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Research Article

Comparing Soybean Productivity, Soil Health, and Economic Viability Under No-Tillage and Conventional Tillage in the Lower Mississippi Delta

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No-tillage (NT) management protects soil from wind and water erosion and improves soil health. Uncertainty in farm production under location-specific NT practices poses challenges to adopting it by the farming community. To address this challenge, a 4-year study (2019–2022) was conducted on farm-size plots (~1.25 ha) focused on comparing soybean (*Glycine max* [L.] Merr.) yield and soil health benefits of an NT system with a conventional tillage (CT) system in silt loam soil. The NT and CT plots were under corn production over the previous 11 years. Compared to CT, in the 0–20 cm layer, soil bulk density (ρ), total nitrogen (TN), and soil organic carbon (C) increased, but field-saturated hydraulic conductivity (K_{fs}) decreased in the 10 cm below the soil surface under NT. Higher ρ was also noticed in the 10–30 cm soil. There were no significant differences between NT and CT in water stable aggregate stability for 0.25–0.5, 0.5–1.0, 1.0–2.0, and 2.0–4.0 mm aggregate classes. While the higher ρ and lower K_{fs} under NT can potentially restrict plant root expansion, the beneficial effects of C and TN appear to make up for those adverse effects, culminating in comparable seed yield returns. Over four years, soybean seed harvested from NT (5440 kg ha^{-1}) was 1% less than CT (5480 kg ha^{-1}). Therefore, adopting the NT system increases net returns by reducing tillage-associated expenses without compromising soybean yields in the Lower Mississippi Delta region, which can improve soil and water conservation.

Keywords: conservation agriculture; conventional tillage; Mississippi Delta; no-tillage; soil carbon; soil health; soil total nitrogen

1. Introduction

In modern agriculture, cultivating the soil with mechanized plows was preferred to reap the benefits of enhanced crop yields associated with crops raised in well aerated and weed-free soils compared to untilled soils [1–4]. In the 20th century, enhanced food production associated with tillage, irrigation, and other soil-water-crop management practices could produce enough food for the increased population [5]. However, with time, agronomists started recognizing many undesirable consequences of tillage-focused soil management in crop production systems, mainly from the loose uncovered soil after tillage operations, which were exposed to wind and water erosion [3, 6, 7]. By about the 1970s, agricultural systems across many soils and climates worldwide started experiencing deteriorated soil qualities, especially those associated with soil nutrient and water availabilities for sustainable yields [8–10]. Intensive soil tilling and associated removal of plant debris covering the soil were reported to be the main factors for the soil fertility loss and production in many soils across the world [11–13]. Toward the end of the 20th century, considerable attention from scientists worldwide has been focused on reversing the soil health degradation associated with intensive tillage in various crop production systems [3, 8, 10, 14]. Reducing the frequency and intensity of soil tillage operations on farmlands has been proposed for reversing and regenerating soil for sustainable agriculture [8, 15].

Worldwide investigations in the direction of prescribing viable solutions for improving soil health for sustainable agriculture, conservation tillage, which leaves a cover over soil surfaces with previous crop residues were promoted [3, 5, 16–18]. Reduction in tillage operations also reduces labor and energy inputs by lowering the use of tillage machinery that uses fossil fuel energy. The reduced tillage and residue covering the soil surface were reported to help reduce soil erosion to wind and water and enhance soil carbon and water-holding capacities [19, 20]. In a typical conservation tillage-focused soil management, the intensity or frequency of tillage is reduced, and last crop residues are left unaltered on the soil surface that covers about 30% of the soil area [21–23]. Among the conservation tillage practices, in no-tillage (NT) management, with a residue covering the soil, sequestered more carbon protected the system from losing water through soil evaporation and water and wind erosion losses of soil carbon and nutrients [19, 24, 25].

Early investigations on conservation tillage revealed that tilling the soil may not be an essential soil management practice for maximizing yields in soybean production systems in the mid-south region of the USA [26]. The Lower Mississippi Delta area (LMD) in the mid-south region, where cotton, soybean, and rice are grown extensively, is one of the sizable agricultural production regions in the USA [27]. Crop growth in the LMD is mainly confined to March/April-September/October. Heavy precipitation and floods characterize the spring (March-April) season in the LMD with a high potential for soil fertility loss through water erosion [27, 28]. However, adopting conservation agriculture, especially NT practices in soybean farming systems, is not a well-accepted soil-management practice due to the difficulty in controlling weeds under untilled soils [29]. The evolution of weed resistance to glyphosate, the most widely used herbicide, also caused farmers to return to more intensive tillage regimes to control weeds. Notwithstanding the recent commercialization of multiple herbicide-resistant crops (e.g., cultivars resistant to glyphosate and glufosinate, and dicamba) offer more options to manage weeds and opened the door for adopting more NT-based cropping systems for water and soil conservation benefits in the LMD.

When conservation tillage carries the potential to conserve the soil–environmental resources for enhanced water use efficiencies in cropping systems, the realized outcomes in practicing NT versus CT at locations can depend on the soil and varying climate conditions [5, 30, 31]. Therefore, this study focused on investigating NT impacts on soybean production and soil health benefits in farm-scale experiments in the humid climate of the LMD region.

2. Material and Methods

In the experiment, soybean was planted on two farm-scale plots (~1.25 ha each) under CT and NT management on Dundee silt loam (fine-silty mixed, thermic Aeric Ochraqualf) soil at Stoneville, Mississippi (33.42°N; 90.92°W, 32 amsl), located in the LMD. The measured soil pH in the plots at 0–30 cm depth varied between 6.1 and 6.5, with the organic carbon between 10 and 20 g kg^{-1} (Table 1). The location's climate is characterized by a humid climate with a warm summer (Köppen–Geiger climate classification) [32]. The average (1960–2020) annual rainfall at the location was about 130 cm, and the minimum and maximum air temperatures were between −3 and 18°C and 22 and 39°C, respectively [33, 34].

These plots were under corn maintained as CT and NT soil management practices from 2008 to 2018. From 2019 until 2022 (4 years.), soybeans replaced corn while maintaining respective NT and CT fields. The farm-size plots gave us a unique flexibility for conducting all agronomic crop management practices, closely emulating the CT ("business as usual farming scenario" as followed by local farmers) versus NT ("aspirational" for soil and water conservation and environmental protection) as conducted by local farmers in their fields. Therefore, the knowledge and technology developed in the experiment can be recommended for decision support in local farming operations in producer fields [31, 35]. The field-scale plots also minimize interactions between the NT- versus CT-maintained plots, eliminating edge effects in the small-plot experiments [36]. The edge effects in small plots generally result from distinct microclimates created by the soil tillage–residue–crop exchanges of heat energy between and within the plot and adjacent land or plot areas. In the NT treatment, the previous crop was shredded using a four-row Balzer Flail mower (Blazer Inc. Mountain Lake, MN) and retained on the soil surface without tillage operations. The CT treatment consisted of (1) one to three passes of deep tillage using chisel plows (CP, locally fabricated four-row subsoiler) to a depth of about 45 cm (subsoiling) every other year, (2) tillage to a depth of about 15–20 cm using hipper plow (Four Row W & A Manufacturing Company, Pine Bluff, AR) to prepare ridges and furrows for planting every season, and (3) cultivations (C, Four-row, row crop cultivator, John Deere 886, Dickey Machine Works, Pine Bluff, Arkansas) to a depth of about 10 cm before planting and within the season to remove weeds and facilitate furrow irrigations (Table 2). The NT plots were left untilled except for the single application of a John Deere 886 cultivator-middle-row plow (John Deere, Moline, IL) applied to rake the surface trash in the middle of rows about 5 cm deep in 2019 and 2020. The plots were treated with paraquat at 1.12 kg a.i. ha^{-1} before planting to kill existing weeds and, further, maintained weed-free using preemergence and postemergence herbicide applications. S-metolachlor at 1.12 kg a.i. ha^{-1} plus pendimethalin at 1.12 kg a.i. ha^{-1} were applied preemergence. Glyphosate at 1.12 kg a.i. ha^{-1} and S-metolachlor at 1.12 kg a.i.ha^{-1} were applied postemergence. Soybean was ridge planted using a John Deere 1705 Soybean Planter (John Deere, Moline, IL) on

Table 1: Selected physical and chemical properties of conventional till (CT) and no-till (NT) soils under soybean at Stoneville, MS, measured at planting in 2021 and 2022.

Crop season	Soil depth (cm)	Soil texture	pH	Organic matter (%)	CEC (Meq 100 g^{-1})	Mehlich-3 extractable nutrients (mg Kg^{-1})						
						P	K	Ca	Mg	Zn	S	Cu
CT												
2021	0–15	SL	6.1 ± 0.03	1.7 ± 0.01	16.8 ± 0.01	51 ± 2.8	231 ± 16	1938 ± 99	379 ± 23	4.2 ± 0.28	13.2 ± 0.64	2.8 ± 0.14
2022	16–30	SL	6.1 ± 0.01	1.0 ± 0.01	17.5 ± 0.07	25 ± 0.71	207 ± 4.9	2067 ± 21	381 ± 1.4	1.8 ± 0.01	10.8 ± 0.57	2.8 ± 0.00
NT												
2021	0–15	SL	6.2 ± 0.01	2.0 ± 0.03	16.8 ± 0.21	54 ± 1.4	230 ± 4.9	2109 ± 37	375 ± 7.8	6.9 ± 0.07	14.5 ± 0.21	2.7 ± 0.00
2022	16–30	SL	6.5 ± 0.05	1.0 ± 0.04	16.3 ± 0.64	22 ± 0.7	207 ± 6.4	2136 ± 97	361 ± 18	2.1 ± 0.07	7.6 ± 0.14	2.7 ± 0.14

Note: The number following ± represents one standard deviation from the mean. K_{sf} = field saturated hydraulic conductivity.
Abbreviations: CT, conventional tillage; NT, no-tillage; SL, silt loam.

Table 2: Soil tillage, residue, cost of tillage operations, and number of irrigations under soybean grown under conventional tillage (CT) and no-tillage (NT) soil management practices from 2019 to 2022.

Year	Surface residue in NT before planting kg ha^{-1}	CT	NT	Cost of tillage under CT USD ha^{-1}	Cost of tillage under NT USD ha^{-1}	Net savings from tillage under NT	Irrigations
2019	1449 ± 182*	RT^F, CP^F, RT^F, RT^S, DA^S, RC^S, MP^S	DA^S, MP^S	183	86	97	1
2020	1262 ± 201	RT^S, DA^S, RC^M, MP^M, RT^F, CP^F, RT^F	DA^S, MP^S	265	86	178	4
2021	—	RT^F, CP^F, RT^F, RC^M, DA^S		183	—	183	3
2022	1706 ± 179	DA^S, RC^S, MP^S, RT^F		173	—	173	1
Mean	1462 ± 184			201	22	179	2

Note: ^{F} = fall season. ^{S} = spring season, ^{M} = summer. DA = do-all (one pass of do-all blade https://www.nicholstillagetools.com to level crest of ridges/furrows) for seedbeds for planting. RC = regular four-row cultivator (Dickey Machine Works, Pine Bluff, Arkansas) with three shanks with 25 cm plows per row about 8–15 cm deep. MP = middle plowing to rake the surface trash to help with irrigation that has a four-row John Deere 886 cultivator (John Deere, Muscotah, Kansas) but a single plow about 12″ wide and about 13–15 cm deep on CT plots and 2–5 cm deep in NT. RT = ridge till or hipper till for seedbeds-four-row hipper about 101–105 cm deep (w & a manufacturing, Arkansas). CP = chisel plow four-row subsoiler (fabricated onsite) has four shanks that are run down the center of the row at approximately 45–50 cm deep and 3 cm wide.

*is one standard deviation.

ridges in a furrow-ridge pattern, with a row spacing of 1.02 and 248 m long in the north-south and 48 m wide (24 rows per CT and NT) in the east-west directions. The plots were partitioned into four equal 62 m long and 24 m wide sections in the east-west direction, across the rows, for four replicated samplings of all plant-soil-related measurements. Soybean seeds were harvested using a Case IH 5140 8-Row Combine with Ag Leader Yield Monitor and reported at 13% moisture content.

For soil texture, bulk density (ρb), soil organic carbon (C), and soil total nitrogen (STN) measurements, soil samples were collected from 0–10, 10–20, and 20–30 cm randomly on the ridges. TN and C were analyzed using an Elementar Vario Max combustion analyzer. The ρ in these layers was determined by extracting undisturbed soil core from the same depths, computed as oven-dried weight per unit volume of soil [37]. The field-saturated hydraulic conductivity (K_{fs}) of the soil was measured using a SATURO infiltrometer (METER, Pullman, WA, USA).

The wet sieving method (Eijkelkamp Agrisearch Equipment, the Netherlands) was used to determine the wet aggregate stability of the soil samples collected at the same soil depths as above [38]. Water-stable aggregates were determined for > 0.25, > 0.5, > 1.0, 0–10, and 2.0–4.0 mm aggregate classes as described by Feng et al. [39] using a wet sieving apparatus made by Eijkelkamp Equipment Company for the 0–10, 10–20, and 20–30 cm depths. Briefly, 4 g of soil aggregates (> 2–4 mm) class put in 0.25 mm sieve-size for cups were raised and lowered in distilled water in metal cans for 3 min at 36 strokes per minute, collecting unstable aggregates in soil. The metal cans were switched with a set filled with 2 g L^{-1} NaOH dispersing solution, which collected water-stable aggregates of soil. The soil collected was oven-dried at 105°C for 24 h. The process was repeated using 0.5, 1.0, and 2.0 mm sieve-size cups. The soil's water-stable aggregate fraction (WSAF) was computed as follows:

$$\text{WSAF} = \left(\frac{(\text{WSA})}{(\text{WSA} + \text{WUA})}\right), \tag{1}$$

where WSAF is water-stable aggregate fraction, WSA is water-stable aggregates, and WUA is water-unstable aggregates.

In the experiment, soybean MG IV variety AG45X8 was planted on April 30, 2019, and May 5, 2020, and AG45XFO was planted on May 14, 2021, and May 4, 2022 (Table 2). The average seeding rate over the four years was about 340,000 seeds ha^{-1}. The amount of crop residue on the NT soil surface at planting averaged across the whole plot was 1499 kg ha^{-1} in 2019, 1262 kg ha^{-1} in 2020, and 1706 kg ha^{-1} in 2022, and 1460 kg ha^{-1} averaged across years (Table 2). An AccuPAR LP-80 ceptometer (Meter Inc, WA, USA) was used to measure the leaf area index (LAI) nondestructively, biweekly, depending on the availability of sunny days for measurements. The phenological growth stages of the crops were recorded from visual observations of 10 plants (Table 3). If eight or more plants reached a particular stage at the time of observation, the crop was assumed to have reached that stage. Soybean seed yield under NT (NTy) as a percentage of yield under CT (CTy) was computed (NT%) as

$$\text{NT\%} = \left(\frac{\text{NTy}}{\text{CTy}}\right)100. \tag{2}$$

Irrigations were surface applied by lay-flat polyethylene tubes at the head of the furrows (the field has about 1% slope) and were allowed to run down its whole length. Each irrigation was about 4 cm, applied when water in the top 45 cm soil layer fell below 65% of the plant available water (Table 2). Irrigations were 42 days after planting (DAP) in 2019; 45, 78, and 91 DAP in 2020; 47, 56, and 88 DAP in 2021; and 50 DAP in 2022. There were no nitrogen fertilizer applications.

The growing degree days (GDD) for the crop were computed using a lower base temperature (Tbase) of 10°C and an upper threshold of 30°C [40]:

$$\text{DD} = \text{Ta} - \text{Tbase}, \tag{3}$$

$$\text{Ta} = \left(\frac{\text{Tx} + \text{Ty}}{2}\right). \tag{4}$$

If the daily mean air temperature (Ta) is less than Tbase (10°C) or greater than 30°C, GDD = 0, where Tx and Ty are the daily maximum and minimum values of air temperatures.

The economic impact of following NT over CT in terms of net profit margin was computed following crop planning budgets published by the Department of Agricultural Economics, Mississippi State University [41]. All field crop management across NT and CT were kept constant in the experiment; as such, they differed only due to differences in tillage and amount of soybean seeds harvested. For computing net revenue differences between NT and CT, the soybean market price (0.17 USD kg^{-1}) was obtained from the "Markets Insider" website (https://www.businessinsider.com) report on February 29, 2024.

The bulk density (ρ), wet aggregate stability, K_{fs}, and total soil C and N at various soil depths and yield data were analyzed using Proc GLIMMIX using SAS Version 9.4 (SAS Institute Inc., Cary, NC). The GLIMMIX procedure combines generalized linear and mixed models' characteristics. Treatment was considered a fixed effect and blocks a random effect for the measured parameters. Block was nested within the year for ρ, wet aggregate stability, K_{fs}, and total soil C and N at various depths in the soils, and yield data when analyzed by year. For the combined analysis of the 4 years of the experiment, years were treated as repeated measurements with years, and their treatment interactions were considered fixed effects. Mean separations were determined using Fisher's protected least significant difference (LSD) at $p < 0.05$ when the analysis of variance (ANOVA) was significant at $p < 0.05$

Table 3: Non-destructively measured soybean phenological growth stages of cv, AG45X8, planted in 2019 and 2020, and cv, AG45XFO, planted in 2021 and 2022, Stoneville, Mississippi.

Phenology	2019		2020		2021		2022	
	DAE	GDD	DAE	GDD	DAE	GDD	DAE	GDD
Planting	Apr 30	0	May 5	0	May 14	0	May 4	0
Emergence (VE)	5	75	6	106	4	114	8	141
Beginning bloom (R1)	44	656	45	718	38	623	34	519
Full bloom (R2)	48	717	49	919	45	716	47	721
Beginning pod (R3)	53	800	55	900	53	865	62	1021
Full pod (R4)	62	947	62	1036	59	964	69	1115
Beginning seed (R5)	72	1136	68	1142	72	1208	72	1209
Full seed (R6)	86	1379	78	1301	81	1390	93	1578
Beginning maturity (R7)	98	1579	89	1462	87	1572	100	1680
Full maturity (R8)	117	1767	107	1528	106	1662	121	1760

Note: DAE is the day after seedling emergence. GDD is growing degree days (°C day).

3. Results and Discussions

3.1. Weather Conditions During the Experiment. Seasonal average air temperatures during the four (2019–2022) crop seasons (the time interval between seedling emergence stage, VE, and beginning soybean seed maturity (R7) stage were considered as crop growth season) of the experiments varied between 20.3°C and 21.1°C for daily maximum, and between 31.2°C and 32.7°C for daily maximum temperatures. As reflected in the measured temperature values across the four seasons, air temperature experienced by the crops did not vary substantially between seasons (Figure 1). Substantially higher values were recorded only in the daily maximum air temperature, 37.2°C, on June 25, 2022, the highest daily value among the four crop seasons. Seasonal total rainfall recorded across the four crop seasons ranged from 246 mm (23 rainy days out of 93 days) in 2020, the driest year, to 657 mm (30 rainy days out of 81 days) in 2019, the wettest year (Figure 1(b)). Crop seasons 2021 and 2022 recorded, respectively, 397 mm (32 rainy-days out of 82 days) and 340 mm (27 rainy-days out of 99 days). The highest daily rainfalls received were 155, 41, 94, and 46 mm during the four crop seasons. Daily average air relative humidity observed ranged from 59% to 89% in 2019, 64% to 86% in 2020%, 66% to 98% in 2021, and 65% to 90% in 2022.

3.2. Effect of Tillage on ρ and K_{fs}. Measured ρ at 0–10 cm and 10–20 cm in 2020 and 2021 was significantly different between NT and CT systems (Table 4). In 2022, the ρ measured was significantly different at the 0–10, 10–20, and 20–30 cm depth separations ($p < 0.01$) (ρ was not measured in 2019). The ρ varied from 1.08 g cm^{-3} in the 0–10 cm layer to 1.67 g cm^{-3} in the 20–30 cm layer under CT treatment in 2020. In 2021, corresponding ρ values ranged from 1.24 g cm^{-3} in the 0–10 cm layer to 1.61 g cm^{-3} in the 20–30 cm layer under CT, and from 1.37 to 1.67 g cm^{-3} under NT. In 2022, the ρ values for the 0–30 cm depth, measured at 10 cm intervals as above, were significantly different, ranging from 1.35 to 1.60 g cm^{-3} under CT and from 1.49 to 1.77 g cm^{-3} under NT. In general, the ρ of the soil under both CT and NT increased with depth. The maximum value between the two tillage treatments was 0.17 g cm^{-3}, observed randomly across the soil layers (Table 4). Measured K_{fs} in the NT treatment was lower than those under the CT treatment. Average K_{fs} in the CT and NT soils was between 0.24 cm hr^{-1} and 0.09 cm hr^{-1}, respectively, in 2019 and between 0.29 cm hr^{-1} and 0.09 cm hr^{-1} in 2022 (Table 4). In general, K_{fs} declined with tillage in the experiment.

In experiments in the same soil and tillage systems, under irrigated corn for 8 years, Anapalli, Reddy, and Jagadamma [31] observed significant differences in soil bulk density between NT and CT at 15–30 cm depths. Continuous soybean is a common soybean-based production system in the MS Delta region [26]. However, the differences at 0–15 and 30–60 cm were insignificant ($p > 0.01$). The reported bulk densities under NT varied from 1.41 to 1.50 g cm^{-3} and under CT from 1.38 to 1.42 g cm^{-3}. In our study, the average bulk density for the 0–30 cm soil layer increased only by 1% due to NT in three years (2020–2022) (Table 4, calculations not shown). Anapalli, Reddy, and Jagadamma [31] noticed a bulk density increase of about 6% in the same soil layer under corn 8 years before planting soybeans in this experiment.

In the literature, the ρ and K_{fs} of the soils have usually been included in minimum datasets used to evaluate tillage and crop management effects on soil quality [15, 42, 43]. Generally, the higher the ρb, the lower the K_{fs} with higher soil compaction level, which increases the likelihood of exerting soil restriction on plant root growth [44, 45]. However, depending on the soil macroporosity, aggregate stability, compaction, and crop residue cover, both enhancing and declining effects of tillage on the hydraulic properties of soils were reported (e.g., [43, 46]).

Hill and Cruse [46], after 8 years of various tillage treatments from NT to full tillage, did not observe any statistically significant effects on the ρb. Also, ρ values strong enough to have any detrimental effect on plant root growth were absent. Lower or negligible effects on ρ under NT also have been reported [47, 48]. In our experiments, though minor (1%), there was an increase in soil bulk density due to the NT practice.

Producers often identify soil compaction as a fundamental problem in maintaining soil tilth for optimum agricultural productivity. However, an appreciable impact of soil compaction on crop growth was reported only when the

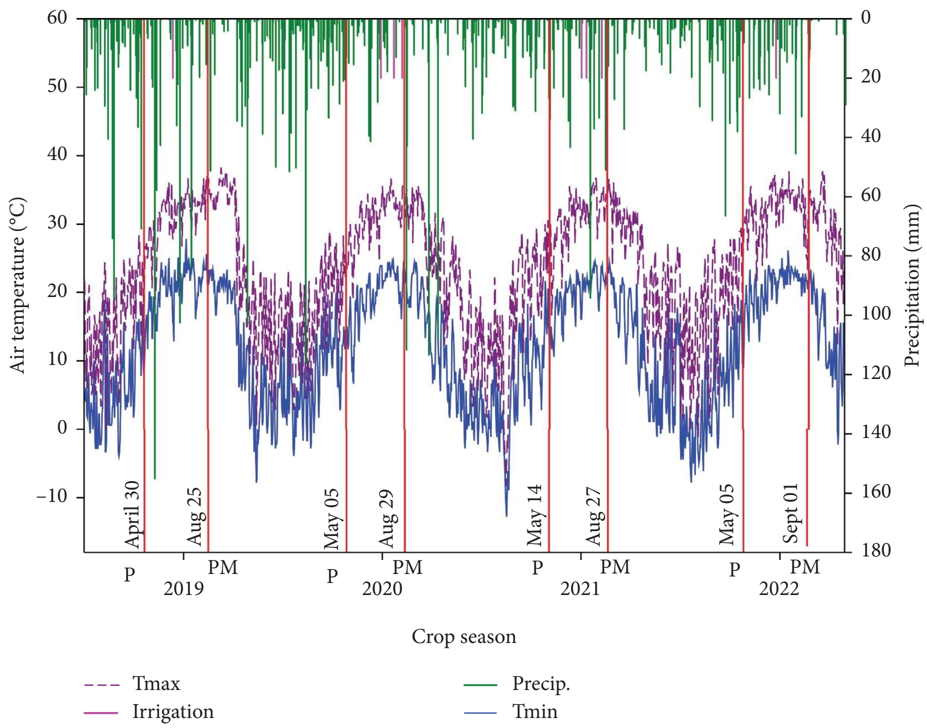

Figure 1: Observed rainfall, solar radiation, and maximum and minimum air temperatures during soybean growing seasons (April to August) from 2019 to 2022. Red vertical lines indicate the date of planting or physiological maturity. P = date of planting and PM = date of physiological maturity.

ρ was enhanced above 1.5 g cm^{-3} due to the tillage treatment (Hamza and Anderson) [49]. In our experiments, ρ values remained above this threshold limit under both the CT and NT systems; hence, the tillage treatment, per se, should not have affected crop root growth significantly, but there are no measurements to substantiate this argument (Table 4). As expected from the enhanced soil compaction (higher bulk density) under the NT compared to the CT, the field saturated hydraulic conductivity measured in 2019 and 2022 (not measured in 2020 and 2021) under CT was significantly higher than under NT (Table 4). Notwithstanding, as presented below, no significant reduction in the measured soybean seed yield can be attributed to soil bulk density changes in our experiments.

3.3. Total C and N in the Soil. C measured at crop harvest in the top 0–10 cm soil layer tended to increase under the NT treatment compared to the CT (Table 4). The C in the 0–10 cm soil layer in the NT was significantly higher than CT in 2019 (38%) and 2022 (11%) (Table 4). However, the differences in C in 2020 and 2021 were insignificant. In 2019, C measured in a 10–20 cm layer was also significantly higher in NT compared to CT, but on the contrary, in 2020, C was significantly lower under NT (Table 4). The NT systems typically enhance soil C sequestration, and the tillage of the soil either enhances decomposition and loss of organic matter at the topsoil or redistributes C to the deeper soil layers [3, 50, 51] and [4]. However, the amount and quality of crop residue management on the soil control the C and N dynamics and C sequestration [52]. Tillage potentially enhances the crop residue decomposition and nitrification processes by facilitating closer contact of the decomposing microorganisms with the substrate organic matter in tilled fractions of the soil [53, 54]).

In summary, NT's role in soil C sequestration is not reflected in this study's measured C contents in different soil layers (Table 4). Exceptions are in the top 10 cm soil layer in 2019 and 2022, where measured C under NT was significantly higher than under CT. After 8 years of corn under NT versus CT treatments in the same plots, Anapalli, Reddy, and Jagadamma [31] also reported significantly lower ($p < 0.01$) C content in the 0–15 cm depth under NT when compared to CT.

Nitrogen content in the soil after crop harvest can mainly be attributed to the amount of N available through mineralization and other processes and its leaching losses to water that runs off or percolates beyond the root absorption zone of crops the soil [55, 56]. After the soybean harvest in 2019, the TN in the 0–20 cm soil depths was significantly higher under NT than in CT (Table 4). However, TN in the 20–30 cm soil layer under NT was comparable to CT ($p > 0.01$). In 2020, measurements showed that TN in the soil after harvest under NT was significantly less than CT (Table 4). Based on a meta-analysis of global nitrate leaching studies under various NT soil management, Li et al. [57] detected that the level of removal of N from the soil due to leaching depends on the soil organic matter and physical properties, climate, and other soil-water-crop management factors of the soil to which the study is compared. The more

Table 4: Comparison of bulk density (ρ), wet aggregate stability, field saturated hydraulic conductivity (K_{fs}), and total soil C and N at various depths in the soils sampled in no-till (NT) and conventional till (CT) plots.

Soil depth (cm)	Bulk density, ρ (g cm^{-3})		Aggregate stability (> 0.25 mm) (fraction)		K_{fs} (cm hr^{-1})		C (%)		% Change due to NT	N (%)	
	CT	NT	CT	NT	CT	NT	CT	NT	%	CT	NT
2019											
0–10	—	—	—	—	0.24^b	0.09^a	0.89^b	1.23^a	38	0.10^b	0.13^a
10–20	—	—	—	—	—	—	0.63^b	0.81^a	29	0.08^b	0.33^a
20–30	—	—	—	—	—	—	0.37^a	0.38^a	3	0.05^a	0.06^a
2020											
0–10	1.08 ± 0.05^b	1.25 ± 0.01^a	0.38 ± 0.01^a	0.41 ± 0.01^a	—	—	0.74^a	0.69^a	−7	0.08^a	0.06^b
10–20	1.48 ± 0.07^b	1.64 ± 0.03^a	0.38 ± 0.01^a	0.40 ± 0.02^a	—	—	0.58^a	0.38^b	−34	0.06^a	0.03^b
20–30	1.67 ± 0.10^a	1.70 ± 0.05^a	0.23 ± 0.01^a	0.22 ± 0.02^a	—	—	0.39^a	0.33^b	−15	0.05^a	0.02^b
2021											
0–10	1.24 ± 0.05^b	1.37 ± 0.04^a	0.39 ± 0.03^a	0.42 ± 0.03^a	—	—	0.77^a	0.73^a	−5	0.10^a	0.10^a
10–20	1.45 ± 0.02^b	1.56 ± 0.05^a	0.25 ± 0.03^a	0.23 ± 0.03^a	—	—	0.48^a	0.43^a	−10	0.07^a	0.06^a
20–30	1.61 ± 0.04^b	1.67 ± 0.09^b	0.18 ± 0.01^a	0.17 ± 0.01^a	—	—	0.37^a	0.42^a	14	0.05^a	0.06^a
2022											
0–10	1.35 ± 0.06^b	1.49 ± 0.01^a	0.43 ± 0.01^a	0.45 ± 0.01^a	0.29^b	0.09^a	0.66^b	0.73^a	11	0.09^a	0.11^a
10–20	1.53 ± 0.08^b	1.67 ± 0.02^a	0.24 ± 0.01^a	0.21 ± 0.02^a	—	—	0.44^a	0.46^a	5	0.06^a	0.06^a
20–30	1.60 ± 0.06^b	1.77 ± 0.04^a	0.12 ± 0.01^a	0.14 ± 0.01^a	—	—	0.37^a	0.42^a	14	0.05^a	0.06^a

Note: Samples were collected after harvesting soybeans each season.
[a] and [b] the same letter attached to data in both columns under NT and CT denote no significant difference between average data ($p > 0.05$), and different letters denote a significant difference ($p < 0.05$).

significant leaching from NT, thus less N available in the soil, was mainly attributed to more substantial drainage from untilled soils. Because of the negative charges of NO_3^- produced by the nitrification process, it cannot be quickly immobilized by adsorption by the soil particles and, hence, can be leached out of the soil through runoff of water inputs from rainfall or irrigation events. As such, one expects less N in CT than those maintained under NT [58]. Enhancement of N availability in soil layers with reduced leaching has also been reported in CT systems (e.g., [59]). These observations corroborate the statistically insignificant differences between the two tillage systems in N content in layers 0–30 cm that we observed in 2021 and 2022.

3.4. Effect of Tillage on Soil Aggregate Stability. Aggregate stability describes how strongly soil particles group together. This influences whether heavy rainfall will infiltrate into the soil column or run off a landscape, taking valuable nutrients dissolved in water that are detrimental to water quality [60]. Soil aggregates influence erosion, aeration, root growth, and plant nutrient uptake. As stated above, the soil in this study was under identical tillage management under corn for 11 years before starting the current experiment (NT vs. CT) under soybean. The investigation revealed that water-stable soil aggregate stabilities (> 0.25, > 0.5, > 1.0, and 2.0–4.0 mm aggregate classes) in soils under CT and NT in 0–30 cm depth were not statistically significant (Table 4).

The aggregate fraction in aggregate class > 0.25 mm in the three soil depths analyzed was between 0.23 and 0.38 under CT, 0.22 and 0.41 under NT in 2020, 0.18 and 0.39 under CT, and 0.17 and 0.42 under NT in 2021. In 2022, it varied between 0.12 and 0.43 under CT and 0.14 and 0.45 under NT. Though not statistically significant, the fraction stability in this class was slightly enhanced under NT compared to CT (Table 4). The location receives frequent rainfall as a characteristic of the humid climate [32] (Figure 1). The splash erosion caused by raindrops hitting soil particles may reduce aggregate stability in the silt loam soil at the location; however, this needs further investigation to ascertain [61]. Incorporation of a cover crop to serve as a cover for reducing raindrop impact in the soil can help the formation of wet-stable aggregates in the soil.

3.5. Soybean Growth: Phenology. Soybean seeds in the NT system were planted about 1.5 cm deeper than in the CT system. Phenology measurements were taken to investigate if the difference in planting depth and any other unknown environmental conditions that differed between the tillage treatments influenced the growth of soybean in the experiment. However, the number of days to seedling emergence was not substantially different between the two tillage systems (Table 3). Observed other phenological growth stages, as listed in Table 3, did not show any substantial differences between CT- and NT-managed soybean plants. The days from planting seeds to seedling emergence from the soil varied between 4 and 8 during the four crop seasons. The GDD computed with a base temperature of 10°C was between 75°C and 106°C d from planting to seedling emergence of the soybean variety AG45X8 planted in 2019 and 2020. It varied between 114°C and 141°C d for the AG45XFO variety planted in 2021 and 2022. The number of days the soybean plants took to reach physiological maturity was 117 d (GDD = 1767°C d) and 107 d (GDD = 1528°C d) for the variety AG45X8 in 2019 and 2020. In 2021 and 2022, the variety AG45XFO took 106 (GDD = 1662°C d) and 121 d (GDD = 1760°C d) (Table 3). The phenological measurements, along with other growth data collected in this experiment, can help in calibrating and simulating the soybean growth using dynamic cropping system models for developing decision support tools for managing the crop under varying interannual climate and longer-term climate change impacts on CT versus NT soybean production systems in the LMD environment [33, 34].

3.6. Effect of Tillage on Crop Growth: LAI. The LAI measured under CT versus NT during all four crop seasons (2019–2022) was not significantly different ($p > 0.01$) (Figures 2(a), 2(b), 2(c), and 2(d)). However, the LAI measured was slightly higher under CT than NT after the maximum growth of the plants was attained (about R7 stage) in two out of four years (2019 and 2020) (Figures 2(a) and 2(b)). During the same period in the 2021 crop season, LAI values under CT were slightly lower compared to NT (Figure 2(c)). However, in 2022, the LAI values across the tillage treatments were close to each other or coincided (Figure 2(d)). The maximum LAI measured was close to each other in 2019 (7.2 under NT vs. 7.4 under CT) and 2020 (6.9 under NT vs. 7.1 under CT). Nonetheless, in the 2021 season, the maximum LAI measured was lower under the CT (6.2) than under NT (6.5) (Figures 2(a) and 2(b)). In 2022, LAI measured was significantly higher ($p < 0.05$) under CT (7.8) compared to NT (7.0) (Figures 2(c) and 2(d)). Notwithstanding, the differences in LAI measured were minimal and did not affect seed yields under these treatments substantially, as presented below. Lasisi and Aluko [62] reported higher growth of soybean plants, number of leaves, and leaf area under CT soil management than NT in sandy loam soil in a tropical climate. Similarly, significant reductions in LAI with NT (deep tillage vs. shallow to NT) soil management were reported under corn [63]. ÖNTürk and Söğüt [64] also reported a significant reduction in measured LAI of soybean crops with NT in Turkey. As observed in our experiments, the LAI maximum for the optimum yield of soybean varieties in Brazil's subtropical climate was reported to be about 6.0 [65]. From this, it appears the crops raised in this experiment exceeded the optimum growth required for optimum yield.

3.7. Effect of Tillage on Crop Growth: Seed Yield and Economic Impact. In 2019, plant density measured in CT (220,000 plants m^{-2}) did not differ significantly ($p > 0.01$) from those measured under NT (240,000 plants m^{-2}). As every soybean plant produces multiple pods, plant density impacts harvested soybean yield substantially [66]. In NT-managed soils, chances of establishing poor plant stand due to

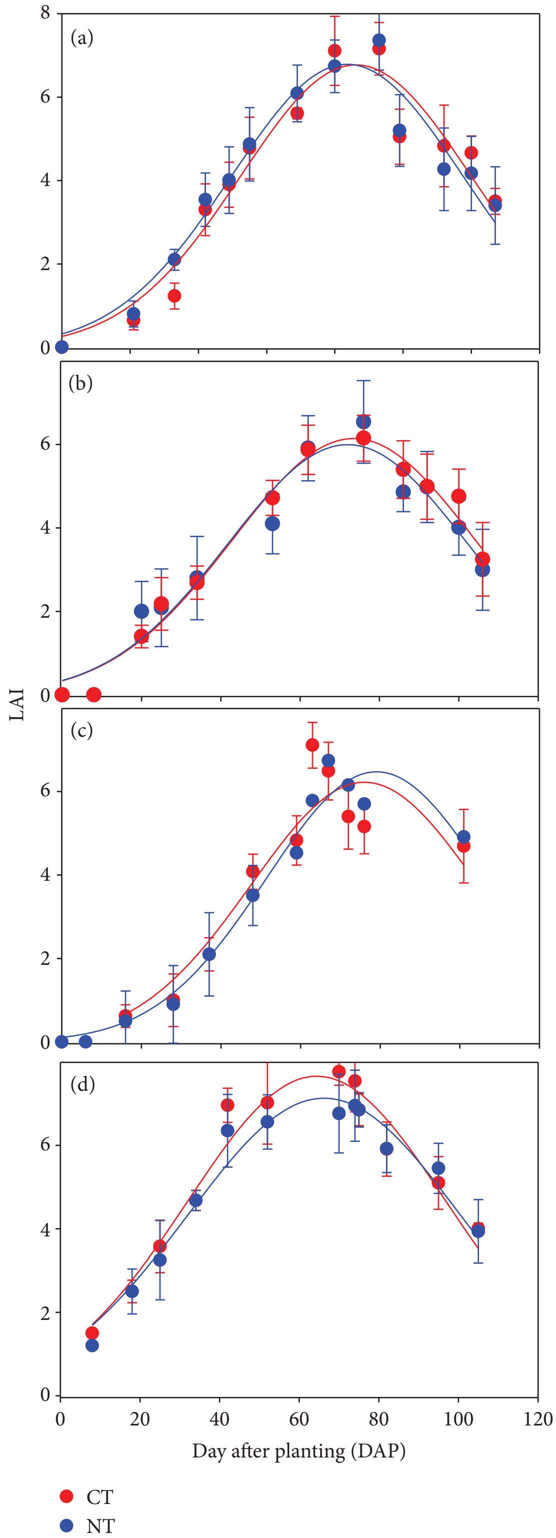

Figure 2: Soybean leaf area index (LAI) in 2019, 2020, 2021, and 2022 crop seasons. Circular symbols represent the measured data averaged across the replications, and the error bars represent one standard deviation from the mean. Blue (NT) and red (CT) continuous lines are polynomials fitted to the measured LAI data. (a) 2019, (b) 2020, (c) 2021, and (d) 2022.

slower seedling emergence from compacted soils were reported [67]. We did not have measurements of plant density in other years of the experiment; however, the measured values in 2019 strongly indicated that the slightly lower (insignificant) plant densities from NT were not a significant issue that impacted soybean productivity substantially.

Among the various conservation tillage practices, NT soil management generally has the highest potential for crop production with minimum disturbance to the soil–water–air environment, conserving those natural resources [22]. When conserving natural resources is critical in the socioeconomic arena, it is crucial to maintain or enhance seed yields commensurate with conventional agriculture to sustain profitability in crop production. Soybean harvest in the four years (2019–2022) averaged 5490 kg ha^{-1} (standard error, SE = 232 kg ha^{-1}) under CT and 5561 kg ha^{-1} (SE = 214 kg ha^{-1}) under NT (Figure 3). In summary, soybean harvested under NT was 1% higher than those harvested under the CT treatment. In 2021, soybean yields were lower than the other three years, yet yields were not significantly different between CT treatment (4808 kg ha^{-1}, SE = 92 kg ha^{-1}) and NT treatment (4753 kg ha^{-1}, SE = 179 kg ha^{-1}). Soybean seeds harvested in all 4 years under CT and NT were not significantly different ($p > 0.05$). There was no significant interaction between year and treatment ($p = 0.26$). While the maximum realized yield under CT (6085 kg ha^{-1}, SE = 238 kg ha^{-1}) and NT (6371 kg ha^{-1}, SE = 150 kg ha^{-1}) was obtained in 2019, the year immediately following the 11 year continuous corn production under similar tillage management scenario [31]. The yield enhancement in NT over CT was also the highest (5%) in 2019, while the yield difference due to tillage treatment in other crop seasons was between −2 and 1%. It is possible that the higher yield realized in 2019 was from a rotation effect on the soil microbiome but not investigated in this report, enhancing subsequent soybean yield return, as Neupane et al. [68] reported. Averaged across 4 years, the yield differences between NT and CT treatments were less than 1% (not significant $p > 0.05$) (Table 5). The finding aligns with observations in NT soybean production systems in the US corn belt, where tillage practices seldom reduced soybean yield returns significantly [69]. Pieta and Kesik [70] observed that one of the main reasons for the observed trend in NT soybean yield was increased beneficial microorganisms' growth in soils, especially the symbiotic N-fixing bacteria in the soybean plant roots; however, we have no measurements to show this effect in this study.

The cost of tillage operations under the two treatments is summarized in Table 2 and Figure 3. Under NT, there was a do-all tillage blade (https://www.nicholstillagetools.com) pass to level the crest of ridges for planting seeds and a middle row plowing using John Deere 886 regular cultivator (John Deere, Moline, IL), which consisted of a 25 cm wide single plow to clear the middle of rows for water flow during irrigations. With a total seasonal cost of 86 USD ha^{-1}, these tillages were necessary to maintain rows for surface

Table 5: Summary statistics for soybean yield response to tillage (CT vs. NT) and interactions with years from 2019 to 2022.

Year	CT	NT	*p* value
2019	$6085^{a} \pm 238$	$6371^{a} \pm 150$	0.17
2020	$5612^{a} \pm 144$	$5964^{a} \pm 107$	0.069
2021	$4808^{a} \pm 92$	$4753^{a} \pm 179$	0.52
2022	$5176^{a} \pm 276$	$5156^{a} \pm 331$	0.93
Mean	$5490^{a} \pm 232$	$5561^{a} \pm 214$	0.75
Trt. *year	—	—	0.26

Note: Trt. = treatment (CT and NT). Values after ± represent standard error.
[a] attached to mean data in columns under NT and CT denotes no significant difference ($p > 0.05$).

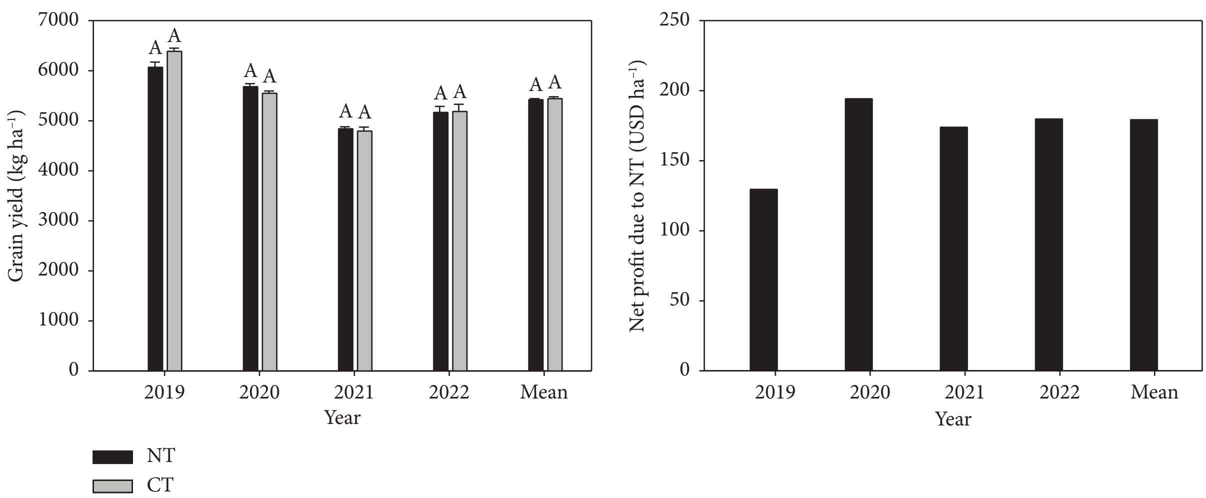

Figure 3: (a) Soybean yields in conventional till (CT) versus no-till (NT) treatments, 2019 to 2022, and (b) net profit from following NT compared to CT.

row irrigations in 2019 and 2020 but not in other years. The cost of tillage operations under CT was 183, 265, 183, and 173 USD ha^{-1}, respectively, from 2019 through 2022. Net profit from following NT over CT in the four years was 97, 178, 183, and 173 USD ha^{-1} (Figure 3). The 4-year mean profit from following NT over CT was 179 USD ha^{-1}. Though the harvested soybean seed yield did not differ significantly ($p > 0.05$) among treatments, due to the avoidance of costs otherwise incurred toward tillage operations, the NT can have an additional average profit margin of 179 USD (Table 2).

4. Conclusion

Developing production practices that conserve soil and water resources is critical in sustainable agriculture. Even after decades of research and adaptation, as reported in the literature, uncertainty still hovers around the transferability of conservation tillage research results and technology across varying soils and climates for reaping the benefits of crop husbandry with reduced soil disturbance. Therefore, in the Mississippi Delta region, adopting NT in farming systems, especially under soybean, has not gained sufficient momentum, irrespective of studies indicating the potential positive benefits of such systems over conventionally tilled systems. This study reported a farm-size investigation on the production and soil health benefits of growing soybeans under NT. This farm-scale investigation can help ease farmers' uncertainty associated with research results from small-plot studies when applied at the farm scale. The plots used in this study were under NT management for 11 years under corn before switching to soybean for the next 4 years of this study. All the soil-crop-water management practices adopted for CT and NT in this study were similar to those followed by soybean farmers in the region, except for the absence of tillage under the latter. The soil bulk density, STN,, and soil organic carbon (C) increased, and field-saturated hydraulic conductivity (K_{fs}) decreased with NT in the top 10 cm of soil under NT. However, wet-stable soil aggregates remained similar across the two tillage treatments. Averaged across four years of the study, soybean yield from NT was slightly higher than CT (5480 and 5440 kg ha^{-1}, respectively). The profit margin from avoidance of tillage under NT averaged over 4 years of the study was United States Dollar (USD) 179 ha^{-1}. The study revealed that following the NT system in the region can help farmers reap the natural resources conservation benefits of NT soil management while maintaining seed yield and cost savings from fuel and labor-associated soil-tillage operations. Caveats: (1) The study was conducted only in a "sandy loam" soil in the location's climate; the results may vary in other soils and climates at other locations. (2) The economic impact of following NT over CT in terms of net profit margin was computed following crop planning budgets published by the Department of Agricultural Economics, Mississippi State University in 2024, which are amenable to change from year to year based on many socioeconomic factors including crop prices; as such the net economic benefits can vary across crop seasons. (3) Results presented are based on soybean planted in single crop sequence; however, the results can vary if the crop is used in rotation with other crops. Future research should emphasize repeating the investigation at different locations, soils, and climates for comparison and developing recommendations tailored to location-specific problems. Long-term effects of NT on root and soil carbon dynamics, water movement and conservation, and insect-pest dynamics need also to be investigated and included in the recommendations.

Data Availability Statement

Data used in this study will be available on request.

Disclosure

An earlier version of this article has been presented at the American Society of Agronomy Annual Meeting 2023 (https://scisoc.confex.com/scisoc/2023am/meetingapp.cgi/Paper/148000).

Conflicts of Interest

The authors declare no conflicts of interest.

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General Statement

Mentioning a tradename, proprietary product, or specific equipment does not constitute a guarantee or warranty by the United States Department of Agriculture. It does not imply approval of the product to the exclusion of others that may be available.

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