the non-fertilized CT treatment during this period of 57 kg N ha^{-1} at the intercept was higher than the HGNCβ_0 of the NT (43 kg N ha^{-1}; P<0.01; Figure 3a; Tables 1 and 2). In the last two years of this period (2006 to 2007), the HGNC$\hat{Y}_p$ of the CT (125 kg N ha^{-1}) was still higher than the HGNC$\hat{Y}_p$ of the NT (98 kg N ha^{-1}; P<0.01; Figure 3b; Tables 1 and 3). However, the HGNC$\hat{Y}_p$ values of the NT and CT were lower than the HGNC$\hat{Y}_p$ of the ST (136 kg N ha^{-1}; P<0.01; Figure 3b; Tables 1 and 3). The HGNCβ_0 for the CT and ST were 56 and 57 kg N ha^{-1},

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respectively, and were both higher than the HGNCβ_0 of 37 kg N ha^{-1} with the NT (P<0.01 Figure 3b; Tables 1 and 3). For the 2006 to 2017 growing period, the HGNC$\hat{Y}_p$ of the ST (131 kg N ha^{-1}) was still higher than the HGNC$\hat{Y}_p$ of 123 kg N ha^{-1} with NT (P<0.10; Figure 3c, Table 1 and 4).

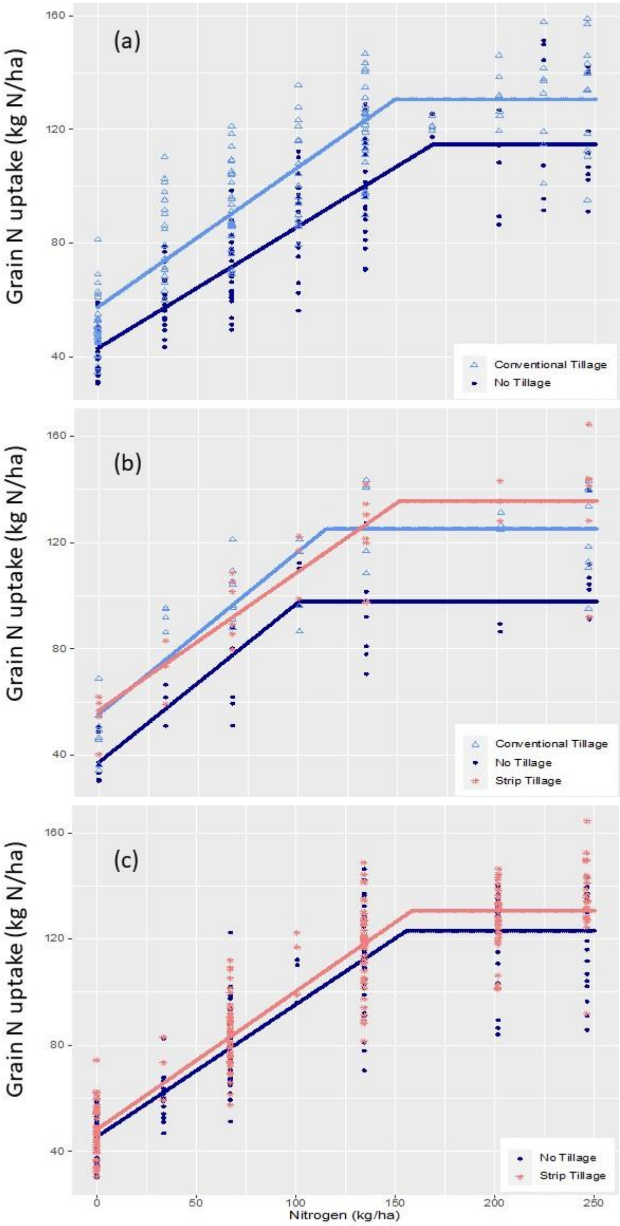

Figure 3. Effect of N fertilizer rates on N uptake of irrigated corn grain grown on a clay loam soil (fine-loamy, mixed, mesic Aridic Haplustalfs) with a 1 to 2% slope at the Agricultural Research, Development, and Education Center (ARDEC) from 2001 to 2007 under CT and NT systems (a); from 2006 to 2007 under CT, NT, and ST systems (b); and from 2006 to 2017 under ST and NT systems (c). Data fitted with a linear-plus plateau model.

3.4. Effect of Long-Term Tillage on Total N Uptake

For the 2001 to 2007 growing period, the total aboveground N uptake at the plateau (TBNC$\hat{Y}_p$) of 196 kg N ha^{-1} with the CT treatment was higher than the TBNC$\hat{Y}_p$ of 179 kg N ha^{-1} with the NT (P<0.01; Figure 4a; Tables 1 and 2). From 2006 to 2007, the TBNC$\hat{Y}_p$ of the CT (192 kg N ha^{-1}) was not significantly different from the TBNC$\hat{Y}_p$ of 175 kg N ha^{-1} with the NT (Figure 4b; Tables 1 and 3), and was also not significantly different from the TBNC$\hat{Y}_p$ of 195 kg N ha^{-1} with the ST. However, during 2006 to 2007 the TBNC$\hat{Y}_p$ with the ST of 195 kg N ha^{-1} was significantly higher than the TBNC$\hat{Y}_p$ of

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175 kg N ha-1 with the NT (P<0.10; Figure 4b; Tables 1 and 3). From 2006 to 2017, the TBNC$\hat{Y}_p$ values for ST and NT were similar and averaged 196.5 kg N ha-1 (Figure 4c; Tables 1 and 4). The TBNC$\hat{Y}_p$ of the NT from 2001 to 2007 (179 kg N ha-1; Figure 4a; Table 1) increased from 179 to 197 kg N ha-1 from 2006 to 2017 (Figure 4c; Tables 1 and 4). In both time periods, the CT (2001 to 2007) as well as the NT and ST (2006 to 2017) had TBNC$\hat{Y}_p$ values that were above 190 kg N ha-1 (Table 1). For the 2001 to 2007 period, the TBNCβ_0 was significantly higher with the CT (81 kg N ha-1) than the TBNCβ_0 with the NT (68 kg N ha-1) (P<0.01; Figure 4a; Tables 1 and 2).

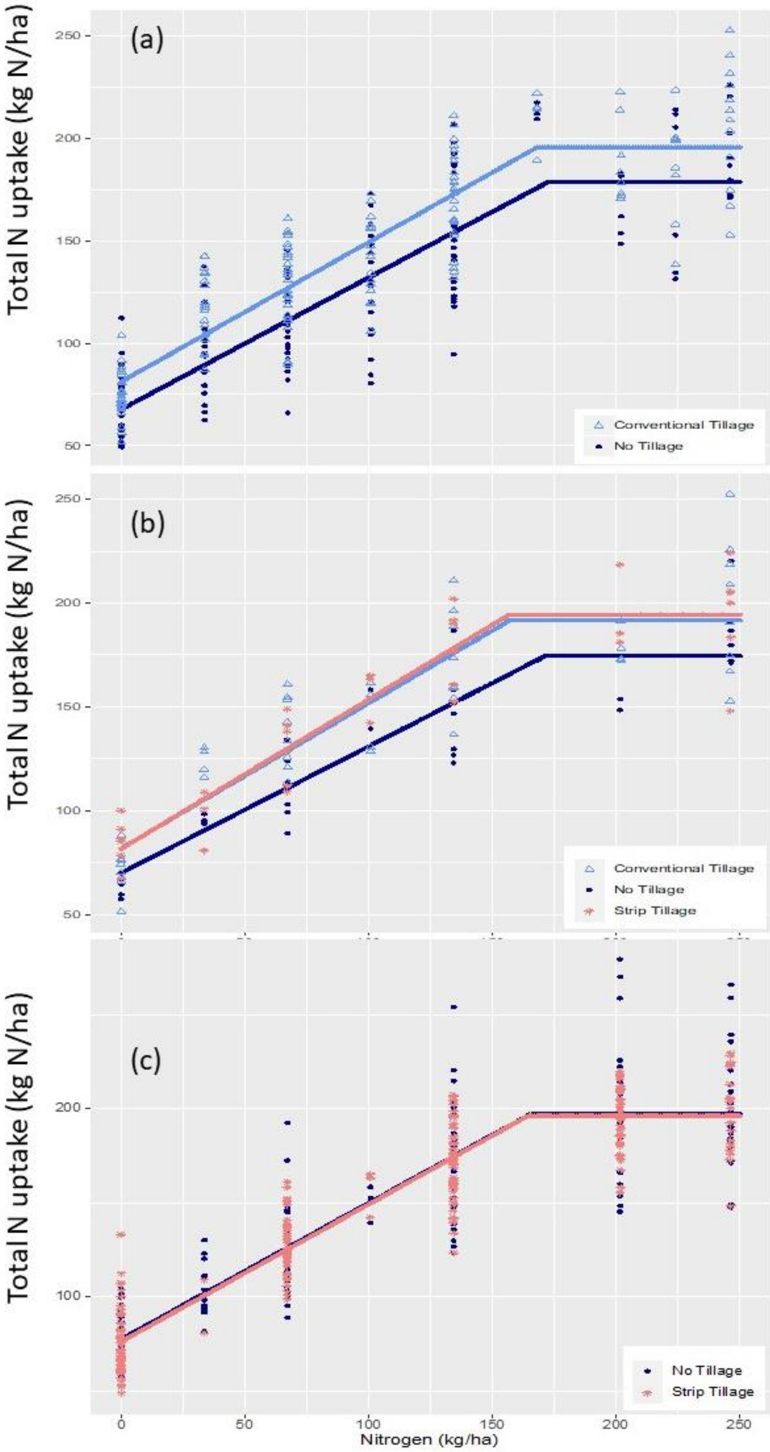

Figure 4. Effect of N fertilizer rates on total aboveground N uptake (grain, stalks, leaves, and cobs) of irrigated corn grain grown on a clay loam soil (fine-loamy, mixed, mesic Aridic Haplustalfs) with a 1 to 2% slope at the Agricultural Research, Development, and Education Center (ARDEC) from 2001 to

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2007 under CT and NT systems (a); from 2006 to 2007 under CT, NT, and ST systems (b); and from 2006 to 2017 under ST and NT systems (c). Data fitted with a linear-plus plateau model.

3.5. Effect of Long-Term Tillage on Crop Residue N Uptake

There were no significant differences between tillage treatments as far as the crop residue N uptake at the plateau (CRNC$\hat{Y}_p$) during 2001 to 2007 (Figure 5a; Tables 1 and 2). The average CRNC$\hat{Y}_p$ during the 2001 to 2007 period was 64 kg N ha^{-1} for the CT and NT treatments (Figure 5a; Tables 1 and 2). The 2001 to 2007 CRNCβ_0 for the CT and NT systems was not significant and averaged 24 kg N ha^{-1}. From 2006 to 2007, the CRNC$\hat{Y}_p$was 76 with the NT and 69 kg N ha^{-1} with the CT, both of which were higher than the CRNC$\hat{Y}_p$ of 62 kg N ha^{-1} with ST (P<0.05; Figure 5b; Tables 1 and 5). The CRNC$\beta_0$values of the non-fertilized plots for the NT, CT, and ST were not significantly different and averaged 26 kg N ha^{-1}. For the 2006 to 2017 period, the CRNC$\hat{Y}_p$ of 65 kg N ha^{-1} with ST was lower than the CRNC$\hat{Y}_p$ of 74 kg N ha^{-1} with NT (P<0.10; Figure 5c, Table 1 and 4). The crop residue of the NT treatment estimated with the CRNC$\hat{Y}_p$tended to return larger quantities of N to the soil (ranging from 64 to 76 kg N ha^{-1}) than the crop residue of the CT and ST systems estimated at CRNC$\hat{Y}_p$, which tended to return 62 to 69 kg N ha^{-1}.

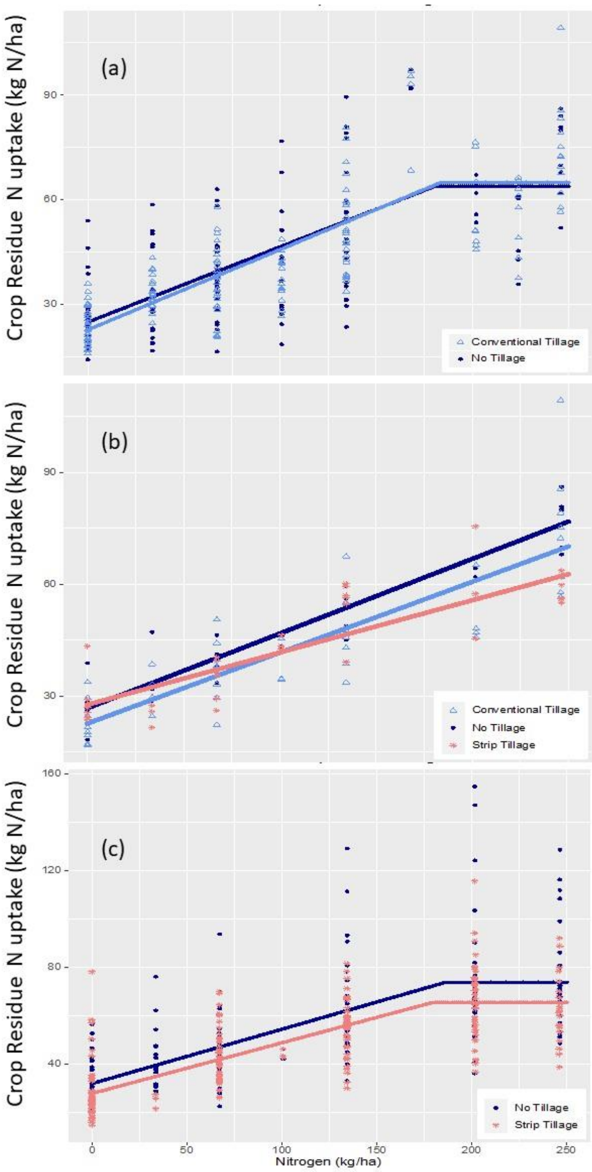

Figure 5. Effect of N fertilizer rates on N uptake of crop residue biomass (stalks, leaves, and cobs) of irrigated corn grain grown on a clay loam soil (fine-loamy, mixed, mesic Aridic Haplustalfs) with a 1

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to 2% slope at the Agricultural Research, Development, and Education Center (ARDEC) from 2001 to 2007 under CT and NT systems (a); from 2006 to 2007 under CT, NT, and ST systems (b); and from 2006 to 2017 under ST and NT systems (c). Data fitted with a linear-plus plateau model.

4. Discussion

4.1. CT had higher ANUE than NT and ST

The higher grain yield (9.852 kg ha^{-1}) with CT from 2001 to 2007 was obtained with a lower N rate of 88 kg N ha^{-1} (Figure 1a) compared to the NT grain yield of 9.852 kg ha^{-1} with a higher N rate of 161 kg N ha^{-1} (P<0.01). Thus, the ANUE$_{HG}$ of 112 kg grain kg N^{-1} with the CT was almost double the efficiency of that of the NT (58.7 kg grain kg N^{-1}). The data suggest that during the last two years of this 2001 to 2007 period, the NT yields were improving with time with respect to the CT since from 2006 to 2007 the ANUE$_{HG}$ of the NT increased from 58.7 kg grain kg N^{-1} (2001 to 2007) to 83.7 kg grain kg N^{-1} (2006 to 2007). Predicted-plateau NT yields were achieved with 161 and 112 kg N ha^{-1} for the 2001 to 2007 and 2006 to 2007 periods, respectively. However, the 2006 to 2007 ANUE$_{HG}$ for NT was still significantly lower than the ANUE$_{HG}$ for CT of 123.7 kg grain kg N^{-1}. The ANUE$_{HG}$ with the CT was also higher than the ANUE$_{HG}$ with the ST from 2006 to 2007 (87.4 kg grain kg N^{-1}).

These findings of lower grain yields with NT than CT agree with findings by Halvorson et al. for the 2001 to 2005 period [21]. Halvorson et al. reported that the higher yields with CT and ST tillage systems during the early years of the study (2000 to 2005) were due to early higher soil temperatures and faster emergence with CT and ST [21]. Our findings also agree with other reports of lower grain yields with NT compared to CT systems [19,24–27].

4.2. Improvement of NT Performance with Time with Respect to Other Tillage Systems

The predicted-plateau yields with ST from 2006 to 2007 were achieved with 113 kg N ha^{-1}. Since during 2006 to 2007 predicted-plateau yields for the NT and ST conservation systems were obtained at the same N rate of about 113 kg N ha^{-1}, the ANUE$_{HG}$ of 87.4 kg grain kg N^{-1} with the ST was higher than the ANUE$_{HG}$ of 83.7 kg grain kg N^{-1} with the NT during this period. It is important to note that these higher yields observed with the ST were in a system that was transitioning from NT to ST, most likely adding N into the system. However, although the ST was likely cycling more N from the soil system, the higher yields were obtained at the same level of N fertilizer application (close to 113 kg N ha^{-1}).

For the 2006 to 2017 period there were no differences between NT and ST for the needed N rate to achieve predicted-plateau grain yields. The N rates at the plateau of 121 kg N ha^{-1} with NT and 116 kg N ha^{-1} with ST from 2006 to 2017, for an average of 119 kg N ha^{-1}, were not significantly different. These results suggest that the NT grain yield continued to improve with respect to other tillage systems with time during the 2001 to 2017 period.

Since NT, CT, and ST responded significantly to N fertilizer additions, these long-term responses in ANUE$_{HG}$ also suggest that N cycling could also have been a factor in increasing the yields with NT with time. The responses of the control (zero N fertilizer) plots during these time periods suggest that N cycling and/or N recovered was increasing with time in the NT system with respect to other tillage systems (Figs. 3, 4, and 5; Table 1). Similarly to how the differences between NT and tillage systems such as ST disappeared with time (Figs. 1, 2, 3, 4 and 5), the differences in the non-fertilized plot between the NT and other tillage systems such as ST also disappeared with time during this 2001 to 2017 period (Figs. 1, 2, 3, 4 and 5). The long-term linear plus plateau analysis also suggests that although the N fertilizer rate of the NT system at the plateau is decreasing with time (2006 to 2017; 156 kg N ha^{-1}; for a HG$\hat{Y}_p$ of 10,067 kg N ha^{-1}; Table 1), initially the highest grain nitrogen content was reached with a higher N rate at the plateau (2001 to 2007; 169 kg N ha^{-1}; for a HG$\hat{Y}_p$ of 9,445 kg N ha^{-1}; Table 1).

The NT yields were increasing with time at this site, and during the 2006 to 2007 period the NT grain yields were higher than the CT, although they were lower than the ST (Figure 1 and Table 1). However, in the long term (2006 to 2017), both NT and ST systems had the same grain yields, so these increases in yields in NT with respect to the other tillage systems agree with the 25-year study conducted by Dick et al. that found initially lower grain yields with NT during the first 18 years and then similar CT and NT yields afterwards [28]. These findings highlight the importance of conducting long-term yield studies to determine the responses of tillage systems with time. However, the positive response in NT grain yield relative to CT and ST was seen after only five to seven years of NT, which is a much faster response than the 18 years observed in the 25-year study conducted by Dick et al. [28].

The positive effect of increasing yields with time as a function of N fertilizer for the NT with respect to other tillage systems was also seen in the non-fertilized grain yields with the NT, CT, and ST systems. The NT grain yield of 4,866 kg ha^{-1} with the control (intercept) during the 2001 to 2007 period was significantly lower than the yield with the non-fertilized CT (5,694 kg ha^{-1}; P<0.01; Figure 1a; Table 1). The non-fertilized NT grain yield of the control (4762 kg ha^{-1}) during the last two years of this period (2006-2007) was significantly lower than the 5,593 and 5,643 kg ha^{-1} for the ST and CT, respectively (P<0.01). However, for the 2006 to 2017 period the non-fertilized NT grain yield of 5,216 kg ha^{-1} was no different from the 5,405 kg ha^{-1} with ST (Figure 1c; Table 1).

4.3. ANUE$_{CR}$ for NT Increased with Time with Respect to Other Tillage Systems

The NT and CT crop residue production from the 2001 to 2007 period were no different and were achieved with the same N rate of 168 kg N ha^{-1} (Figure 2a; Table 1). Since there was no difference between the NT and CT crop residue production achieved at the same N rate, the ANUE$_{CR}$ of 53.7 kg residue kg N was the same for this plant compartment from 2001 to 2007 with these two tillage systems. For the last two years of this period there was also no difference in crop residue production or N rate for predicted-plateau production between the NT and CT systems, but the agronomic efficiency of the predicted-plateau crop residue production was lower at 45.2 kg residue kg N^{-1} than the ANUE$_{CR}$ of 53.7 kg residue kg N^{-1} from 2001 to 2007. The ANUE$_{CR}$ of the ST at predicted-plateau yield was higher at 73.1 kg residue kg N^{-1} than the 2001 to 2007 average crop residue agronomic efficiency. The ANUE$_{CR}$ of the NT continued to increase with time since the ANUE$_{CR}$ with NT of 138.3 kg residue kg N^{-1} was higher from 2006 to 2017, and ST also had a similarly high crop residue agronomic efficiency of 144.3 kg residue kg N^{-1}. These increases in crop residue production and ANUE$_{CR}$ suggest a higher efficiency of the applied N with time for the NT, supporting the idea that the N cycling of NT is increasing with time with respect to ST and CT.

4.4. The t-Test Analyses Are in Sync with the Linear-Plus-Plateau Model Analyses

The above discussion sections summarize all the periods monitored from 2001 to 2017. An additional detailed discussion, arranged by the 2001 to 2007 (NT and CT); 2006 and 2007 (NT, ST, and CT) and 2006 to 2017 (NT and ST) periods, is also included in the supplementary materials (Tables S20 and S21). Additionally, all of the datasets used for these analyses can be found in the supplementary materials. The year-by-year and nitrogen rate t-test analyses of HGY, CRB, HGNC, TBNC, and CRNC are in sync with the determination of CRB$\hat{Y}_p$ and CRBβ_0 made with the linear-plus-plateau model for the 2001 to 2007, 2006 to 2007, and 2006 to 2017 periods (Tables S5, S6, S7, S8, S9, S10, S11, S12, S13, S14, S15, S16, S17, S18, S19, S20, and S21). Some readers may wish to use these datasets to conduct additional analyses and/or to facilitate modeling simulations of the tillage systems studied at this site for further interpretations of the 17 years of research data collected at this site.

4.5 Need for Long-Term Research

The present work found that short-term (two-to-three-year, or even five-year) studies will not necessarily reflect the changes that affect long-term NUE and the potential for N losses for a given tillage system, and that long-term studies are necessary to assess how a given cropping system under a given tillage system like NT could change with time (e.g., increased NUE and increased N cycling). Our assessment of NUE for the NT system, which used the linear-plus-plateau model, is in agreement

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with the N balance study conducted by Delgado et al. that found that the long-term N losses from this irrigated NT system ranged from 20 to 50% [1]. The present work is further evidence of the importance of conducting long-term research studies since the responses to treatment effects such as tillage systems are dynamic and change with time, and the initial responses are not necessarily the same responses that would be expected in long-term applications of best management practices (BMPs). This illustrates the importance of long-term research and shows there is a need for long-term research across the USA.

Although total N removal with grain was higher for CT and ST than NT, the total N uptake by aboveground crop biomass was not significantly different between NT, ST, and CT after five years, when the total uptake of the NT increased to levels comparable to ST and CT. More crop residue N was cycled back to the field with NT than with ST, and even initially when NT had lower total N uptake than CT, the N cycled back with NT was not significantly less than the N cycled back with CT. The N fertilizer rate at the harvested grain plateau was 161 kg N ha^{-1} in the first seven years following establishment of NT (from 2001 to 2007) and 121 kg N ha^{-1} during the final 11 years (from 2006 to 2017; Table 1).

5. Conclusions

We conclude that NT systems initially reduce yields compared to more intense tillage systems such as CT and ST, and with time, NT reaches at least similar yield responses to CT and ST under irrigation at this site in Colorado. Additionally, the present work on tillage effects shows that the agronomic efficiency of the N applied to the NT system was increasing with time with respect to CT and ST, suggesting that N cycling in the NT system increased over time. NT has the potential to be a viable management tool with similar agronomic efficiencies to other tillage systems like ST. However, the agronomic efficiencies were lower than those observed with CT.

The crop residue results suggest that if we want to continue N cycling that supplies N to the soil system at high levels with the crop residue, we may have to apply N in greater quantities (Table 1; 180 to 246 kg N ha^{-1}) than needed for achieving grain production at the linear plus plateau N rate; otherwise, the N cycling with the crop residue may be reduced in the long term. The long-term studies and comparison with other tillage systems show that NT is a potential viable practice as far as recoveries of N, and the long-term total aboveground biomass NUE of about 70% is comparable to the long-term total aboveground biomass NUE with CT and ST (about 4% difference). These long-term studies show that NT harvested grain recoveries are lower at about 50% and that there is a need to continue developing BMPs to increase harvested grain N recoveries and yields of NT, ST, and CT systems.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

Author Contributions: Conceptualization: J.A.D., R.E.D. and A.H.V.; methodology: J.A.D., A.H.V. and R.E.D.; software, J.A.D., R.E.D. and A.H.V.; validation, J.A.D., R.E.D. and A.H.V.; formal analysis, J.A.D., R.E.D. and A.H.V.; investigation: J.A.D., R.E.D., A.H.V., A.D.H., C.E.S., J.A., S.J.D., D.K.M. and B.A.F.; data curation, J.A.D., R.E.D. and A.D.H.; writing—original draft: J.A.D.; writing—review and editing: J.A.D., R.E.D., A.H.V., A.D.H., C.E.S., J.A., S.J.D., D.K.M. and B.A.F.; visualization: J.A.D., A.H.V. and R.E.D.; supervision: J.A.D., A.D.H., C.E.S., S.J.D. and D.K.M.; project Administration: J.A.D., A.D.H., C.E.S., S.J.D., D.K.M., B.A.F. and R.E.D. All authors have read and agreed to the published version of the manuscript.

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