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Assessing the effects of no-tillage with rye and mixed cover crops on soil water and nitrogen dynamics and soil carbon sequestration in semi-arid irrigated cotton production systems

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ABSTRACT

Amarillo fine sandy loam is a benchmark soil series in the Southern High Plains (SHP) of Texas, a region known for extensive cotton (*Gossypium hirsutum* L.) production. Its coarse texture affects the soil's ability to maintain soil organic carbon (SOC) and water storage, which is compounded by the semi-arid climatic conditions and lack of mulch cover to protect the soil from wind erosion. Soil conservation practices such as reduced/no-tillage (NT) and cover cropping are therefore recommended to sequester SOC, increase water storage, and reduce susceptibility to wind erosion. The objective of this study was to evaluate the long-term (1991–2020) effects of NT with cover crops on SHP cotton production systems using the DeNitrification-DeComposition (DNDC) model. Field data (2014–2020) from an experimental site near Lamesa, TX, USA, in the SHP region was used for model calibration and validation. The field experiment included three treatments: conventional tillage without a cover crop (CT, as control), no-till with rye (*Secale cereale* L.) cover (R-NT), and no-till with mixed cover (M-NT) including rye, hairy vetch (*Vicia villosa* Roth), radish (*Raphanus sativus* L.), and winter pea (*Pisum sativum* L.). The average percent error (PE) between the simulated and measured seed cotton yield was 2.1 % and −4.4 %, and 4.5 % and −8.8 % between the simulated and measured aboveground rye biomass during the calibration and validation, respectively. The 30-year long-term simulations showed that, on average, R-NT and M-NT increased SOC by 40.2 % and 59.2 %, and total nitrogen (TN) by 22.6 % and 25.8 %, respectively, compared to CT. Greater variability in yield and soil water was found under cover crop treatments compared to CT. Overall, the results from this study highlight the potential benefits of cover crops and NT on soil carbon sequestration and TN in semi-arid cotton production systems of the SHP without negatively affecting seed cotton yield.

1. Introduction

Soils in the Southern High Plains (SHP) of Texas are vulnerable to degradation, and they are not favorable for soil organic carbon (SOC) sequestration because of several factors including low water holding capacity due to coarse texture, a semi-arid environment with limited rainfall and extreme temperatures during the summer growing season, limited residue retention due to intensive cotton production and elevated decomposition rates, and exposure of soil to erosion due to reduced residue cover with conventional tillage (CT) practices (Bronson et al., 2004; Haq Husein et al., 2021; Mauget et al., 2021). Soil water storage can be improved, and erosion be reduced with the adoption of soil conservation practices such as conservation/no-tillage (NT) and cover cropping (Burke et al., 2021; 2022; Follett, 2001; Bordovsky et al., 1994; Keeling et al., 1989). These practices, which provide residue cover, can reduce evaporation losses and susceptibility to wind and water erosion (Colazo and Buschiazzo, 2010; Lascano and Baumhardt, 1996). In semi-arid environments, where irrigation water is used to overcome soil moisture deficiency, conservation tillage/NT and cover crops could help improve soil water use efficiency (Lewis et al., 2018).

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For example, Baumhardt et al. (2013) observed an increase in soil water storage with NT compared to conventional disc tilled system in a dryland cotton (*Gossypium hirsutum L.*) production system near Bushland, TX. In addition, Mauget et al. (2021) reported notable increase in SOC following the adoption of NT and winter cover cropping, which resulted in significant improvement in soil water retention in benchmark sandy soils of SHP. Furthermore, Burke et al. (2021) found that decreases in soil water during cotton growth were less severe following cover crops in an irrigated cotton production system at Lamesa in the SHP region based on a three-year study. Himanshu et al. (2022) have also found that cover crops did not impact cotton yields at Chillicothe in the neighboring Texas Rolling Plains region based on a simulation study. The above two studies reported that although cover crops reduced soil water prior to their termination, soil water was replenished by spring rainfall and/or deficit irrigation before planting cotton.

Several other researchers have found and discussed positive impacts of NT and cover crops in semi-arid cotton production systems. For instance, Mutchler et al. (1985) found that adopting NT in cotton production systems reduced overall erosion by 47 % and increased seed cotton yield by 20 % compared with CT cotton in a field experiment on a silt loam soil in Mississippi. Harman et al. (1989) found that NT increased overall soil water storage by 45 mm, thereby increasing lint yield by 110 kg ha^{-1} as compared to CT in a cotton-barley (*Hordeum vulgare* L.) double crop production system of the Central Texas High Plains. In another study in the sandy soils of Alabama (Touchton et al., 1984), cover crops such as crimson clover (*Trifolium incarnatum*) and hairy vetch (*Vicia villosa* Roth), were found to supply enough nitrogen (N) for achieving maximum lint yields. In addition, organic materials returned with cover crops can stimulate microbial activity and lead to SOC accumulation (Fu et al., 2017; Singh et al., 2020). Although the adoption of cover crops has some proven benefits, there are still concerns about excessive soil water use by cover crops and subsequent reduction in soil water availability for summer cash crops in some semi-arid regions such as the Texas Rolling Plains (DeLaune and Mubvumba, 2020). In addition, some studies have found that adopting conservation management practices in semi-arid regions tends to reduce cash crop yield (Lewis et al., 2018; Halvorson et al., 2019). More specifically, Lewis et al. (2018) found a significant reduction in cotton lint yield following a rye (*Secale cereale* L.) cover crop compared to cotton grown under a conventional till monoculture system in two out of three years at Lamesa, Texas.

The importance of understanding the long-term effects of conservation practices on SOC accumulation, soil N dynamics, and soil water use in semi-arid agroecosystems cannot be understated. Most cover crop and conservation tillage studies in the SHP region are limited-year field studies that provided limited insights into the benefits and challenges of adopting these practices. Studies evaluating the long-term effects of NT and cover crop production on soil water availability and soil carbon (C) sequestration are still lacking for the SHP region. More specifically, C and N dynamics, along with biogeochemical process rates (e.g., N mineralization and assimilation), in cover crop-based cotton production systems in semi-arid regions remain under-researched. This study addresses this important knowledge gap. Although conducting long-term field studies is the most viable approach for a clear understanding of the effects of cover crops on cotton production systems, it is labor-intensive and costly. Developing recommendations from these field studies alone could also take several years. Using biogeochemical models to assess the long-term effects of NT and cover crops can be a reliable complementary approach to field experiments. Modeling is relatively inexpensive, and it allows the establishment of several hypothetical experiments to answer various "what if" questions and provide recommendations in a much shorter period (Malik et al., 2018). In addition, models provide valuable insights into water, C, and N balances in cropping systems—insights that are often difficult to obtain through field experiments alone. However, the reliability of these models depends heavily on thorough evaluation using measured data from field studies.

Several ecosystem models such as DAYCENT (Parton et al., 1998; DelGrosso et al., 2005), DeNitrification-DeComposition (DNDC) model (Li et al., 1994), Ecosys (Grant , 1998), and the Environmental Policy Integrated Climate (EPIC) model (Wang et al., 2012) have been widely used to assess the potential long-term impacts of cropping systems, tillage, and fertilizer management practices on crop yields, and soil and water quality. These models vary in their approach to modeling soil processes under different management practices. The DNDC biogeochemical model was selected for this study because of its ability to accurately simulate C and N dynamics in cropping systems (Singh et al., 2022, Zhang et al., 2016b). Studies have discussed and shown that the DNDC model can simulate and provide insights to better understand and describe crop photosynthetic processes, soil respiration, C assimilation and allocation, leaf area index, root processes, and N uptake in relation to water balance and N stresses (Shi et al., 2018; Li et al., 2016). These unique features of the DNDC make it a great tool to assess the effects of conservation management practices on soil water, soil N dynamics, and soil C sequestration.

The overall goal of this study was to assess the long-term (1991–2000) effects of NT with rye and mixed species cover crops on soil water and N dynamics and SOC sequestration in the semi-arid SHP cotton production systems using the DNDC model. The specific objectives were to: i) evaluate the performance of the DNDC model in predicting seed cotton yield, cover crop herbage mass, SOC, total nitrogen (TN), and soil water using measured data from the cover crop experiments at Lamesa, TX in the SHP region, and ii) assess the long-term effects of cover crops and NT on soil water use, seed cotton yield, SOC, and TN using the evaluated DNDC model. We hypothesized that the conversion of SHP cotton agroecosystems from traditional CT to NT with cover crops would improve both SOC and TN, but reduce overall soil water available for cotton growth, thereby leading to a decline in cotton yields.

2. Materials and methods

2.1. Study area

This study was conducted at the Agricultural Complex for Advanced Research and Extension Systems (Ag-CARES) located near Lamesa, TX, USA (32°46′ N, 101°56′ W) in the SHP region. The soil at this location is classified as an Amarillo fine sandy loam (*fine-loamy, mixed, superactive, thermic Aridic Paleustalfs*) (Web Soil Survey, 2024). The climate at Lamesa is semi-arid (average annual maximum and minimum temperature of 25 °C and 8 °C, respectively), with June and September being the months with the most rainfall. The average annual rainfall and snowfall at Lamesa is 48.6 cm and 10.2 cm, respectively (US Climate Data, 2023). Cotton, sorghum (*Sorghum bicolor*), corn (*Zea mays*), and winter wheat (*Triticum aestivum* L.) are major crops produced in the region. Due to limited precipitation, about half of the cotton acres in this region are irrigated with water from the Ogallala Aquifer (Burke et al., 2021).

A long-term cover crop experiment was initiated in a continuous cotton system at the Ag-CARES facility in 1998 (Burke et al., 2021) and the measured data from this experiment from 2014 to 2020 was used for the DNDC model evaluation in this study. Prior to the initiation of the cover crop study, the field site was under continuous cotton production with conventional tillage and winter fallow (1948–1998). The field experiment includes three continuous cotton treatments: 1) conventional till (CT) and winter fallow without a cover crop; 2) no-till with rye winter cover crop (R-NT); and 3) no-till with mixed species winter cover crop (M-NT). The mixed cover crop species include hairy vetch, winter pea (*Pisum sativum* L.), radish, and rye. Both cover crop treatments were seeded at 34 kg ha^{-1} with the mixed species cover crop consisting of 50 % rye, 33 % Austrian winter pea, 10 % hairy vetch, and 7 % radish, by weight. While the CT and R-NT treatments were established in 1998, the

Table 1
Details of crop management activities in field experiment at the study site from 2014 to 2020.

Management Practice	2014/2015	2015/2016	2016/2017	2017/2018	2018/2019	2019/2020
Cover Crop						
Planting date	12/2/14[*]	11/4/15	12/12/16	11/17/17	12/4/18	11/21/19
Termination date	4/10/15	3/11/16	4/3/17	3/27/18	4/9/19	3/27/20
Cotton						
Planting date	5/13/15	5/24/16	5/12/17	5/15/18	5/19/19	5/18/20
Harvest date	10/28/15	11/22/16	11/7/17	11/19/18	10/28/19	10/31/20
N fertilization ($kg\ ha^{-1}$)	58	57	58	46	58	58
Irrigation (mm)	180	155	201	295	274	290

[*] Dates are shown as mm/dd/yy.

Table 2
Details of tillage dates and methods adopted for conventional till plots at the study site from 2014 to 2020.

2014/15 growing season		2016/17 growing season		2018/19 growing season	
3/23/2015	Harrow	1/10/2017	Shredded stalks	4/8/2019	Harrow
4/30/2015	Rod Weeder	3/22/2017	Harrow	5/17/2019	Rod Weeder
5/12/2015	Bedding	4/10/2017	Harrow	5/16/2019	Bedding
6/16/2015	In-season till	4/10/2017	Rolling cultivator	6/17/2019	In-season till
6/26/2015	Sweeps	4/27/2017	Rod weeder	7/17/2019	In-season till
8/5/2015	In-season till	6/16/2017	In-season till	10/29/2019	Shredding
10/29/2015	Shredding	7/7/2017	In-season till	10/30/2019	Chisel plow
10/30/2015	Chisel plow	11/8/2017	Shredding		
		11/9/2017	Chisel plow		
2015/16 growing season		**2017/18 growing season**		**2019/20 growing season**	
3/11/2016	Harrow	3/27/2018	Harrow	3/27/2020	Harrow
5/22/2016	Rod Weeder	5/13/2018	Rod Weeder	5/16/2020	Rod Weeder
5/23/2016	Bedding	5/14/2018	Bedding	5/17/2020	Bedding
7/16/2016	In-season till	6/22/2018	In-season till	6/17/2019	In-season till
7/21/2016	In-season till	7/20/2018	In-season till	7/17/2020	In-season till
11/23/2016	Shredding	11/20/2018	Shredding	11/1/2020	Shredding
11/24/2016	Chisel plow	11/21/2018	Chisel plow	11/2/2020	Chisel plow

M-NT treatment was established in 2014 by seeding mixed species cover crops into 16 of the 32 rows of the rye cover crop plots. The cropping system management in this experiment was described in detail in Lewis et al. (2018) and Burke et al. (2021). Irrigation was applied primarily for cotton growth through a low-energy precision application center-pivot irrigation system and irrigation was not applied for cover crop growth.

2.2. *DNDC model*

The DNDC model is a process-based biogeochemical model that links ecological drivers, soil environmental factors, and biogeochemical processes for simulating soil C and N dynamics (Li et al., 1994). It consists of two components: 1) soil, climate, crop growth, and decomposition sub-models that simulate soil temperature, moisture, pH, and redox potential; and 2) nitrification, denitrification, and fermentation sub-models that predict microbial activity and gas emissions from the soil environment. The required input parameters for the DNDC model are related to climate (rainfall, air temperature, solar radiation), soil (physical and chemical properties), and cropping system and farming management practices. Model outputs include C and N assimilation in the plant, SOC, and soil organic nitrogen contents, crop N uptake, NO_3–N leaching, N runoff, ammonia (NH_3) volatilization, and nitrous oxide (N_2O) emissions. In this study, DNDC 9.5.3 v.CAN (https://github.com/BrianBGrant/DNDCv.CAN) was utilized.

2.3. *Model input data*

2.3.1. *Weather data and crop management data*

Historical weather data required for the model simulations were obtained from the onsite weather station and nearby West Texas Mesonet (Schroeder et al., 2005) and National Oceanic and Atmospheric Administration (NOAA) weather stations. Weather data obtained included precipitation (cm), maximum and minimum air temperature (°C), relative humidity (%), and solar radiation ($MJ\ m^{-2}$). Crop management data necessary to parameterize the model and run long-term simulations were identified based on the practices followed in the field experiment at the study site. Measured data from the field experiment from 2014 to 2020 was reported in Lewis et al. (2018) and Burke et al. (2021); (2022). Information on crop management and tillage used in this study are summarized in Table 1 and Table 2, respectively.

The measured data utilized for model calibration and validation included seed cotton yield; cover crop biomass, N uptake, and C/N ratios prior to termination; SOC, TN, nitrate-nitrogen (NO_3-N) of soil samples collected following cover crop termination each year in early April to a depth of 60 cm; SOC and inorganic-N measured every month (from April 2016 to May 2017) from soil samples collected at 0–15 cm; and soil water monitored to a depth of 140 cm in 20-cm increments.

2.3.2. *Soil Data*

Development of soil input files involved the use of soil data from field measurements and soil sample analysis (Lewis et al., 2018; Burke et al., 2019) and extracting general soil information from the Soil Survey operated by the United States Department of Agriculture - Natural

Table 3
Soil physical and hydraulic properties at the study site.

Depth (cm)	BD ($g\ cm^{-3}$)	SOC ($g\ kg^{-1}$)	pH	FC (wfps)	WP (wfps)	Porosity	K_{sat} ($m\ h^{-1}$)	Clay %
0–15	1.58	2.61	7.9	0.28	0.106	0.404	0.0625	0.07
15–30	1.59	2.50	8.2	0.296	0.137	0.402	0.0565	0.09
30–45	1.58	2.52	8.1	0.34	0.171	0.403	0.046	0.11
45–60	1.56	2.55	8.4	0.34	0.171	0.403	0.046	0.11
60–80	1.59	1.38	8.2	0.399	0.17	0.401	0.0456	0.11
80–100	1.59	1.51	8.2	0.399	0.17	0.401	0.0456	0.11

BD: bulk density; SOC: soil organic carbon; K_{sat}: saturated hydraulic conductivity; FC: field capacity; WP: wilting point; wfps: water fille pore space

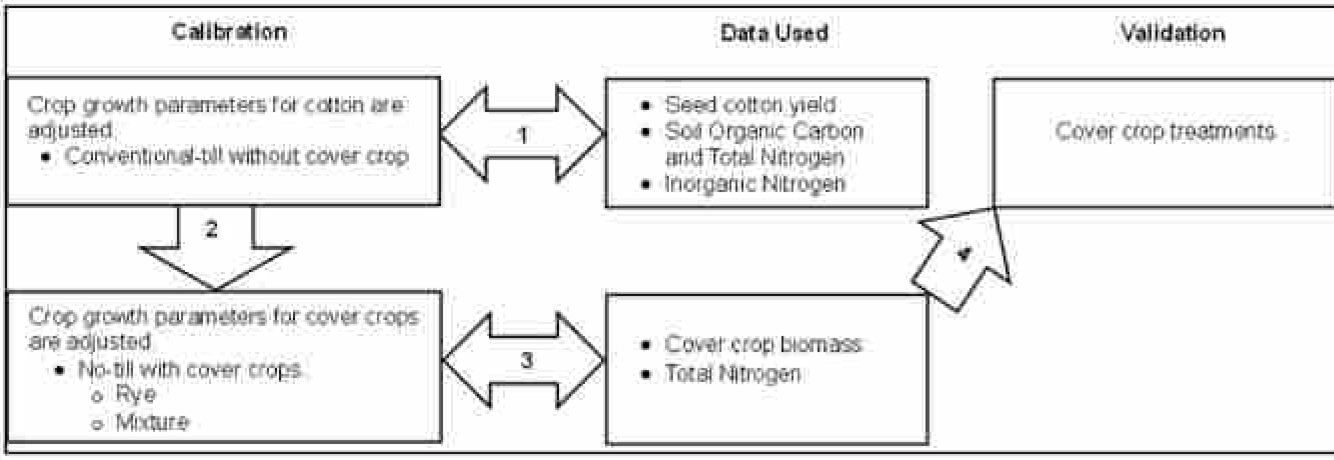

Fig. 1. Flowchart depicting the DNDC model calibration and validation process.

Table 4
Parameters adjusted during the DNDC model calibration.

Crop Parameters	Default Values			Calibrated Values		
	Cotton	Rye	Mixture	Cotton	Rye	Mixture
Grain fraction	0.32	0.34	0.01	0.32	0.01	0.01
Leaf fraction	0.26	0.25	0.40	0.26	0.42	0.3
Stem fraction	0.26	0.25	0.40	0.26	0.42	0.3
Root fraction	0.16	0.16	0.19	0.16	0.15	0.39
Grain C:N ratio	10	22	15	25	20	28
Leaf C:N ratio	45	65	25	25	65	28
Stem C:N ratio	45	65	25	55	65	28
Root C:N ratio	75	50	30	75	50	62
Thermal degree days (base 0 oC)	2500	2000	1300	3900	2000	2100
Water demand (g water g−1 DM)	400	200	300	500	250	200
N fixation index (Crop N/N from soil)	0	0	0	0	0	0.5
Optimum temperature (oC)	25	25	25	25	22	20
Maximum root length (m)	NA	1.5	1.5	1.3	2	2
Root density shape function	NA	5	5	3	5	5
Leaf area index (LAI) maximum	NA	2.5	2.5	3	2.5	2.5

Initial Soil Parameters	Default Values	Calibrated Values
Litter: Humads: Humus fraction	0.01:0.09:0.90	0.07:0.14:0.79
Bulk soil C:N ratio	10	4.421
Bypass flow rate	0	0.7
Field slope	0	0.29
Runoff curve number	NA	75
Manning's coefficient	NA	0.12/0.19

NA: Not Applicable.

Resources Conservation Service (NRCS). Important soil data obtained from the on-site soil sample analysis between July 2016 and May 2017 include the percentages of clay, silt, sand and organic C, total N, pH, and bulk density (Table 3). Additional soil properties such as the soil water content at field capacity and wilting point, saturated hydraulic conductivity, and cation exchange capacity were obtained from Soil Survey (Web Soil Survey, 2024). The depth of the soil profile used in the model was 200 cm. Field soil samples were not collected below 100 cm at the site, and therefore the values from 80 to 100 cm layer were extended to 200 cm during the model setup.

2.4. Model evaluation

The DNDC model was initialized using the local weather data, soil properties, and crop and tillage management information. Model evaluation for each variable was accomplished based on data availability. The model calibration was performed by initially adjusting input parameters related to cotton growth characteristics (e.g., maximum biomass production, biomass fraction, biomass C/N ratio, thermal degree days [TDD], water demand, optimum temperature, and leaf area index [LAI]) to get a good match between measured and simulated seed cotton yield, SOC, and TN under the CT treatment from 2015 to 2020 (2015–2019 for SOC) (Fig. 1). Next, with the cotton parameters set at the calibrated values, cover crop parameters (maximum biomass production and biomass fraction) were adjusted to get a good match between the observed and simulated cover crop biomass for the M-NT and R-NT treatments. Growing seasons from 2015 to 2017 were chosen for biomass calibration.

Model validation for seed cotton yield, TN, and SOC was done by comparing measured and simulated seed cotton yield, TN, and SOC under the M-NT and R-NT treatments from 2015 to 2020 (2015–2019 for SOC). For cover crop biomass, the DNDC validation was achieved by comparing measured and simulated biomass from the 2018–2020 growing seasons for both the R-NT and M-NT treatments. An accurate simulation of crop biomass is very important to accurately simulate SOC and TN dynamics, and hence, SOC and TN values were consistently checked throughout this calibration process.

The crop and soil parameters related to water balances, such as crop water demand, TDD, hydraulic conductivity, and LAI were then adjusted until simulated soil water matched well with the measured soil water. The soil field capacity and wilting point were also slightly adjusted following regional USGS soil survey reports. The model was calibrated for soil water using field data from the CT treatment and validated using data from the M-NT and R-NT treatments, all covering the period from 2017 to 2020.

The model performance during the calibration and validation was

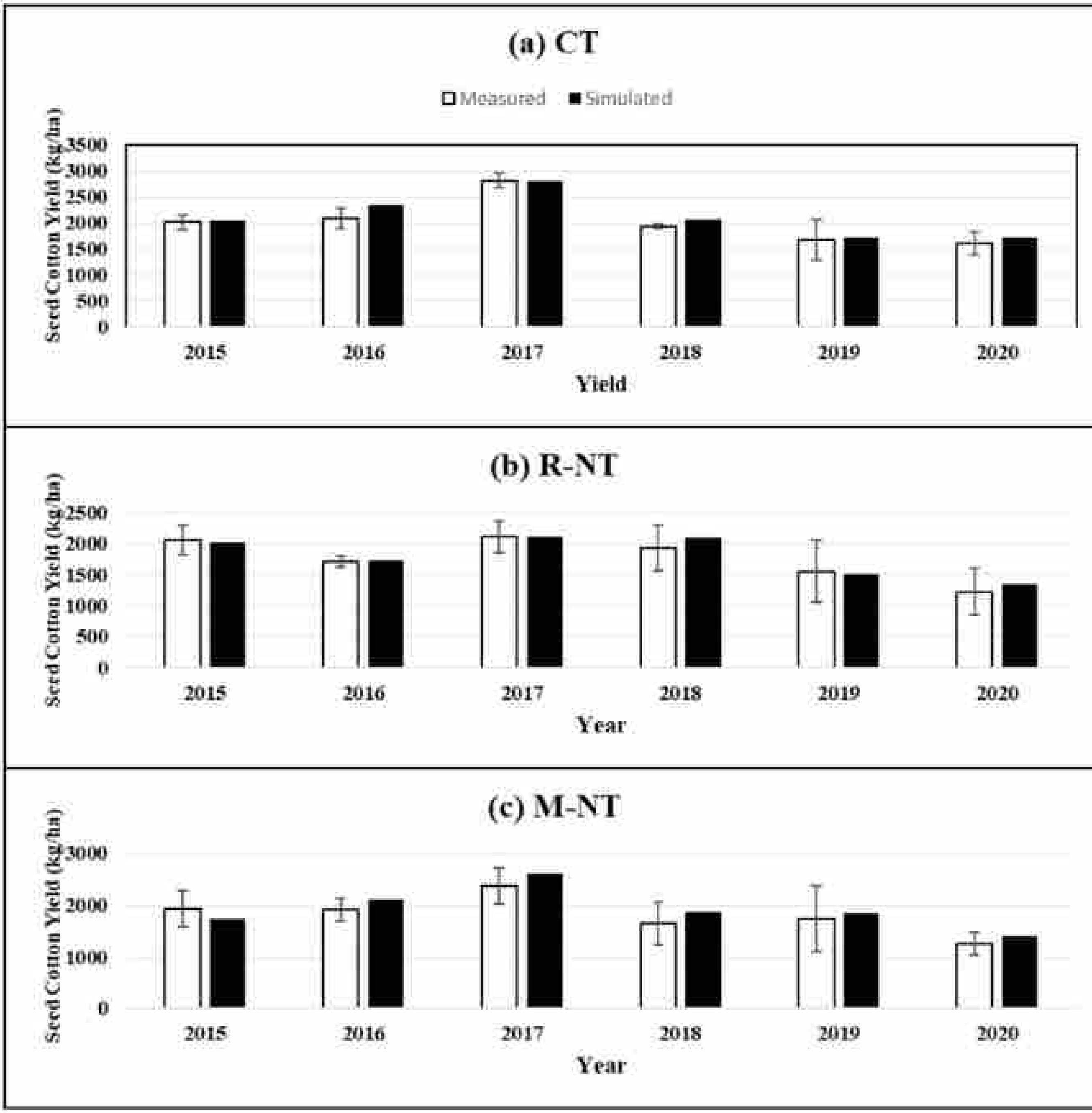

Fig. 2. Comparison of simulated and measured seed cotton yield during (a) the model calibration (CT - Conventional tillage treatment) and (b & c) evaluation [R-NT (No-tillage with rye) and M-NT (No-tillage with mixed cover crop]. Error bars represent the standard error of the sample mean.

assessed using statistics such as the coefficient of determination (R^2), root mean squared error (RMSE), percent error (PE), d-statistic and Nash-Sutcliffe model efficiency (NSE; for soil water evaluation only). These model performance statistics were computed using the equations described in Singh et al. (2022) and other published literature. In this study, model performance was considered satisfactory if $d \geq 0.75$ (Singh et al., 2022; Yang et al., 2014) and PE less than 20 %.

2.5. Simulation of the long-term effects of winter cover crops and no-tillage

Long-term simulations were run with the evaluated model for 37 years (1984–2020, by considering the first 7 years as the warm-up period) and the effects of rye and mixed species winter cover crops and NT on seed cotton yield, soil water use, SOC, and TN were evaluated. The warm-up period was included prior to the long-term simulation period to stabilize the soil C and N pools, and partition SOC pools (litter, active humus [humads], and passive humus) appropriately so that the simulated SOC and TN at the beginning of the long-term simulation period match closely with the observed data.

The information related to crop, tillage, and farming management practices was input based on the practices followed in the field experiments at Lamesa and the typical practices followed in the SHP cotton production systems for both warm-up (1984–1990) and assessment (1991–2020) periods. Only difference was that the CT was simulated as the baseline practice for all three treatments (CT, R-NT and M-NT)

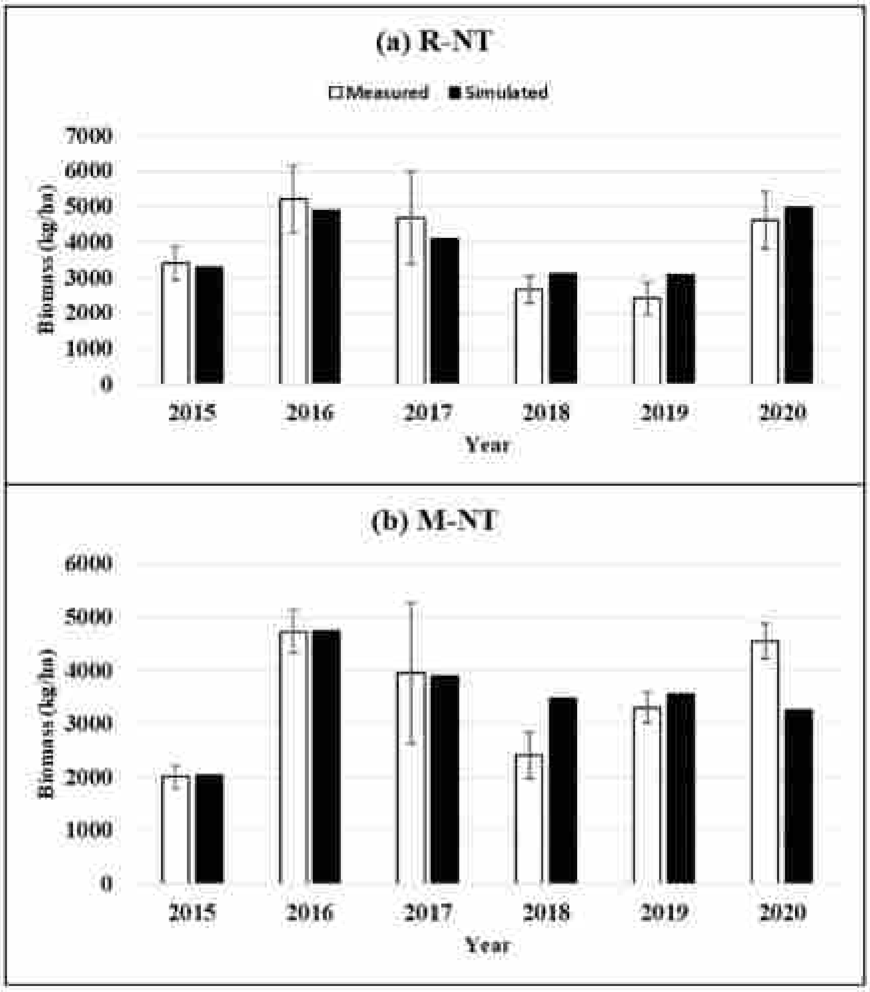

Fig. 3. Comparison of simulated and measured cover crop biomass during the model calibration (2015–2017) and validation (2018–2020) periods for (a) R-NT (No-tillage with rye cover crop) and (b) M-NT (No-tillage with mixed cover crop) treatments. Error bars represent the standard error of the sample mean.

Table 5
Model performance statistics during the DNDC model evaluation for different variables.

Variable	Model calibration				Model evaluation			
	R^2 *	RMSE (kg ha^{-1})	d-index	PE (%)	R^2	RMSE (kg ha^{-1})	d-index	PE (%)
Seed cotton yield	0.96	89.8	0.98	2.1	0.86	159.5	0.95	−4.44
Soil Organic Carbon	0.89	757	0.95	0.2	0.77	1103	0.87	−1.8
Total Nitrogen	0.73	177.6	0.92	1.91	0.70	542.4	0.87	2.6
Cover crop biomass	0.96	282.2	0.98	4.5	0.83	314.5	0.89	−8.8
Soil water	0.41	30.0**	0.79	3.2	0.26	26.2	0.71	−0.41

* R^2 – co-efficient of determination; RMSE – root mean square error; PE-percent error.
** RMSE unit for soil water is mm

during the warm-up period as was done in other DNDC studies (Singh et al., 2022, 2023). Cotton was planted on May 28 and harvested on November 7 each year. Cover crops were planted on December 2 each year and terminated on March 25 of the following year. About 30 kg ha^{-1} of nitrate-N and 30 kg ha^{-1} of Ammonium-N were applied on July 16 each year to meet the N requirement of cotton crop. To ensure a consistent supply of soil moisture and minimize moisture stress, auto irrigation was set up for cotton at 66 % ET-replacement level to closely represent the seasonal irrigation amount applied in the field experiment. This was done by setting the DNDC model irrigation threshold index to 0.66. For CT treatment, tillage was simulated to 10 cm depth using a moldboard plow. For NT treatments, no-till drill use was simulated to plant cover crop seeds. Suggestions on soil health benefits, such as soil C sequestration and increases in total N associated with the adoption of cover crops, were provided based on the analysis of results from long-term simulations.

3. Results and discussion

3.1. Model calibration and validation

3.1.1. Seed cotton yield and cover crop biomass

The parameters adjusted during the DNDC model calibration are presented in Table 4. Overall, seed cotton yield and cover crop biomass were simulated well in most years, as shown in Figs. 2 and 3, and as indicated by the model performance statistics (Table 5). The simulated

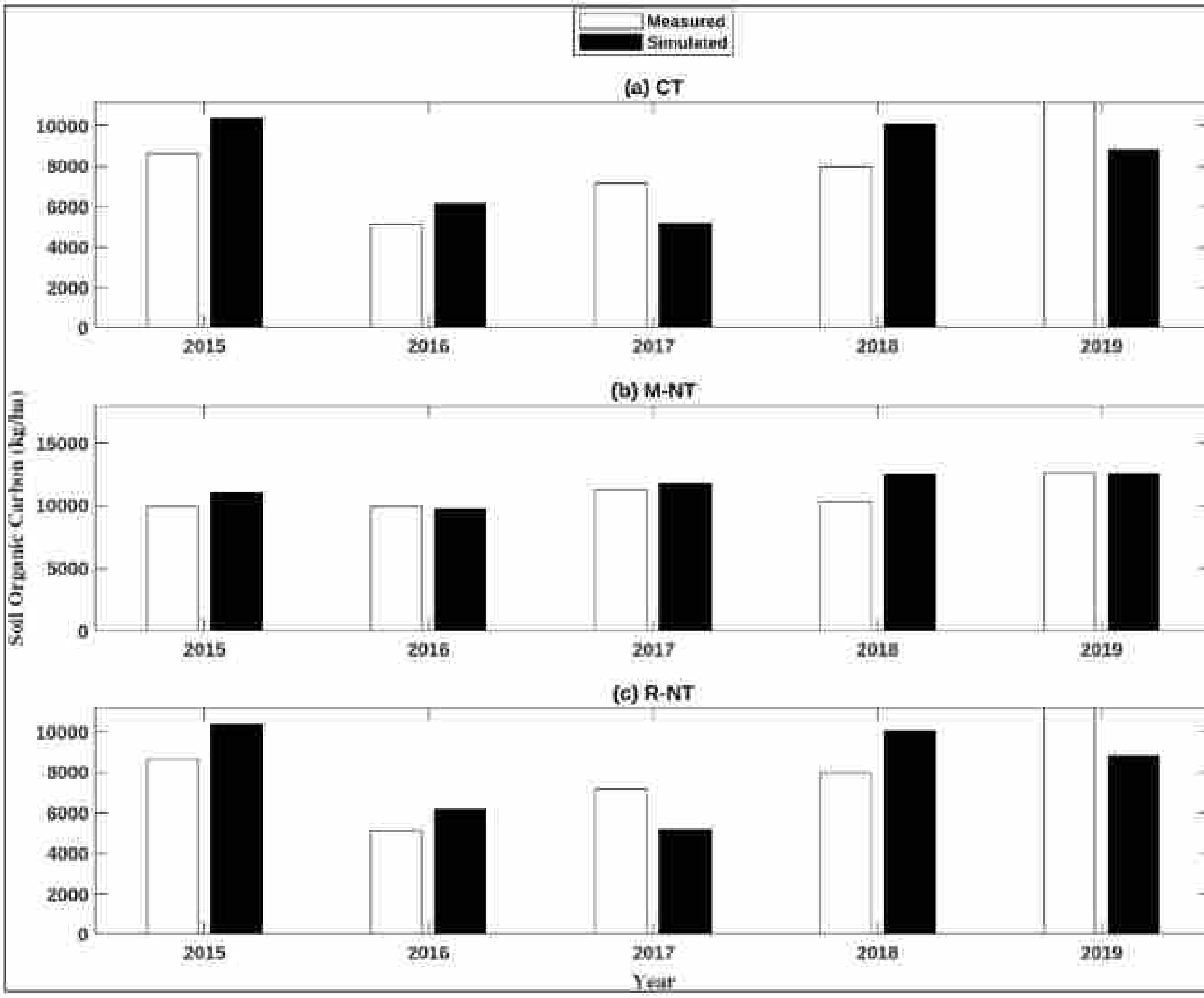

Fig. 4. Comparison of simulated and measured soil organic carbon at 0–30 cm depth during (a) the model calibration (CT – Conventional tillage treatment) and (b & c)evaluation [R-NT (No-tillage with rye cover crop) and M-NT (No-tillage with mixed cover crop)].

seed cotton yield during both calibration and validation fell within the range (mean ± standard deviation) of the measured values (Fig. 2). For seed cotton yield calibration, the d-index, RMSE, R^2, and PE values were 0.98, 89.3 kg ha^{-1}, 0.98, and 2.1 %, respectively (Table 5). For biomass calibration, R^2 of 0.96, d-index of 0.98, RMSE of 282.2 kg ha^{-1}, and PE of 4.5 % were achieved. These model performance statistics are comparable to other published DNDC modeling studies (Abdalla et al., 2020; Xu et al., 2018; Singh et al., 2022; Zhang et al., 2019).

The model performance during the cover crop biomass validation, although satisfactory, was not as good as that during biomass calibration (R^2: 0.83, d-index: 0.89, RMSE: 514.5 kg ha^{-1}, and PE: −8.8 %), mainly due to substantial overprediction and underprediction of mixed cover crop biomass during the 2018 and 2020 growing seasons, respectively (Fig. 3). Simulated mixed cover crop biomass during these two growing seasons was out of the range of the measured biomass values. Poor biomass prediction in these years could be attributed to some of the limitations of DNDC's crop growth sub-model. The crop growth sub-model (Li et al., 1992) was introduced in later versions of the DNDC model, and it still undergoes modifications to improve the simulation of crop growth and water balances (Zhang and Niu, 2016b). Differences between the actual and recommended planting dates could have also contributed to poor biomass prediction. For instance, according to Burke et al. (2021), during the 2018 growing season, all cover crops were seeded in early December to avoid the first freeze kill. For the M-NT treatment, which contained legumes, the recommended planting date was about 6–8 weeks prior to the actual planting date. Burke et al. (2021) present that the late planting likely limited the growth of legumes under the M-NT thereby leading to overall lower cover crop herbage mass production in 2018. The DNDC model likely did not capture the effects of late planting of legumes under the M-NT on biomass production well, thereby leading to higher predicted herbage biomass compared to the measured biomass at the site. Overall, the model performance statistics over the entire calibration and validation periods were satisfactory and supported the model's ability to accurately simulate long-term trends in seed cotton yield and cover crop biomass.

3.1.2. Soil organic carbon and total nitrogen

An acceptable match between simulated and measured SOC was achieved during the model calibration (CT treatment) and validation (cover crop treatments) (Fig. 4; Table 5). For calibration, the PE was 0.2 %, the d-index was 0.95, and the R^2 was 0.89. The model performance was good during the validation, as indicated by related model performance statistics of R^2 (0.77) and d-index (0.87), further increasing our confidence in the model's ability to accurately predict SOC. Past

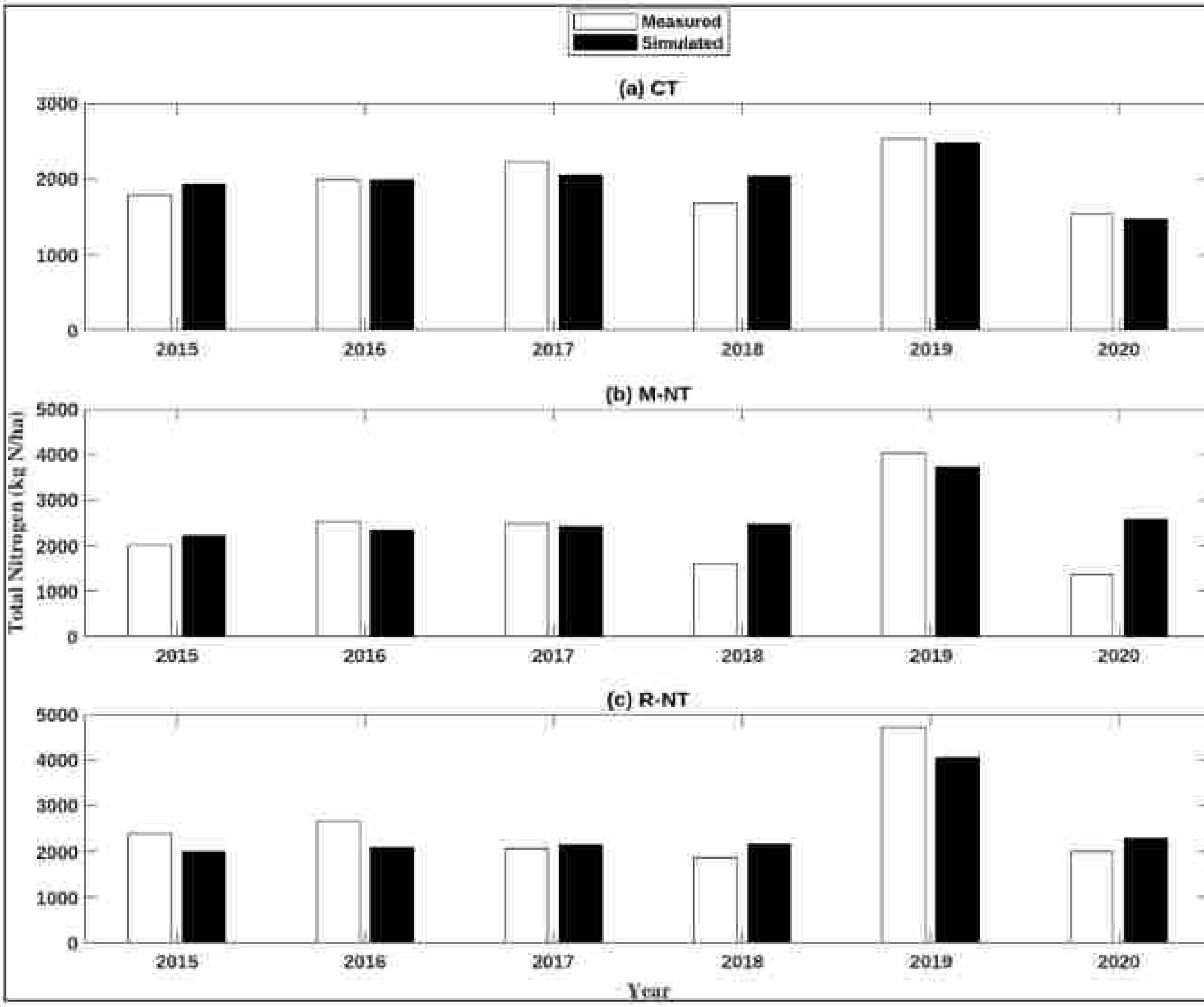

Fig. 5. Comparison of simulated and measured total nitrogen at 0–30 cm depth during (a) the model calibration (CT – Conventional tillage treatment) and (b & c) evaluation [R-NT (No-tillage with rye cover crop) and M-NT (No-tillage with mixed cover crop)].

studies have also reported the DNDC model's strength in accurately predicting SOC (e.g., Li et al., 2016; Zhang et al., 2017). The model's capability to simulate TN was acceptable (Fig. 5). Although the model overpredicted TN in some cases (e.g., 2018 and M-NT and R-NT treatments in 2020) and underpredicted in some other cases (e.g., M-NT and R-NT treatments in 2019), the overall model performance statistics fell within the acceptable ranges. These results are comparable to those of Singh et al. (2022) (R^2 ranged from 0.7 to 0.73, d index from 0.87 to 0.92, and PE from −6.6–1.9 %) for a DNDC study in the neighboring Texas Rolling Plains region.

Singh et al. (2022) also discussed the challenges associated with the DNDC model calibration for TN. Some of the reasons, such as structural uncertainty in the model, could justify the discrepancies between simulated and measured TN values found in this study. The DNDC model is designed to turn over soil daily N from added crop residues (and other sources, including synthetic fertilizers and N deposition) in multi-cropping systems (Abdalla et al., 2020), and some studies (e.g., Behnke et al., 2018) suggested improving related algorithms to improve the model's performance in simulating daily soil N. Other factors, such as measurement or sampling errors and limitations in data availability (Boote et al., 2016; Kersebaum et al., 2015) could have also contributed to the simulated disparities (Seidel et al., 2018).

3.1.3. Soil water

The DNDC model simulated soil water under different treatments fairly well as indicated by the model performance statistics (Table 5) and as shown in Fig. 6. For soil water calibration and validation, the d-indices were 0.79 and 0.71 and the PEs were 3.2 % and 0.41 %, respectively. Although low, the positive values of PE reported in this study show that the DNDC model underpredicted soil water content for the most part. The d-indices reported in this study are slightly lower than the d-indices (ranged from 0.80 to 0.88) reported for soil water prediction in a DNDC cover crop impact assessment study at Chillicothe in the Texas Rolling Plains by Singh et al. (2022). The PE values reported for soil water prediction in Singh et al. (2022) ranged from −3.6 % to −0.4 %, suggesting consistent overprediction of the soil water by their model. Other studies, however, have reported positive PE values demonstrating the tendency of DNDC model to underpredict soil water, and these trends are consistent with our findings. For instance, Bierer et al. (2021) reported PE values ranging from 9 % to 46 % for DNDC model soil water evaluation in an irrigated study. Abdalla et al. (2009) and Uzoma et al. (2015) have also reported underestimation of soil water content with PE ranging between 13–30 % and 13–26 %, respectively.

The estimated NSE values for soil water evaluation under the CT, R-

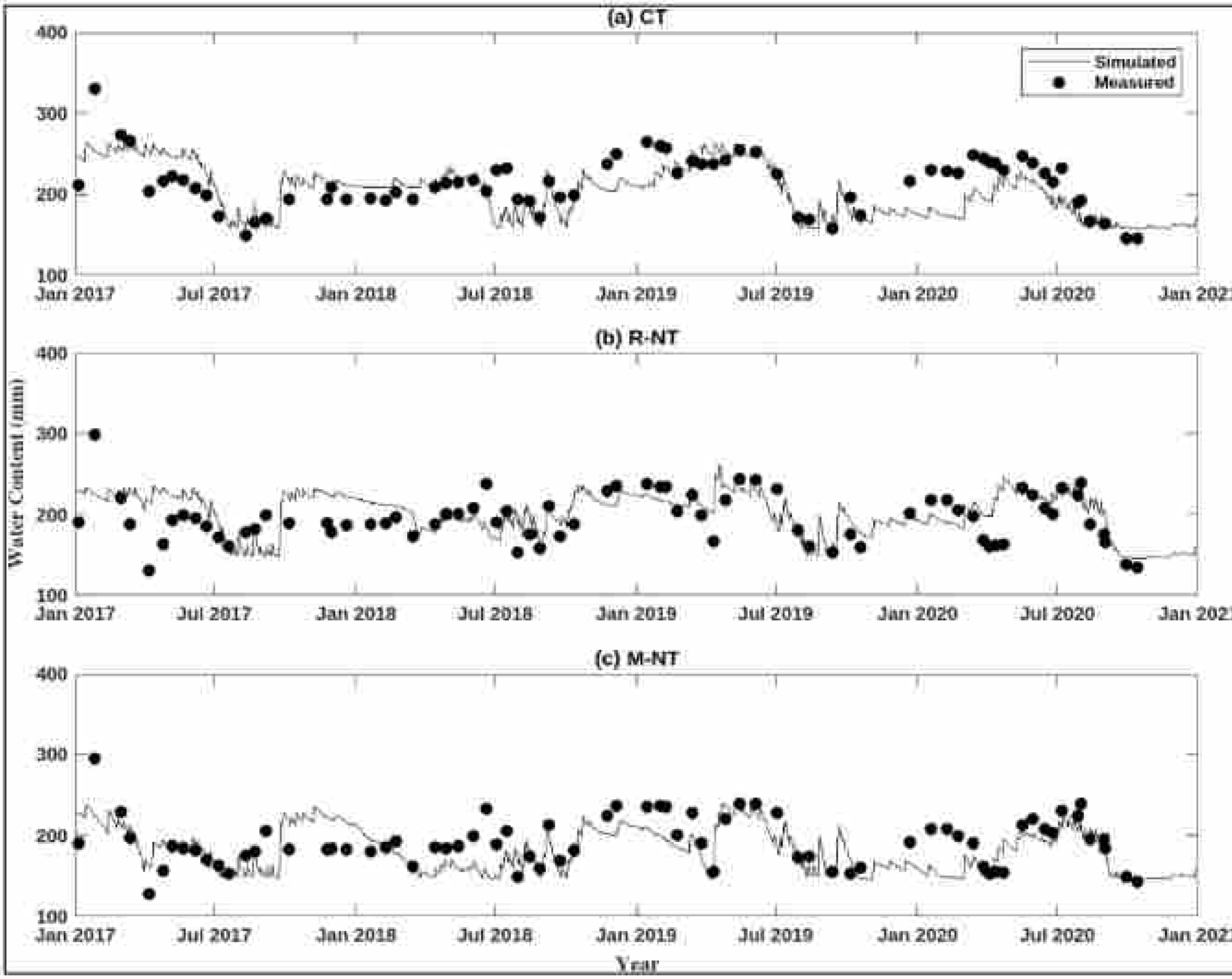

Fig. 6. Comparison of simulated and measured soil water at 0–80 cm depth during (a) the model calibration (CT – Conventional tillage treatment) and (b & c) evaluation [R-NT (No-tillage with rye cover crop) and M-NT (No-tillage with mixed cover crop)].

NT, and M-NT treatments were 0.53, 0.61, and 0.45, respectively, indicating fair performance of the model in simulating soil water dynamics. Potential reasons for the inconsistencies in soil water prediction could be the tipping bucket approach used in the model for simulating soil water movement and some measurement errors (e.g., unrealistically high measured soil water in January 2017 compared to measured values in other times; Fig. 6). Several other studies have discussed the weaknesses of the DNDC model in accurately predicting soil hydrology (Smith et al., 2020; Smith et al., 2019; He et al., 2020,2018; Congreves et al., 2016; Dutta et al., 2016a; Cui et al., 2014; Abdalla et al., 2011; Deng et al., 2011). For instance, Krobel, (2009) found that the DNDC model tended to overestimate soil water content, and its performance was poor compared to the Daisy model (Hansen et al.,1991; Abrahamsen and Hansen, 2000), another well-known biogeochemical model. Due to these known structural uncertainties in the model, published studies suggest that future DNDC developments should focus on improving the simulation of soil hydrology.

3.2. *Effects of cover crops on seed cotton yield, soil water use, soil organic carbon, and total nitrogen*

3.2.1. *Impact of tillage and cover cropping on seed cotton yield*

A one-way ANOVA test for multiple means showed that there was no statistically significant difference in average (1991–2020) seed cotton yield across the three treatments (P = 0.875) (Fig. 7). This finding therefore rejects our hypothesis that NT with cover crops would lead to a significant decline in seed cotton yield when compared to CT. The is consistent with the results from field experiments at the same site reported by Lewis et al. (2018) and Burke et al. (2022). Lewis et al. (2018) found no differences in cotton lint yield and gross margins between the CT and M-NT treatments. Burke et al. (2022) also reported that cover crop adoption did not significantly reduce cotton lint yield. Similar findings were published and discussed in numerous modeling studies from semi-arid regions, including Singh et al. (2022) and Adhikari et al. (2017) from the Texas Rolling Plains region. The results from this study are also consistent with field studies conducted by DeLaune et al. (2020) in the Texas Rolling Plains over six years (2013–2018). They found no significant difference in cotton lint yield between CT and cover crop treatments (mixture and winter wheat). Additional field studies by DeLaune et al. (2012a, 2012b) have also found cotton yields between NT and CT treatments to be similar.

Simulated variability in seed cotton yield was slightly reduced under the CT (coefficient of variation (CV): 27.3 %) as compared to R-NT (CV: 29.2 %) and M-NT (CV: 29 %) treatments (Fig. 7). The reason for simulated higher yield variability under cover crops could be greater competition for water and nutrients (e.g., N), especially during the years with increased cover crop biomass production. In those years, soil water storage under the cover crop treatments was reduced substantially at the

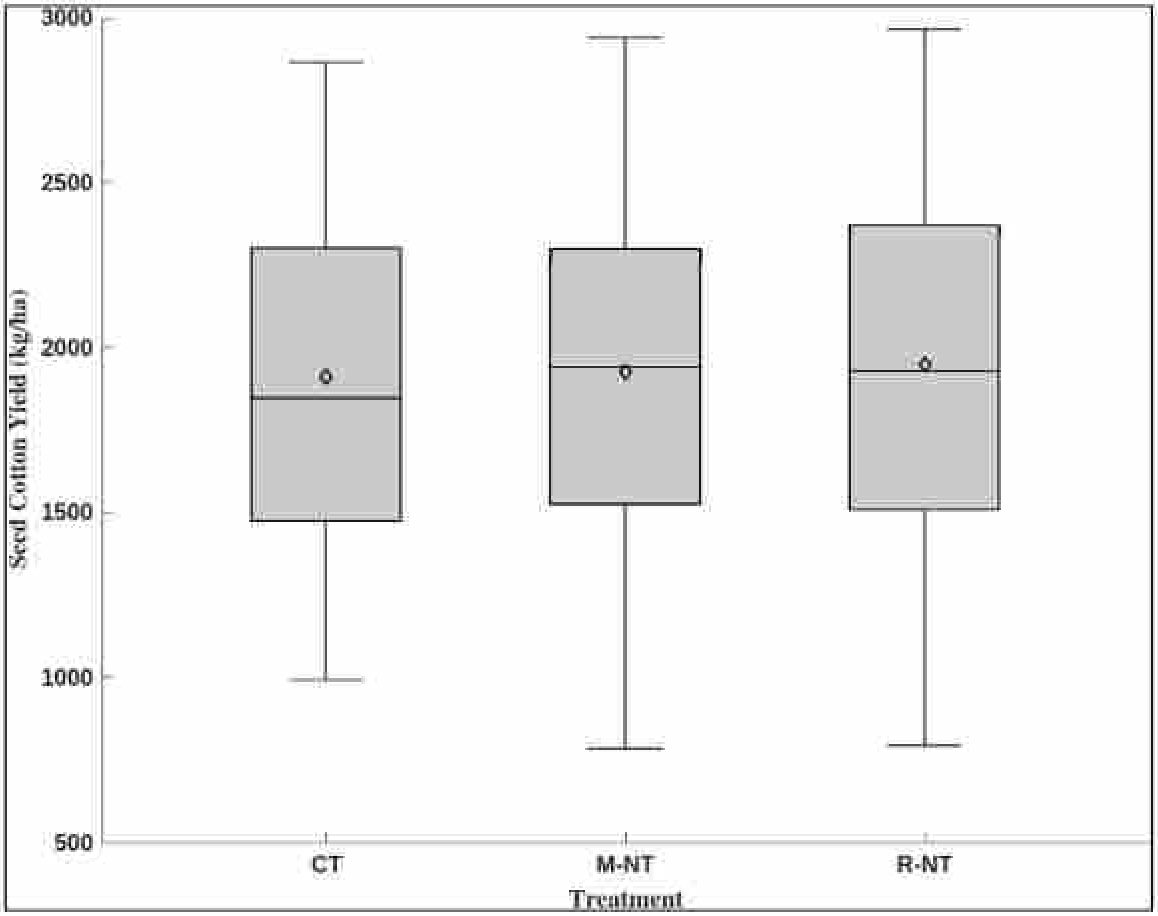

Fig. 7. Long-term (1991–2020) variability in simulated seed cotton yield under different treatments: CT - Conventional tillage; M-NT - No-tillage with mixed cover crop; R-NT - No-tillage with rye cover crop.

time of cotton planting as compared to CT, which can negatively impact cotton yield. In contrast, when cover crop biomass production is moderate, the amount of soil water stored at the time of cotton planting is almost the same under cover crop and no-cover crop treatments. As a result, cotton yield following lower cover crop biomass production is about the same between cover crop and no-cover crop treatments. The simulated trends were similar to Burke et al. (2022), except soil water at planting was greater in the cover crop treatments due to timely rainfall and/or irrigation.

In case of the CT treatment, variability in seed cotton yield was due to the variability in soil moisture and nutrients, increased susceptibility to soil erosion and related nutrient loss due to soil disturbance, and increased soil water evaporation from tillage. Six et al. (2002) have also found tillage to: i) increase soil carbon loss by exposing soil organic matter to oxygen, thereby accelerating its decomposition where SOC is transformed into CO_2 and released into the atmosphere, ii) expose soil aggregates at the surface to wet-dry and freeze-thaw cycles, and iii) increase aggregate disruption. They report that the disrupted aggregates expose large amounts of protected labile organic C to microorganisms, stimulating microbial activity, and contributing to SOC decomposition. Tillage can also impact topsoil temperature and aeration (Wang et al., 2016). All these factors were found to affect soil water and nutrient availability, thereby affecting the overall ability of soil to support crop growth (Unger, 1999; Alhameid et al., 2019).

3.2.2. *Impact of tillage and cover crops on soil water*

The addition of cover crops led to an overall reduction in soil water compared with CT by the time of cover crop termination (Fig. 8). However, depleted soil water was replenished with spring rains. In the events of higher, continued water supply through rainfall/irrigation, cover crop systems were found to recover fast and maintain higher soil water during the cotton growing season than CT systems. This finding also rejects our hypothesis that cover crops would contribute to the overall reduction of soil water in irrigated cotton production systems of the SHP. These results are consistent with those reported by Burke et al. (2022), who found that the soil water depleted by cover crops was replenished following cover crop termination by spring rains and deficit irrigation, and soil water was maintained at a higher level throughout the cash crop (cotton) growing season under cover crop treatments as compared to the CT treatment. This enhancement of soil water holding capacity by NT with cover crops could likely reduce management costs associated with irrigation in the long run, which is a paramount finding for the stakeholders in the SHP (and similar areas) where water resoucers are rapidly depleting (SARE, 2012).

The negative effects of cover crops on soil water use have been discussed extensively. For instance, Krstić et al. (2018) found that, in rainfed cropping systems, soil water storage was reduced by the introduction of cover crop treatments, especially during the dry years. The greatest soil water deficiency in their study was observed during the cover crop growing season followed by water stress on subsequent cash crops. The soil moisture depletion problems associated with cover crops could therefore be more pronounced in semi-arid regions compared to humid, higher rainfall areas. Further research on creative strategies to adopt cover crops is needed to harness their benefits.

Cover crop termination timing can serve as a potential strategy to overcome the negative effects of cover crops on soil water. For instance, early termination of rye cover resulted in significantly greater soil water content compared to the late termination (Munawar et al., 1990; Jones

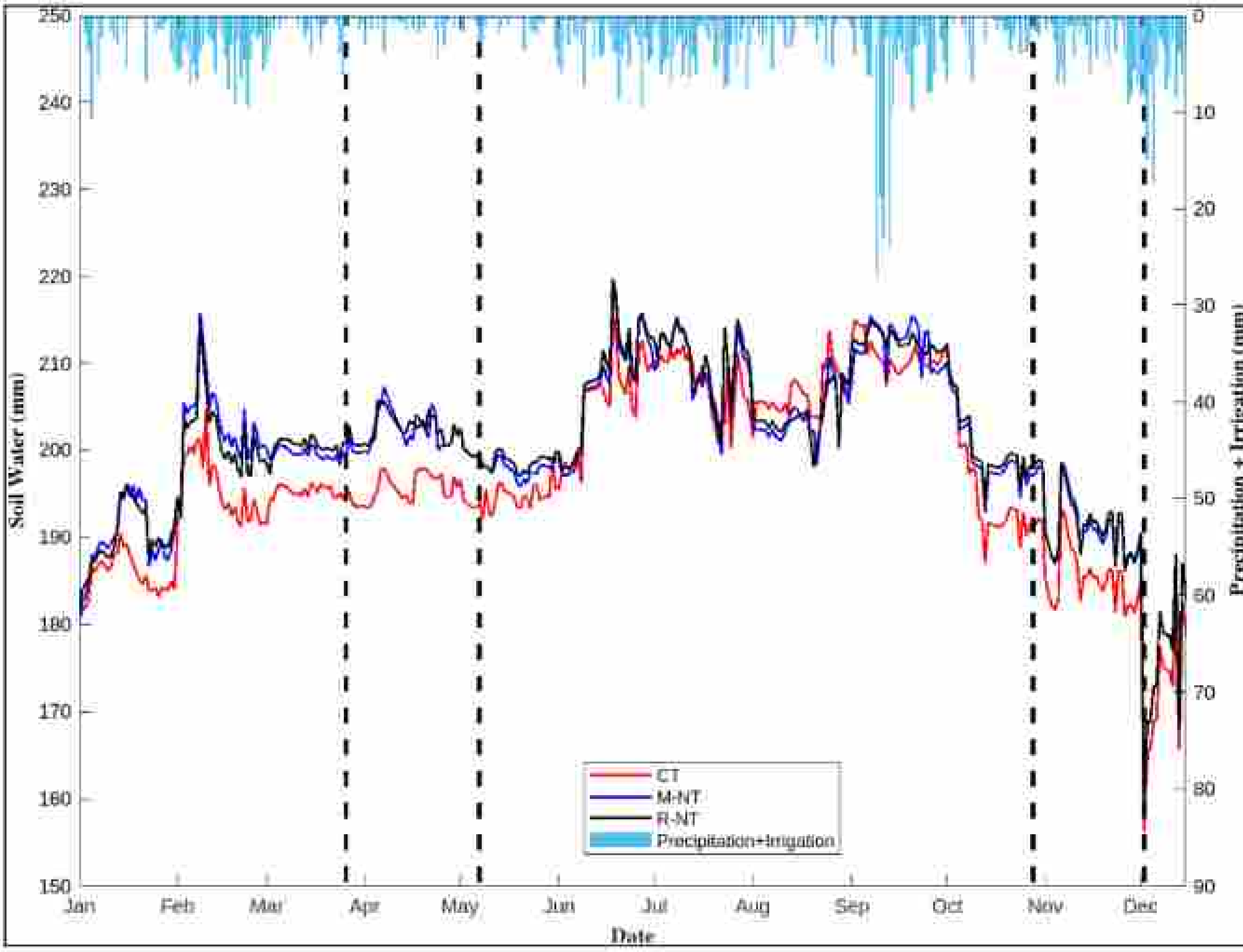

Fig. 8. Simulated effects of tillage and cover crops on average (1991–2020) daily soil water at 0–80 cm soil depth. The dashed lines show cover crop harvest (March 26), cotton planting (May7), cotton harvest (Oct 28) and cover crop planting (Dec 2). Abbreviations: CT - Conventional tillage; M-NT - No-tillage with mixed cover crop; R-NT - No-tillage with rye cover crop.

et al.,2020; Singh et al., 2023). Therefore, cover crop termination management is another important area to be explored to better understand the best ways to integrate cover crops in semi-arid cotton production systems to achieve the desired benefits.

Cover crop termination timing can serve as a potential strategy to overcome the negative effects of cover crops on soil water. For instance, early termination of rye cover resulted in significantly higher soil water content compared to the late termination (Munawar et al., 1990; Jones et al.,2020; Singh et al., 2023). Therefore, cover crop termination management is another important area to be explored in order to better understand the best ways to integrate cover crops in semi-arid cotton production systems for achieving desired benefits.

3.2.3. Impact of tillage and cover cropping on soil organic carbon

As hypothesized, the long-term simulation results showed a continuous increase in SOC with all three treatments, although the rate of this increase was notably different across the treatments (Fig. 9). The SOC increase in irrigated cotton production systems was primarily due to the continuous return of cotton and cover crop residues into the soil following cotton harvest and cover crop termination. The rate of SOC increase for a treatment was proportional to the amount of crop residues produced, which potentially explains why simulated SOC was higher under cover crop treatments [15.47 Mg C ha^{-1} (40.2 % higher) and 17.57 Mg C ha^{-1} (59.2 % higher) in case of R-NT and M-NT treatments, respectively] compared to the CT treatment (11.03 Mg C ha^{-1}). These findings are consistent with the results from a field experiment at the study site in Lamesa, TX, in which Lewis et al. (2018) found that SOC doubled following a R-NT adoption in a 17 yr conventional tillage cotton production system. Singh et al. (2022) also reported similar results from a DNDC study in the Texas Rolling Plains. Several other simulation studies have also reported improvements in SOC following the adoption of NT and cover crops (Halvorson et al., 2002; Alhameid et al., 2019; Marshall et al., 2016; Singh et al., 2020).

Different reasons and hypotheses for the improvement in SOC following cover cropped NT systems were discussed in the past studies. One of the potential reasons for lower SOC under CT treatment compared to NT because tillage exposes soil organic matter to oxygen, thereby accelerating its decomposition where SOC is transformed into CO_2 (Six et al., 2002; Unger, 1999). Sainju et al. (2002) also demonstrated that NT with rye, hairy vetch, and crimson clover cover crops reduced SOC and N losses in runoff by reducing soil erosion and N mineralization and by sequestering atmospheric CO_2 and N_2. Furthermore, a review by Thapa et al. (2023) found that the introduction of cover crops in semi-arid cash crop monocultures, including wheat and sorghum, increased SOC in 91 % of reviewed studies They found that SOC increase ranged from 28 % to 66 % when comparing conservation agriculture with CT. While these findings justify our results, the extent by which other factors, including irrigation management and cultivar

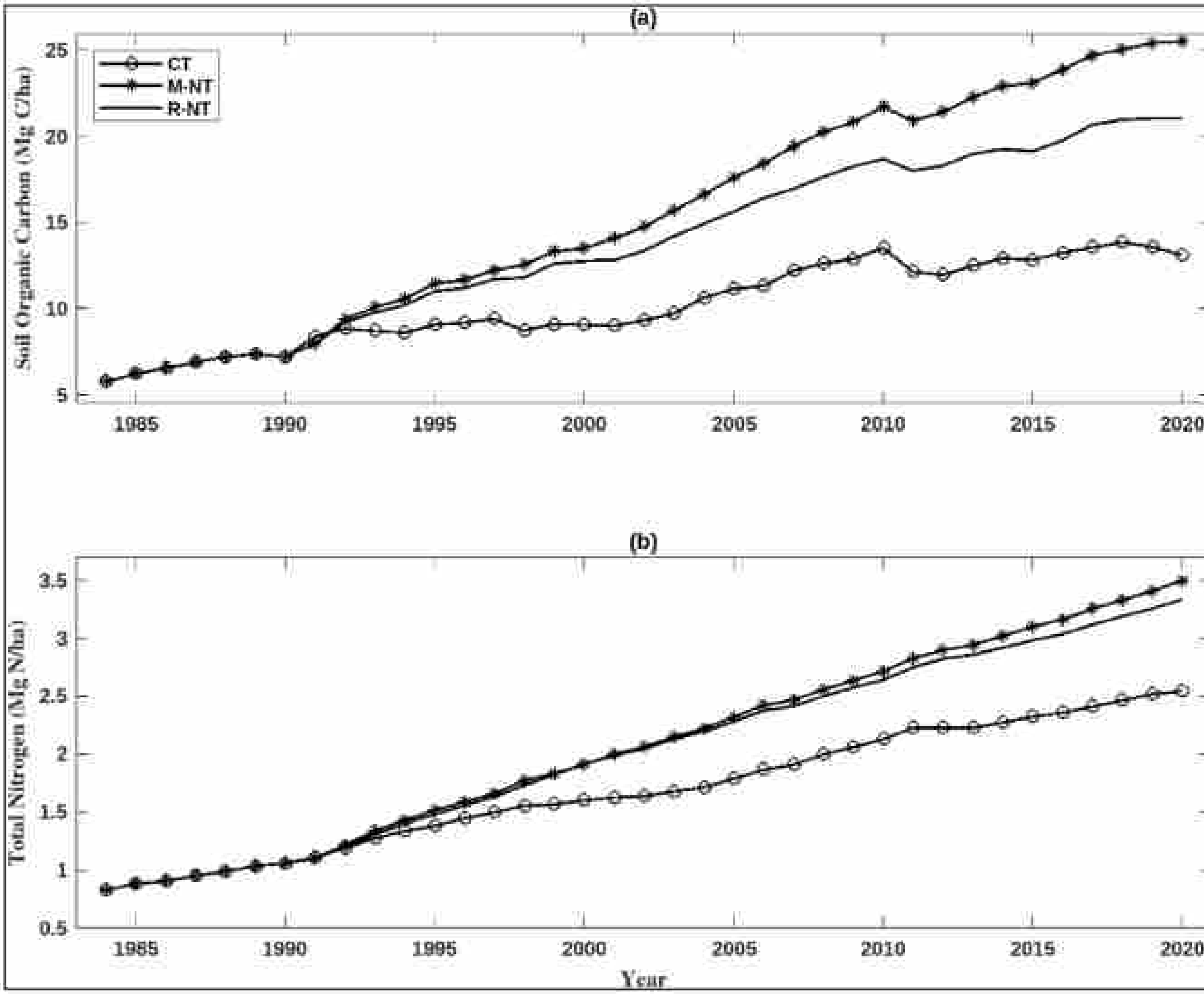

Fig. 9. Simulated impact of tillage and cover crops (1991–2020) on (a) annual soil organic carbon and (b) total nitrogen in the 0–30 cm soil layer. Abbreviations: CT – Conventional tillage; M-NT - No-tillage with mixed cover crop; R-NT - No-tillage with rye cover crop.

Table 6
Simulated average (1991–2020) annual nitrogen inputs and outputs across the different treatments.

Variables	Tillage	Rye	Mixture
N-inputs			
Fertilizer N application (kg ha^{-1})	148.0	148.0	148.0
Litter N input (kg ha^{-1})	56.0	90.9	117.1
Fixed N (kg ha^{-1})	0.0	0.0	26.0
Gross mineralized N kg ha^{-1})	142.4	146.3	170.3
Total N-inputs(kg ha^{-1})	346.4	385.2	461.4
N-outputs			
Crop N uptake (kg ha^{-1})	69.0	96.6	96.4
Assimilated N (kg ha^{-1})	105.7	137.8	178.2
N leaching (kg ha^{-1})	97.6	60.5	59.3
Total N-outputs (kg ha^{-1})	272.3	296.9	333.9
Change in soil N (kg ha^{-1})	74.1	88.3	127.5

type, affect the discussed results is not well explored and understood.

3.2.4. Impact of tillage and cover cropping on total soil nitrogen

The simulated trends for TN followed the simulated changes in SOC (Fig. 9). The average simulated TN was the lowest for CT treatment (1.86 Mg N ha^{-1}) followed by R-NT (2.28 Mg N ha^{-1}) and M-NT (2.34 Mg N ha^{-1}). Overall, cover crop treatments showed greater TN content (by 22.6 % and 25.8 % in the case of R-NT and M-NT, respectively) compared to the CT treatment. These results support our hypothesis that NT with cover crops would increase overall TN, and are consistent with the findings from Singh et al. (2022), who reported higher TN contents from cover crop treatments in comparison to no-cover crop treatments. Reduced TN under CT treatment could be attributed to higher N losses through leaching and runoff (Unger, 1999; Six et al.,2002; Wang et al., 2016). Greater soluble N in leachates from soils managed under CT compared to the leachates from NT systems was also reported previously (Randall et al., 1995; Jiao et al., 2004; Hafif, 2014). Improvement in TN following the adoption of cover crops was also discussed in other literature. For example, a review by Paramsha et al. (2022) reported significant improvements in TN and other inorganic nutrients following the adoption of NT and cover cropping due to the reasons discussed above.

3.2.5. Tillage management, cover crops, and soil nitrogen dynamics

Simulated average annual N inputs and outputs under CT and cover crop treatments are summarized in Table 6 and Fig. 10. For the most part, greater positive changes in soil N storage were simulated under the M-NT treatment (127.5 kg N ha^{-1}), followed by R-NT (88.31 kg N ha^{-1}) and CT (74.11 kg N ha^{-1}). Simulated N leaching was greatest under the

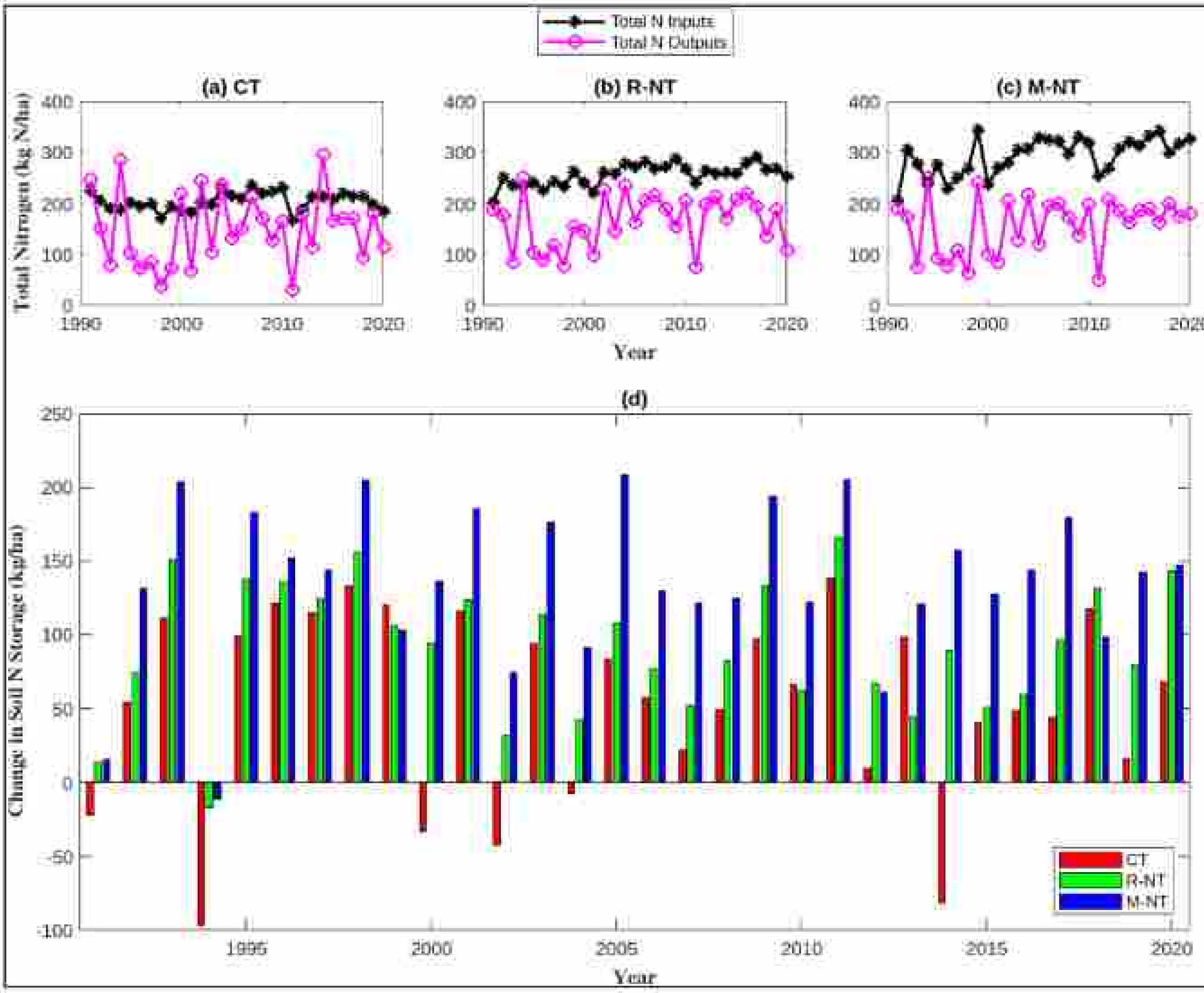

Fig. 10. Comparison between the simulated total nitrogen inputs and outputs (1991–2020) across the three treatments: (a) CT (conventional till), (b) R-NT (No-tillage with Rye cover), (c) M-NT (No-tillage with mixed cover), and, d) simulated change in soil nitrogen storage.

CT treatment (97.6 kg ha^{-1}) compared to R-NT (60.5 kg ha^{-1}) and M-NT (59.3 kg ha^{-1}). Past studies also reported that CT contributed to soil N and other nutrient losses through leaching and runoff (Unger, 1999; Six et al., 2002; Hafif, 2014; Alhameid et al., 2019; Thapa et al., 2023). These findings indicate that improvements in soil N by NT could potentially be further enhanced by cover crop adoption.

Simulated increases in soil N storage under cover crop treatments (M-NT and R-NT) could be justified by the presence of more litter originating from NT and cover crops. Perhaps the most viable reason for the improvement in soil N storage can be better understood by exploring the direct and indirect abilities of cover crops to change N dynamics and pools in soils. Parmaha et al. (2022) discuss that legume cover crops can directly improve soil fertility by fixing atmospheric N through symbiosis. The ability of mixed cover crops to fix atmospheric N (about 26 kg N ha^{-1}, on average) can explain the greatest increase in soil N simulated under M-NT compared to the other two treatments. Parmaha et al. (2022) also suggest that cover crops can improve soil N indirectly by capturing nutrients before they leach out of the soil profile. This mechanism provides a potential explanation for the simulated increase in soil N under cover crops (M-NT and R-NT) compared to CT.

The effects of tillage and residue management on soil N pools were discussed in several other studies. Halpern et al. (2010) conducted long-term field experiments on Canadian sandy loam soils and found greater soil C and N contents as well as microbial biomass and potentially mineralizable C and N concentrations under both NT and reduced tillage treatments compared with moldboard plowed CT treatment. In addition, Wright et al. (2021) and Kabiri et al. (2016) investigated the impact of tillage on soil C sequestration and N and found that NT or reduced tillage increased soil organic N concentrations as well as microbial biomass N, which could potentially lead to increased N mineralization under NT as compared to CT.

Our simulation results also show that the rate at which soil N is stored could be affected by rainfall and associated soil moisture status. For example, during the 2011 growing season, record breaking drought conditions were recorded in Texas and most of the US, leading to below average yields. Simulated seed cotton yields for CT, M-NT and R-NT during the 2011 growing season were 653.5, 537 and 513.1 kg ha^{-1}, respectively. These yields are notably below the computed long-term averages across the treatments (CT: 1909.5 kg ha^{-1}, M-NT: 1923 kg ha^{-1}, and R-NT: 1945 kg ha^{-1}). The lower yield in 2011 also meant that less N was used by the crops during the growing season (Fig. 11) thereby resulting in a notable increase in soil N storage as depicted in Fig. 10.

One of the reasons for the reduced plant N uptake (in addition to limited water availability for crops) in 2011 is a lack of enough plant

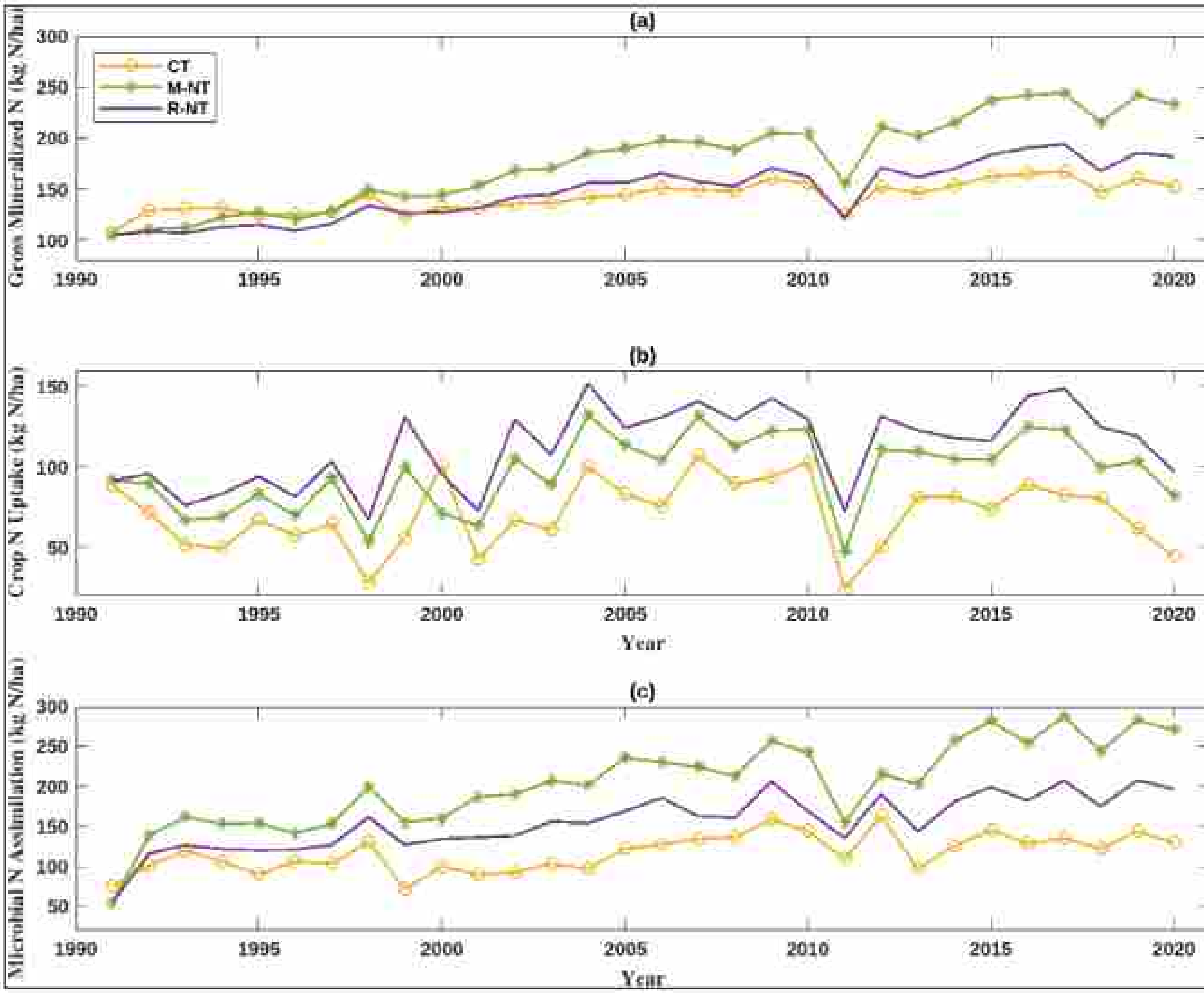

Fig. 11. Simulated (1991–2020) (a) gross mineralized nitrogen (N), (b) crop N uptake, and (c) assimilated N under different treatments: CT – Conventional tillage; M-NT - No-tillage with mixed cover crop; R-NT - No-tillage with rye cover crop.

usable N (NO_3^-, NH_4^+), possibly due to the simulated reduction in soil N mineralization (Fig. 11). The reduction in mineralized N could potentially be attributed to the declined microbial activity (microbial N assimilation was also notably lower during the 2011 growing season) under unfavorable soil moisture and temperature conditions (Barros et al., 1995; Carranza et al., 2009; Zhou et al., 2017). In semi-arid regions like the SHP, microbial activity is mostly limited by soil moisture because soil temperature is usually optimum.

Gross N mineralization and microbial N assimilation were also increased under the cover crops (R-NT and M-NT) compared to CT (Fig. 11). These findings are consistent with past studies which showed that cover crops have the potential to increase microbial activity and overall soil fertility (Hafif, 2014). Cordeiro Dos Santos et al. (2021) evaluated the potential of cover crops in improving microbial activity and fertility in a sandy soil and found that cover crops increased microbial biomass C and N by approximately 66 % and 90 %, respectively as compared to winter fallow systems. These improvements were followed by improved yields and soil chemical properties after two growing seasons. Overall, findings from this study show that cover crops have the potential to improve soil N by improving various processes by which crop usable N is delivered in soil.

4. Conclusions

The DNDC model was successfully evaluated for seed cotton yield; cover crop: biomass, and C/N ratios prior to cover crop termination; soil water; SOC; and TN using measured data from field experiments conducted at Lamesa, TX during 2014–2020 growing seasons. The long-term simulation results showed that adoption of NT with cover crops resulted in a significant increase in SOC and TN, suggesting that the benefits of NT could be enhanced by adoption of cover crop farming in semi-arid cotton production systems. There was no significant change in seed cotton yield across the three treatments in this study. However, a notable variability in soil water and seed cotton yield was found in M-NT and R-NT treatments as compared to CT, suggesting that there could be some risk associated with cover crops, especially under limited water availability such as in dry years. Overall, findings from this study recommend that the adoption of NT and cover crops could contribute to improved soil water (durnig the cash crop growing season), TN, and SOC in the long-term. The discussed soil improvements associated with cover crops could result in reduction of input costs (fertilizer, irrigation water, etc) associated with cash crop (cotton) production, which is a key consideration for farmers whose primary interest is to run profitable farming operations. Findings from this study also provide farmers and other stakeholders with a better understanding of the impacts of cover crops and tillage practices on soil C and N dynamics in semi-arid irrigated cotton production systems. Our future efforts will focus on assessing the impacts of cover crops and NT on dryland cotton production systems.

CRediT authorship contribution statement

Katie L. Lewis: Writing – review & editing, Funding acquisition, Data curation. **Joseph A. Burke:** Writing – review & editing, Investigation, Data curation. **Rabi H. Mohtar:** Writing – review & editing, Supervision. **Christopher J. Cobos:** Writing – review & editing, Data curation. **Rene Francis Simbi Mvuyekure:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Srinivasulu Ale:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Jasdeep Singh:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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