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Janntul Ferdush
Louisiana State University Agricultural Center

Changyoon Jeong
Louisiana State University Agricultural Center

Hwangju Jeon
Louisiana State University Agricultural Center

Jim Wang
LSU Agricultural Center

Kyoung Ro
USDA Agricultural Research Service

See next page for additional authors

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Assessing the long-term effects of conservation agriculture on cotton production in Northeast Louisiana using the denitrification–decomposition model

Janntul Ferdush[1,2] | **Changyoon Jeong**[1,2] | **Hwangju Jeon**[1,2] | **Jim Wang**[2] | **Kyoung Ro**[3] | **Xi Zhang**[1,2] | **Meesook Lee**[4]

[1]Red River Research Station, Louisiana State University Agricultural Center, Bossier City, Louisiana, USA

[2]School of Plant, Environmental, and Soil Sciences, Louisiana State University Agricultural Center, Baton Rouge, Louisiana, USA

[3]USDA-ARS, Florence, South Carolina, USA

[4]Department of Mathematical Sciences, McNeese State University, Lake Charles, Louisiana, USA

Correspondence
Changyoon Jeong, Red River Research Station, Louisiana State University Agricultural Center, 262 Research City Dr., Bossier City, LA 71112, USA. Email: CJeong@agcenter.lsu.edu

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Abstract

Conservation agriculture (CA) aims to sustain agricultural production, soil, and environmental health in agroecosystems and has been promoted throughout the United States. The adoption of CA in cotton (*Gossypium hirsutum*) systems provides both agronomic and environmental benefits. Yet, there is limited information on the long-term effects of CA practices on crop yield and adaptation strategies. An integrated CA system, that is, cover crops with no-tillage (NT) instead of conventional agriculture, was implemented in the long-term field experiments and assessed with an integrated biogeochemical model. Using the denitrification–decomposition model, this study estimated the effects of four different cover crops, for example, native grass (NG), hairy vetch (*Vicia villosa*), winter wheat (*Triticum aestivum* L.), and crimson clover (*Trifolium incarnatum*), on cotton yield under four different nitrogen (N) levels (e.g., 0, 50, 100, and 150 kg N/ha) and estimated responses on carbon (C) sequestration, and ecosystem functionality over a 10-year study. The NT-NG 50 N was used as a calibration dataset to accurately estimate the cotton lint yield with a normalized root mean square error (NRMSE) of 21% and model efficiency of 0.3. The calibration data validated the effects of hairy vetch, winter wheat, and crimson clover under the NT-50 N with NRMSE of 24%, 21%, and 25%, respectively. According to the scenario analysis, the 50 kg N/ha application with a single-irrigation event (10-cm depth) was most beneficial for maximizing the cotton yield with cover crop incorporation at the NT system over the long term. The effects of increasing cover crop biomass (i.e., double seed rate) on C content, regardless of N application rates, varied based on the relationship between the main and cover crop species. Besides, the furrow plow tillage system provided efficient C sequestration. The proposed

Abbreviations: CA, conservation agriculture; CC, crimson clover; DNDC, denitrification–decomposition; DW, dry weight; HV, hairy vetch; ME, Nash–Sutcliffe model efficiency; NG, native grass; NRMSE, normalized root mean square error; NT, no-tillage; OM, organic matter; SOC, soil organic carbon; WH, winter wheat.

approach stands to provide agricultural and environmental sustainability with the implementation of cover crop or crop residue incorporation instead of increased N application, seed rates, and irrigation events under NT practices.

1 | INTRODUCTION

Conservation agriculture (CA) reduces soil mechanical disturbances due to management practices (e.g., tillage), maintains permanent soil cover (e.g., cover crops, mulching, residue management, and diverse crop rotations), and integrates nutrient management practices (Abdollahi & Munkholm, 2014; Camarotto et al., 2018; Farooq & Siddique, 2015; Komatsuzaki & Ohta, 2007; Lal et al., 2007). CA is gaining popularity in meeting the challenges regarding soil health and enhancing crop production without sacrificing producer profits. Soil health is an inherent component of sustainable agriculture maintaining the capacity of soil to function as the dynamic living system within the ecosystem and land management practices, sustaining crop productivity, regulating water and air quality, controlling soil nutrient cycling, and improving plant and animal health (Daryanto et al., 2018; Doran, 2002; Tahat et al., 2020; Wade et al., 2022).

In CA, cover crops benefit from conserving bare lands during nongrowing winter and plowing with additional organic matter (OM) before sowing seeds for the next main crop (Pinto et al., 2017; Poeplau & Don, 2015). Cover crops contribute to agricultural ecosystem and agronomic benefits, such as increasing biodiversity and microbial activity, sequestering soil organic carbon (SOC), improving soil quality and structural stability, conserving soil moisture and nutrients, mitigating soil erosion, runoff, and leaching, increasing crop yields, and improving other soil health parameters (Alhameid et al., 2019; Hoorman et al., 2009; Nouri et al., 2019; Singh et al., 2022). Cover crops are able to enhance the multifunctionality in crop production by improving SOC content, microbial biodiversity, and in turn, soil quality and fertility (Blanco-Canqui et al., 2015; Boyer et al., 2018). However, the effects of cover crops largely vary with the crop species, tillage system, the extent of soil and water conservation during the fallow, and climate change (Alhameid et al., 2019; Kaye & Quemada, 2017).

The no-tillage (NT) system is another conservation practice that reduces soil disturbance induced by field operations, for example, planting, harvesting, and applying pesticides, reducing soil compaction, and improving nutrient restoration (Aziz et al., 2013; Balota et al., 2014). In contrast, the conventional agricultural tillage operations accelerate soil erosion, increase in nitrogen (N) and carbon (C) emission into the atmosphere, disturb soil microbial activity, and deplete OM. Growing cover crops with the NT system can potentially increase crop yields, while the NT system alone may take 7–9 years to improve soil health and crop production. Therefore, adapting the NT for a short period has little benefit for producers (Blanco-Canqui & Lal, 2007). As an integrated agricultural practice, cover crop can compensate for nuisances due to reduction in soil compaction and N demand under the NT system, leading to enhanced ecosystem functionality (Boyer et al., 2018; Keesstra et al., 2018). However, beneficial soil and yield responses from the NT system depend on favorable soil OM content and the C:N ratio.

The researchers in the northwest and Northeast Louisiana have been developing strategies for improved cotton cultivation for decades. Despite the effort, they observed reduced SOC content and increasing demand for irrigation under CA (Ku et al., 2018; Millhollon & Melville, 1991). Previous studies found that residues left very low from cotton fields after harvest and soils were exposed to water-induced erosion and increased susceptibility to nutrient runoff (Nyakatawa et al., 2001; Osteen et al., 2012). The crop residues are recommended to remain in field after the crop harvest for conserving the soil from degradation, erosion, and nutrient leaching, and ensure C sequestration to improve productivity (Mbuthia et al., 2015). The long-term cover crop studies at the Red River Research Station showed improved cotton production after 7 years of cover crop residue incorporation because of sufficient N supply and increased SOC storage (Ku et al., 2018). Nevertheless, there is a knowledge gap on how all the climatic, soil, crop, and farming management practices are integrated under the umbrella of CA system. The complexities of cropping systems may arise at multiple scales due to the interdependencies between natural and anthropogenic factors (Balbi et al., 2015; He et al., 2018).

An integrated tool is necessary for modeling different components of the CA system to understand the various CA practices under different cover crops, management practices, and climate change (Babu et al., 2006; Deng et al., 2016). Several process-based biogeochemical models (e.g., CASA [Potter et al., 1993], CENTURY [Parton et al., 1996], and DAYCENT [Del Grosso et al., 2002]) have been developed to simulate crop production, C and N cycles, and greenhouse gas emissions under different management practices (Basche et al., 2016; Gilhespy et al., 2014). The denitrification–decomposition (DNDC) (Li et al., 1992a, 1992b) model has successfully evaluated the long-term SOC changes and N transformation systems (aerobic and anaerobic) under both small plots and regional studies with various agricultural field conditions in many places around the world (Beheydt et al., 2007; Jarecki et al., 2018; Li et al., 2010). The long-term stimulations on crop yield under the whole range of CA practices (e.g., different cover crops, tillage operations, fertilizer, and irrigation management practices) is a challenging task. However, many researchers enhanced the DNDC model with improved accuracies under dynamic approaches/scenarios (Deng et al., 2016; Gilhespy et al., 2014; Jarecki et al., 2018). The objectives of this paper are (1) to investigate the long-term effects of four different cover crops with NT system on cotton production, (2) to assess the performance of the DNDC model on cotton yields under the cover crops with NT system, and (3) to evaluate the impacts of different N rates, water contents, and seeding rates on cotton yield and SOC storage over the long-term cotton production.

Core Ideas

- Adopting sustainable agricultural practices using tillage and cover crops illustrated agricultural benefits.
- The denitrification–decomposition (DNDC) model predicted the implementation of cover crop incorporation instead of increased N application.
- The DNDC model simulated the maximum crop yields with cover crop incorporation at the non-till system.

2 | MATERIALS AND METHODS

2.1 | Site description

The experiment was conducted in the Macon Ridge Research Station, Louisiana State University Agricultural Center (LSU AgCenter), located near Winnsboro (32.8.55 N, 91.42.99 E) in Northeast Louisiana. The major crops grown in this area were corn (*Zea mays*), cotton (*Gossypium hirsutum*), grain sorghum (*Sorghum bicolor*), rice (*Oryza sativa*), soybean (*Glycine max*), wheat (*Triticum aestivum*), and oat (*Avena sativa*). This experiment cultivated cotton (i.e., Stoneville La 887 cotton) under two legume (e.g., hairy vetch [HV], crimson clover [CC]) and two nonlegume cover crops (e.g., winter wheat [WH], and native grass [NG]) for 10 years. With a humid and warm-temperate climatic condition, the study area recorded an average annual precipitation levels of 280–547 mm, a maximum highest temperature of 39.4˚C, and a minimum lowest temperature of −15.0˚C throughout the 10 years (Figure 1). The dominant soil was Gigger Silt Loam, with a pH of 7.0, and 12–1494 m elevations (USDA–Economic Research Service, 2022). The Gigger soil series is classified as fine-silty, mixed, active, thermic, Typic Frafiudalfs (USDA–NCSS, 2023) and consists of very deep, moderately well-drained, and slowly permeable soils with fragipans formed in a thin mantle of loess over loamy sediments or terraces.

2.2 | Design of experiment and field management

The experimental design was a randomized complete block with a factorial arrangement of three tillage regimes (e.g., no-tillage, ridge-tillage, and conventional tillage), four cover crops (e.g., NG, HV, WH, and CC), and five fertilizer rates, including starter fertilizer (10 kg/ha N, 30 kg/ha P_2O_5) and 0, 50, 100, and 150 kg/ha N. The blocks were replicated four times when the plots were 8-m rows wide, 5.24 m long, and with 1.02 m row spacing. Although the field study examined the long- and short-term effects of 60 treatment combinations on cotton growth, yield, and maturity, this paper mainly focused on emphasizing the long-term effects of the NT system under different cover crops. Cover crop seeds were broadcasted into the standing cotton stalks in each year's second to third week of October, and the seed rates for CC, HV, and WH were 16, 28, and 56, respectively. The cover crops were mowed to a stubble height of 0.3 m with a rotary cutter. The cotton stalks were shredded with a rotary mower immediately after the cover crops were seeded.

Cotton seeds were directly applied to the old beds (six seed/0.3 m) with NT or seedbed preparation. The treatments with starter fertilizer application received 10-30-0 rates of ammonium nitrate-phosphorus pentoxide-potassium oxide (N-P_2O_5-K_2O) as liquid fertilizer in-furrow, incorporated into the soil at the time of cotton cultivation. Besides, the NT treatments with different N rates (0, 50, 100, and 150 kg/ha) were treated with respective rates of ammonium nitrate and applied into the beds of ∼0.08- to 0.20-m depth to the side of the drill. The entire test area was treated with the same doses of pesticides to a 0.5-m band behind the planter to suppress light winter vegetation, resist the preemergence and postemergence of weed, and control insects. A spindle picker was used to harvest the two center rows of each plot. Fifty cotton bolls were randomly selected from the border rows of each plot and hand-picked to provide information about boll size. These boll samples were ginned to prepare lint percentage data. Lint yields were calculated by multiplying machine-picked seed cotton yield with the laboratory-derived lint percentages.

2.3 | The DNDC model

The DNDC model is developed for predicting C sequestration and trace gas emissions from upland/non-flooded agricultural ecosystems (Babu et al., 2006; Zhang et al., 2022). The model governs C and N transport and transformation between

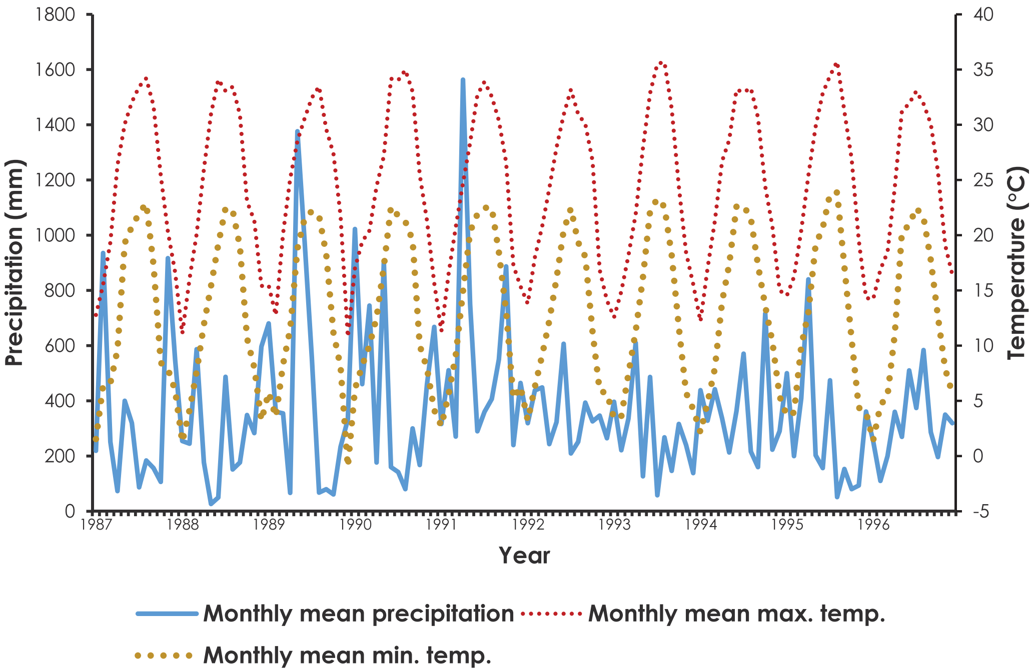

FIGURE 1 Observed monthly mean precipitation and temperature across the 10 years study. Climate datasets were obtained from National Centers for Environmental Information (https://www.ncdc.noaa.gov/).

the plant–soil system and atmosphere by simulating the fundamental processes, and controlling the interactions among various ecological drivers, soil environmental factors, and relevant biochemical or geochemical reactions. The ecological drivers consist of climate, soil, and crop growth sub-models that simulate soil physical, chemical, and biological parameters, for example, temperature, moisture, pH, redox potential or Eh, soil structure, texture, bulk density, SOC content, partitioning decomposition rate, and soil runoff and erosion. Since the environmental factors consist of nitrification, denitrification, and fermentation sub-models, it can predict microbial gas emissions from the soil environments (Li, 2000). DNDC estimates SOC dynamics by quantifying the SOC input/gain from crop litter and/or manure incorporation and the SOC loss/return through decomposition. Moreover, the DNDC model can be utilized for predicting crop yield, plant photosynthesis, respiration, water and N demand/uptake, litter production, soil organic nitrogen, NO_3 leaching, N runoff, NH_3 volatilization, CO_2, CH_4, N_2, and N_2O emissions (Li et al., 2006; Li et al., 2010).

2.3.1 | Model input parameters

The study used the DNDC model (V. 9.5) with a comprehensive set of independent model parameters such as climate (e.g., precipitation, maximum and minimum air temperatures, radiation, latitude, CO_2 concentration in air), soil (e.g., land-use type, soil type, field capacity, slope, salinity, etc.), cropping, and farm management practices to simulate crop yield. Locally observed climate/meteorological data for this study was obtained from the National Climate Data Centre database (http://www.ncdc.noaa.gov/) (Figure 1, Table 1).

Farming management practices included tillage, fertilization, manure amendment, irrigation, flooding, film mulch, grazing/cutting, and so forth. Default values of soil inputs (Table 1) and the information about cropping and farming management practices (Tables 2 and 3) were taken from the Annual Progress Reports of the Northeast (Macon Ridge) Research Station, Winnsboro, LA.

2.3.2 | Model calibration and validation

The calibration process followed the DNDC manual and the previous work conducted (Ku et al., 2018) with adjusting input crop growth parameters (e.g., optimum cotton yield, biomass fraction, and biomass C/N ratio) and farming management practices (cover crop incorporation time and biomass). Using 10-year climate data and a treatment of NT-NG 50 N (non tillage-NG-50 kg/ha N), the DNDC model performance was examined. According to the NT-NG 50 N test, the most sensitive parameter(s) (i.e., N content, water stress) for yield was selected and prioritized for model calibration. The mean value of four replicate blocks of observed cotton yield was directly used for determining the optimum yield of cotton lint during the 10-year test (Table 2).

TABLE 1 Climate and soil parameters used in the denitrification–decomposition (DNDC) model.

Input parameters	Values	Data source
N concentration in rainfall	0 mg N/L or ppm	
Atmospheric background NH_3 concentration	0.06 N/m^3	
Atmospheric background CO_2 concentration	350 µg N/m^3	
Format of climate data	Jday-max T-Min T-Prec (J = Julian)	
Land use	Upland crop	Default
Texture	Silt loam	Measurement
Bulk density	1.3239 g/cm^3	Measurement
Soil pH	7	Measurement
Field capacity	0.33 cm^3/cm^3	Measurement
Wilting point	0.11 cm^3/cm^3	Measurement
Clay fraction	0.2	Default
Hydro-conductivity	0.0259 m/s	Default
Porosity	0.4 cm^3/cm^3	Adjustment
Water retention layer	0.6 m	Adjustment
Drainage efficiency	0.5	Adjustment
SOC in 10 cm	0.0116 kg C/kg soil	Measurement
Microbial activity	1	Default
Slope	2%	Measurement
Salinity index	30	Adjustment
Initial NO_3 concentration	0.05 ppm	Adjustment
Initial NH_4^+ concentration	0.05 ppm	Adjustment
Maximum root depth	0.02 m	Adjustment

Abbreviation: SOC, soil organic carbon.

The crop yield was validated with the observed values under various cover crops plus N treatments across the 10 years of study under NT system because the response of DNDC model was highly sensitive to N stress and SOC contents. The calibrated model with the revised input parameters, including N rate, tillage, and irrigation conditions, was applied to the other three cover crop options (e.g., NT-HV 50 N, NT-WH 50 N, and NT-CC 50 N) to validate the DNDC model. The effects of the N application rate, tillage practices, irrigation, and seed rates were also simulated on the trends of cotton yield and nutrient leaching potential.

2.3.3 | Model performance diagnostics

The DNDC model performance was evaluated using two statistical performance indicators: (i) normalized root mean square error (NRMSE) and (ii) the Nash–Sutcliffe model efficiency (ME). The NRMSE was measured to predict the model fitness. For example, the smaller values of NRMSE (Equation 1) indicate better model performance. The NRMSE illustrates the percentage (%) of the relative difference between observed and predicted values in variable units (Ku et al., 2018).

$$\text{NRMSE} = \frac{100}{\bar{\text{O}}}\sqrt{\sum\nolimits_{i=i}^{n}((yi-\hat{y})^2)/n}, \tag{1}$$

where $\bar{\text{O}}$ is the mean observed data, yi and $\hat{y}$ are the observed and simulated values, respectively, and n is the number of samples. The observed and simulated values are same when the NMRSE is 0. If the NMRSE < 10%, the prediction performance is excellent; if 10% < NMRSE < 20%, the performance is considered good; and poor if NMRSE exceeds 30%.

$$\text{ME} = 1 - \frac{\sum_{i=1}^{n}(yi-\hat{y})^2}{\sum_{i=1}^{n}(yi-\bar{o})^2}, \tag{2}$$

where signs for Equation (2) are the same as described for Equation (1). This study reported the standard errors of the model simulated mean lint yields to indicate the differences with sample mean, and the coefficient of determinations (R^2) indicates the variability of predicted yields.

ME indicates the model's accuracy based on the average value of observation (Equation 2), ranging from −∞ to 1. The model predictions are considered a perfect match between the

TABLE 2 Cropping parameters used in the denitrification–decomposition (DNDC) model.

Input parameters	Values	Data source
Number of cropping system applied, cropping system, years of cycle within cropping system, year in this cycle	1	
Crop	14 cotton	
Planting month	Early to middle-May	
Harvest month	End September to early October	
Maximum grain biomass production	1000 kg C/ha/year	Adjustment
Biomass grain fraction	0.27	Adjustment
Biomass grain C/N ratio	75	Adjustment
Maximum leaf biomass production	1037 kg C/ha/year	Adjustment
Biomass leaf fraction	0.28	Adjustment
Biomass leaf C/N ratio	26.5	Adjustment
Maximum stem biomass production	1333.3 kg C/ha/year	Adjustment
Biomass stem fraction	0.36	Adjustment
Biomass stem C/N ratio	75	Adjustment
Maximum root biomass production	333.33 kg C/ha/year	Adjustment
Biomass root fraction	0.09 kg C/ha/year	Adjustment
Biomass root C/N ratio	75	Adjustment
Annual N demand	74.689 kg C/ha/year	Adjustment
Thermal degree days for maturity	2500	Adjustment
Water demand (g water/g DM)	400	Measurement
N fixation index (crop N/N from soil)	1	Measurement
Optimum temperature	25	Measurement
Vascularity	0	Measurement

Abbreviation: DM, dry matter.

simulation and the observation when the ME value is 1, and the model efficiency declines with a reduced ME value. An efficiency of ME = 0 indicates that the model predictions are as accurate as the mean of the observed data, and an ME < 0 indicates that the observed mean value is a better predictor than the model, which means the model efficiency result is poor (Zhang et al., 2022).

3 | RESULTS AND DISCUSSION

3.1 | Observed effects of different cover crops on crop yield and soil health

The incorporation of cover crop residues had significantly changed the cotton lint yields across the 10 years, although the yield trends fluctuated over the period for each cover crop season (Figure 2). The approximate average cotton lint yield under NG, HV, WH, and CC was 774, 814, 848, and 817 kg C/ha, respectively, during the 10-year study. The trend of cotton yield was slightly altered between legume (HV and CC) and nonlegume (WH and NG) crops. However, yields under cover crop were significantly higher compared with the

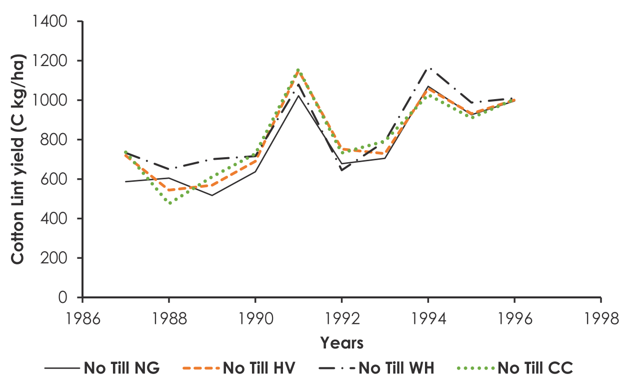

FIGURE 2 Average cotton yield trends observed under cover crop incorporations during the project periods. CC, crimson clover; HV, hairy vetch; NG, native grass; WH, winter wheat.

NT-NG (C:N—17:1) treatment. Incorporation of two legume crops, for example, HV (C:N—11:1) and CC (C:N—17:1), represented similar yield trends, while the nonlegume crop, WH (C:N—80:1) showed distinct cotton yield trend. There are many studies that found greater yield under cover crop incorporation depending on the relationship between cover crop and main crop, based on C:N ratio and N recycling

TABLE 3 Farming management practices parameters used in the denitrification–decomposition (DNDC) model.

Input parameters	Values		
Tillage			
Tillage method			
No of tillage application	1		
Month	April 20		
Fertilization (if any)			
Application type	Manual		
Application depth	surface 0.2 cm		
Urea (kg/ha)	0, 10 (for starter fertilizer), 50, 100, 150		
Phosphate (kg/ha)	30 (for starter fertilizer)		
No of application	1, 2, 3, 4		
Application date	May 1, May 21, June 11, June 31		
Manure amendment (if any)			
	Solid C/N	Organic C (kg C/ha)	Organic N (kg N/ha)
Green manure (hairy vetch)	11	1975	179.4
Green manure (crimson clover)	17	2286.5	134.5
Green manure (winter wheat)	80	8000	100.1
Green manure (native grass)			
No. of manure application	1		
Application method	surface spread		
Depth (m)	0.2		
Irrigation			
Irrigation input mode	Based on irrigation index		
Method	Furrow		
Application method	Scheduled irrigation		

TABLE 4 Effects of cover crops on soil health parameters (0- to 7.6-cm depth) after 10 years of study.

Cover crops	pH	OM (%)	C (% DW)	N (% DW)	C:N (% DW)	P (ppm)	Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	S (ppm)
Native grass	6.1	0.91	0.789	0.1	8.7	82	6	183	736	91	8
Hairy vetch	5.6	1.04	0.994	0.089	11.2	83	3	138	624	71	9
Winter wheat	5.6	0.95	0.874	0.086	10.2	72	3	123	593	70	10
Crimson clover	6	1.07	0.974	0.091	10.6	93	3	141	718	78	8

Abbreviations: DW, dry weight; OM, organic matter.

(Habbib et al., 2017; Hirel et al., 2011; Thorup-Kristensen, 2001; Tonitto et al., 2006). Legume crops could generally fix atmospheric N and store ~56 to 170 kg/ha N in the root by forming nodule-like structures and increase crop yield across the long term. In contrast, the non-legume crops scavenged the leftover N from the previous crop residue. They returned it to roots and aboveground plant materials, suggesting they prevented N leaching loss into water bodies (Nouri et al., 2019; Plaza-Bonilla et al., 2015; Thapa et al., 2018).

Inclusion of cover crops during the winter season in a cotton-dominated cropping system improved the soil health parameters. The final soil analysis showed that cover crop incorporation scavenged the soil nutrients across the 10 years and reduced nutrient loss compared to the first year (Table 4). Notably, soil C content increased and pH decreased in the last year of the study.

Many previous studies described the long-term winter cover crop incorporation to improve soil properties, which ultimately increased crop yield and soil quality and, in turn, ecosystem functionality (Abdollahi & Munkholm, 2014; Blanco-Canqui et al., 2009, 2011, 2013). Cover crop could restore back the lost soil nutrients by adding biomass input, getting the microbes and soil fauna back into balance under the NT system (Snapp et al., 2005; Triplett & Dick, 2008). The soil might experience competition for N during the initial transitional years in a low residue return crop like cotton.

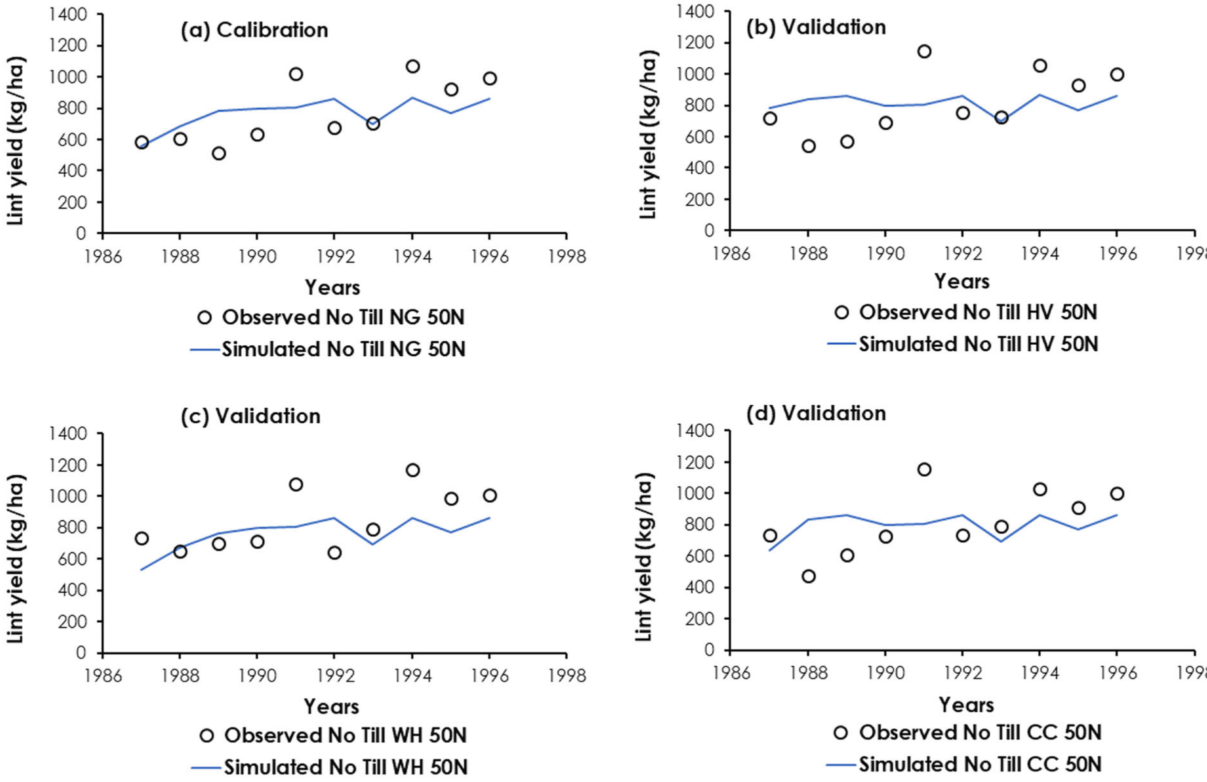

FIGURE 3 Comparisons of long-term cotton lint yields at different cover crops simulated with the denitrification–decomposition (DNDC) model. 50 N = 50 kg/ha N; CC, crimson clover; HV, hairy vetch; NG, native grass; WH, winter wheat.

However, more N was stored in the soil as a form of OM and humus across the long term. For example, using cover crops increased the soil C content in past studies and protected the soil from surface runoff erosion, sustaining crop production (Fronning et al., 2008; Garland et al., 2021).

3.2 | Model calibration and validation

This study used the NT-NG 50 N treatment for model calibration by comparing simulated and observed cotton yields across the 10 years (Figure 3). Observed values above the simulation line indicated underestimations, while values below the line represented overestimations of the model. The relative ME value was 0.3, and the NRMSE value was ~21% for the calibration model, indicating the fair performance of the model.

In Table 5, the simulated values of cotton yield under various cover crops with different N rates (NT-HV 50 N, NT-HV 50 N + starter fertilizer, NT-WH 50 N, NT-WH 50 N + starter fertilizer, NT-CC 50 N, NT-CC 50 N + starter fertilizer) represented the performance of the DNDC model in the validation process. The NT 50 N treatment for other cover crops provided similar model accuracy with ~24%, ~21%, and ~25% NRMSE values for HV, WH, and CC, respectively. The model was also evaluated under NT 50 N + starter fertilizer treatments with HV, WH, and CC cover crops, and it presented a good simulation (NRMSE ~24%) on cotton lint yields across the 10 years. The ME values indicated almost similar values for observed and simulated cotton yields when they have fair model efficiency. Although the DNDC model provided low NRMSE (%), such accuracy provided adequate yield prediction in previous studies due to the long-term experiments with high variability (Ku et al., 2018; Zhang et al., 2022).

3.3 | Scenario analysis

3.3.1 | Prediction of soil C sequestration

The DNDC model generated soil C sequestration trends under various cover crop incorporations by considering crop residue return and manure application (e.g., main crop and cover crop) into the soil throughout each cropping year. This study represented the effects of four cover crops under NT 50 N (Figure 4). The WH incorporation showed the highest C sequestration after 10 years of study, which was significantly noticeable among them. At the end of this study, the simulated SOC content became more than three times in the first year under WH.

Unlike WH, the differences in SOC contents were not noticeable among other cover crops, although the SOC

TABLE 5 Model validation results for cotton lint yields under cover crop residue incorporation.

Treatment/ diagnostic parameter	NT-NG 50 N (calibration)	NT-HV 50 N (validation)	NT-HV 50 N + starter fertil-izer(validation)	NT-WH 50 N (validation)	NT-WH 50 N + starter fertilizer (validation)	NT-CC 50 N (validation)	NT-CC 50 N + starter fertilizer (validation)
NRMSE	21	24	24	21	23	25	24
ME	0.297	−0.032	−0.03	−0.023	−0.17	−0.098	−0.08
Standard error (%)	30	65	65	61	61	65	65
Coefficient of determination (R^2)	0.30*	NS	NS	0.21	0.05*	NS	NS

Abbreviations: 50 N, 50 kg/ha N; CC, crimson clover; HV, hairy vetch; ME, Nash–Sutcliffe model efficiency; NG, native grass; NRMSE, normalized root mean square error; NS, not significant; NT, non tillage; starter fertilizer, N-P_2O_5-K_2O (10-30-0); WH, winter wheat.

*Significant at $p < 0.05$, $n = 10$.

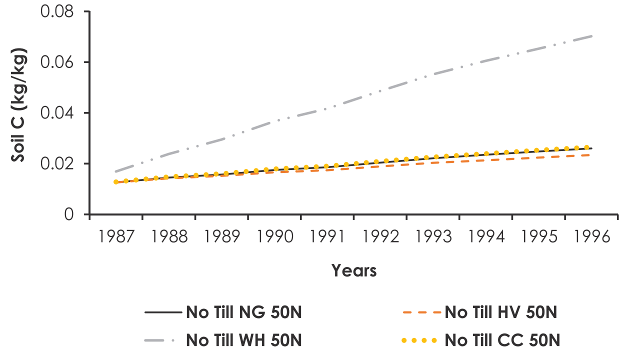

FIGURE 4 Denitrification–decomposition (DNDC) model simulated soil C sequestration under various cover crops. 50 N = 50 kg/ha N; CC, crimson clover; HV, hairy vetch; NG, native grass; WH, winter wheat.

content increased linearly across the 10 years. The model showed the potential of cover crops in sustaining cotton production by improving C contents. Additional aboveground and belowground biomass input from cover crops in the NT system could provide additional benefits to increase soil organic matter (SOM) contents, protect the soil from water and wind erosion, improve soil physical (e.g., aggregate stability, bulk density), chemical (e.g., nutrient status and C and N gas emission), and biological properties (e.g., microbial activity, biodiversity), increase SOC concentration, and sustain crop production. Fronning et al. (2008) reported that 4 years of manure and compost-application increased SOC by 25% and 36%, respectively, compared with the inorganic fertilizer application. Thus, in a NT system, the use of winter cover crops is crucial to sustaining the soil health for cotton production.

3.3.2 | Yield response to nitrogen and water stress

The additional scenario analysis was conducted, emphasizing the cotton yields under four different cover crop residues (e.g., HV, CC, WH, and NG) as green manure amendments, incorporating four N application rates (e.g., 0, 50, 100, and 150 kg/ha) and three irrigation events (e.g., 0, 10, and 10 cm × 2 times) to better understand the long-term cotton yield response under different N applications, water applications, and cover crops. For each time, the DNDC model was utilized using the same input data of climate, soil, and farming management practices, except for fertilization (e.g., different N rates) or green manure amendment (e.g., cover crops of various C:N ratio), or irrigation (e.g., depth) depending on the management condition (Figure 5). According to the scenario analysis I, the WH incorporation resulted in greater yield than other cover crops under no irrigation, and yield increased with N application and irrigation. The HV, CC, and NG cover

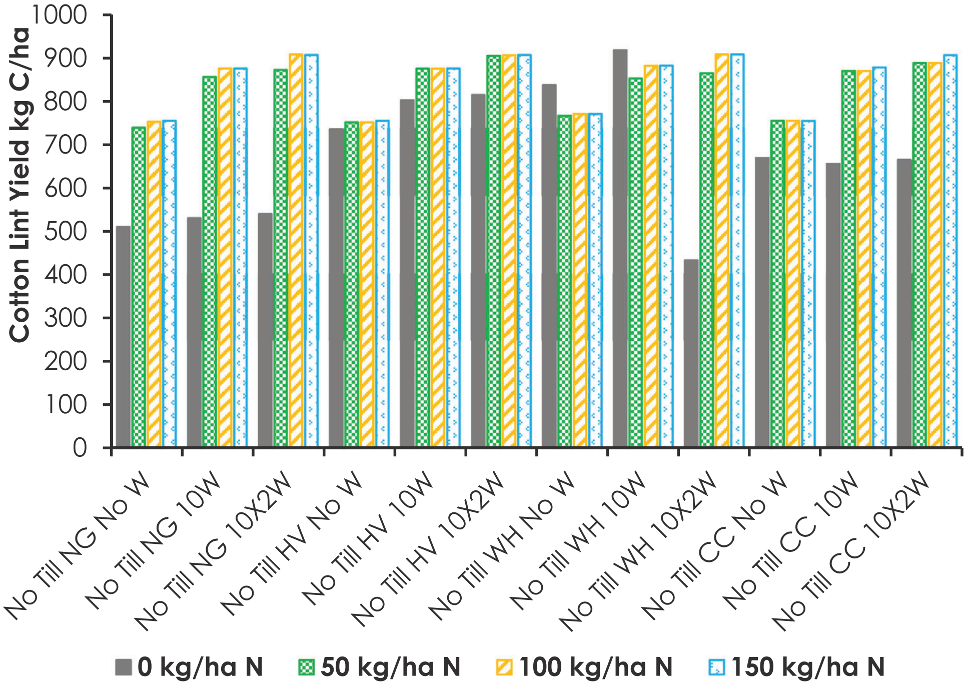

FIGURE 5 Effects of N application and irrigation event on cotton lint yield under different cover crops. Lint yield values are showing the average of 10 years. 10 W = 10 cm irrigation; 10 × 2 W = double application of 10 cm irrigation; CC, crimson clover; HV, hairy vetch; NG, native grass; WH, winter wheat.

crops assured similar increasing yield patterns with increased irrigation events, whereas cotton yield only decreased after receiving double-irrigation events under WH incorporation. Irrigation event was estimated by water application to a certain depth and application frequency per season. The HV incorporated field produced the highest yields after receiving a double-irrigation (10-cm depth × 2 times/season) events. However, in other cover crop residue-incorporated fields, the single-(10-cm depth/season) and double-(10-cm depth × 2 times/season) irrigation events did not show a noticeable yield difference. The model indicated that the irrigation events could efficiently increase the cotton yield after receiving a certain dose. The DNDC model predicted that soil N leaching loss and runoff were increased (e.g., 0–60 kg N/ha) under the raised N levels and irrigation events. Eventually, the scenario analysis I suggested the 50 kg N/ha application and single-irrigation event (10-cm depth) as the most feasible and efficient strategies for improving cotton yields.

Similarly, previous studies predicted 0%–55% N loss of the crop demand by overfertilization of N (Ku et al., 2018; Tonitto et al., 2006). Thus, cover crop was considered an adaptive management in the long-term NT system to obtain N, irrigation efficiency, and sustainability (Habbib et al., 2017; Munkholm et al., 2013). Since cotton production might slightly fluctuate over the long-term period under the effects of various cover crops, depending on N balance (gain/loss), selecting an effective N application rate is crucial. The DNDC model predicted the relationship between cover crop biomass and water stress on crop yields under N application (Figure 6).

The model input value for the increased cover crop biomass was adjusted with the applied seeding rate. This study observed that the increased biomass application had minimal impacts on crop yield. Additionally, the application of irrigation water improved cotton yield regardless of N application rate, when increased biomass without irrigation presented a significantly reduced crop yields. Double-irrigation events with increased biomass application could not increase the yield by 3.3% compared with single-irrigation events with increased biomass application regardless of N application rates.

Effects of increasing cover crop biomass might vary based on the relationship between the main and cover crop species (e.g., saturation index, senescence, and greenness of leaves). In addition to crop species, a variety of factors, including planting date, planting method, and C:N ratio in soils, could lead to a large range of biomass on cover cropped fields (De Notaris et al., 2021; Prabhakara et al., 2015). In this study, the decomposition rate of OM might be faster with legume cover crops with C:N ratio < 20, compared to nonlegume cover crops. Adding more biomass from a leguminous crop like HV could contribute to the cotton field by building up extra N, although most of the extra N might be subjected to leaching loss. Because of the leaching loss, the simulated results might have no noticeable change after excess N fertilization and irrigation events. The high slope (0%–2%), soil texture,

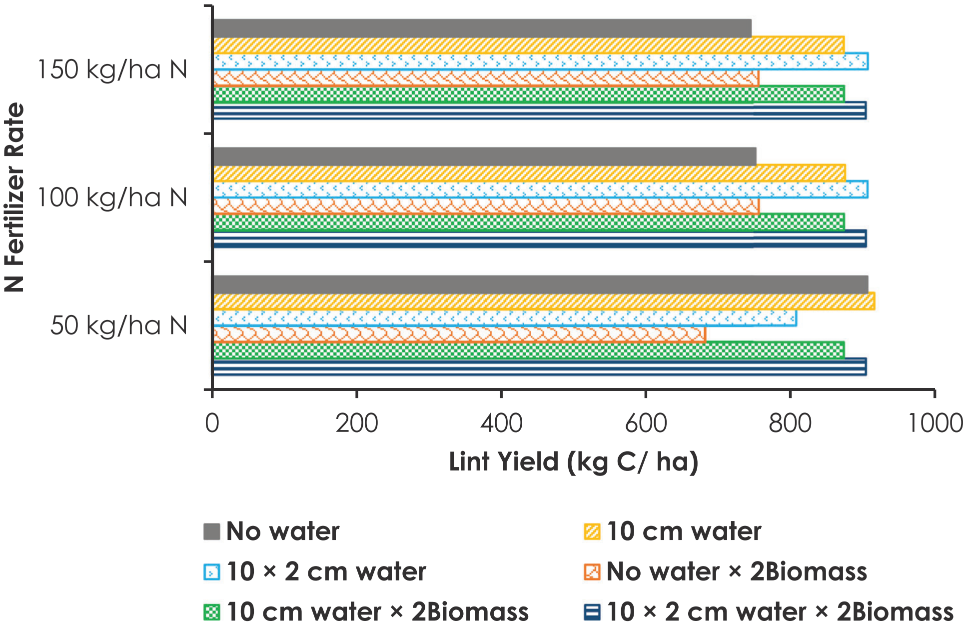

FIGURE 6 Effects of increasing seed rates for hairy vetch (HV) on cotton lint yield under different N and water applications. 10 cm water = 10 cm irrigation, 10 × 2 cm water = double application of 10 cm irrigation, 2Biomass = double seed rate. Lint yield values are showing the average of 10 years.

and precipitation intensity of the study area might exacerbate the N and C loss through leaching and runoff, resulting in a similar yield even after doubling the biomass content. For instance, past studies found no yield difference between no cover crop (e.g., NG) and cover crop, suggesting minimal fluctuations in soil fertility when observed increased drought (DeLaune et al., 2020; Reddy, 2001). However, the farmers could avoid the leaching loss and take advantage of legume crops by selecting certain cover crops, fertilizer rates, irrigation rates, and timing of farming management practices to achieve sustainable agriculture.

3.3.3 | Yield response and soil C sequestration under different tillage systems and irrigation rate

To explore the long-term effects of different tillage systems with irrigation rates over cotton production and soil C sequestration, the DNDC model was used to simulate the effects of five tillage systems, for example, furrow, slight plow (5 cm plough), plowing with chisel/disk (10 cm), plowing with moldboard (20 cm), and deep plow (30 cm). Each time, four irrigation rates (e.g., 0, 10, 10 × 2, and 10 × 3 cm), 50 kg N/ha, and three rates of manure amendments were used for simulation, keeping the same input data of climate, soil, and other farming management practices in the model. The irrigation rates indicated the level (depth) of water and the number of applications. The yield trend was similar under different tillage systems and increased in response to additional irrigation events, presenting similar results as in scenario I (Figure 5). The yield trends of NG, HV, and WH in scenario are shown in Figure 7. Without irrigation events, average cotton yields were increased with WH residue incorporation (~650–750 kg C/ha) (except for moldbold plow). After irrigation application, the DNDC model predicted noticeable increase in lint yield trends with all NG and cover crop systems. The yields from the cover crop systems for all crop species and tillages were slightly higher than NG system. Among cover crops, the legume and non-legume cover crops produced similar lint yields. In addition, the lint yield trends did not fluctuate much with different tillage systems when irrigated. For instance, the average simulated yield ranged from ~850 to 900 kg C/ha under different tillage systems. The model predicted that the furrow plow application presented relatively low lint yield than other tillage systems with all cover crops.

The simulation results showed noticeable changes across the long-term SOC storage (0- to 10-cm depth) under different irrigation systems (Figure 8). The average SOC content was the highest under furrow plow for all cover crops, and the effects of tillage systems were particularly visible for NG. In the case of NG, the SOC sharply decreased with increasing tillage depths, while WH surprisingly maintained the same C content (~0.015 kg/ha) during all irrigation events (Figure 8). The model predicted that the HV residue incorporation showed better resistance against tillage systems and accumulated a significant amount of SOC (~0.016 kg/ha) under furrow and slight plow tillage systems compared to WH.

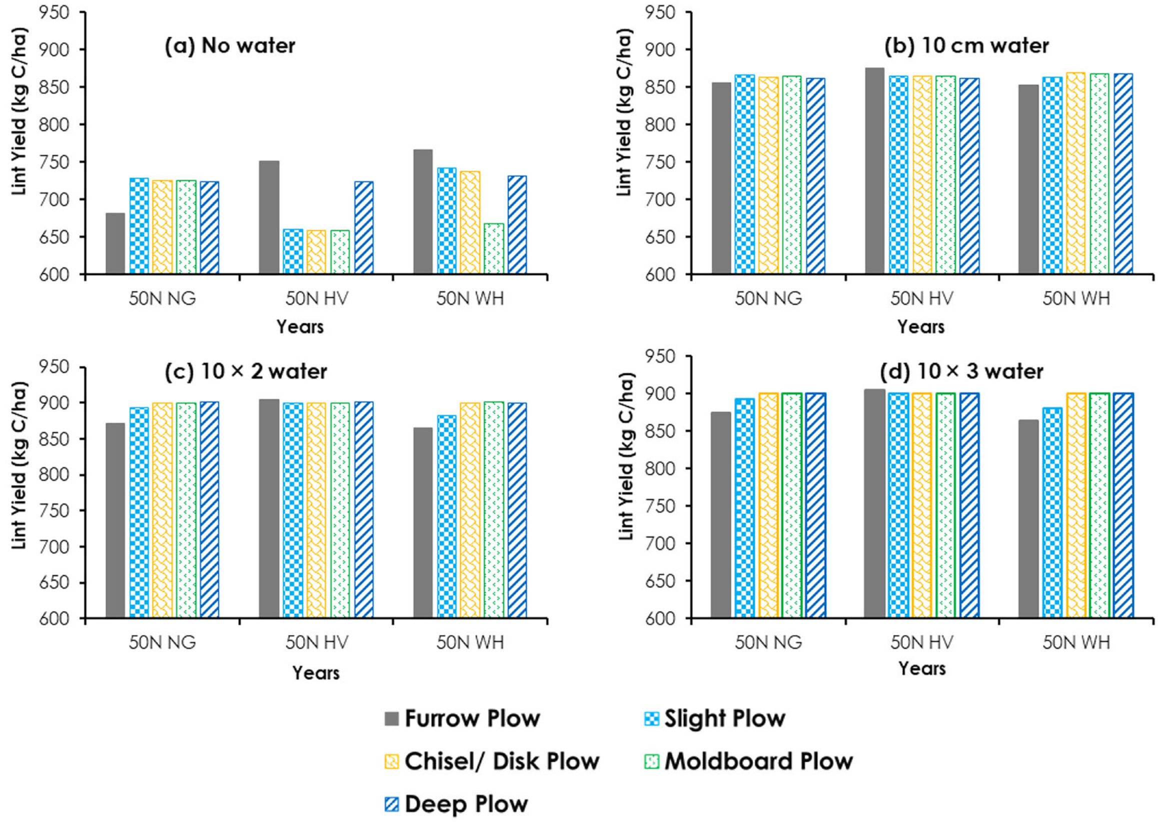

FIGURE 7 Effects of tillage systems and irrigation events on cotton lint yield under different cover crops; (a) no water, (b) 10 cm water = single irrigation, (c) 10 × 2 cm water = double application of 10 cm irrigation, and (d) 10 × 3 cm water = triple application of 10 cm irrigation. Lint yield values are showing the average of 10 years. 50 N = 50 kg nitrogen/ha; HV, hairy vetch; NG, native grass; WH, winter wheat.

In general, tillage operations induce atmospheric oxygen into the soil and stimulate microbial growth and activity. The increased microbial activities enhance the decomposition of organic residues and the release of soil nutrients. Continuous, long-term tillage operations might oxidize or burn up SOM and decline soil productivity, leading to poor soil structure and health (Abdollahi & Munkholm, 2014; Dozier et al., 2017; Erisman et al., 2013). Olson et al. (2014) reported that the trend of cotton yield without cover crop was significantly different under the various tillage systems and the legume sequestrated 26.8 mg C/ha/year in soil (within 0- to 15-cm depth). On average, 30%–70% C contents could be increased under legume-based NT systems (Motta et al., 2007; Olson et al., 2014). In addition to cover crop, the C sequestration rate also varied with leaching, runoff, and evaporation loss depending on the slope, texture, and precipitation events.

4 | CONCLUSIONS

Adopting a CA system that provides environment sustainability and improves agricultural production is crucial. Intensive tillage operations under conventional agriculture accelerate soil C decomposition and increase the C and N loss through different ways (i.e., runoff, leaching, and erosion). On the other hand, the CA preserves the soil from environmental changes and improves soil health and quality by increasing biodiversity and multi-functionality. As a process-based model, the DNDC model presented a rigorous illustration on the cotton yield, N loss, C sequestration, and many other plant and soil properties under various possible management practices. The field data indicated that winter cover crop incorporation under the NT system could not significantly increase cotton yield in the shorter term (e.g., 3/4/5 years) compared to NG. However, the CA maximizes the yield and C storage across the long term. The model predicted the relatively improved cotton yield with optimum N level (50 kg N/ha), irrigation event (single irrigation of 10-cm depth), seed rate (single seed rate), and furrow tillage system. The WH incorporation showed the most effective cotton production among the cover crops under NT practice due to the balanced C:N ratio, although yield fluctuated across the study years, particularly in the initial years. The DNDC model accurately evaluated the cotton production over the long-term study and suggested potential soil C enhancement. Findings from this study would encourage other researchers to explore more possible scenarios using the model and allow farmers to

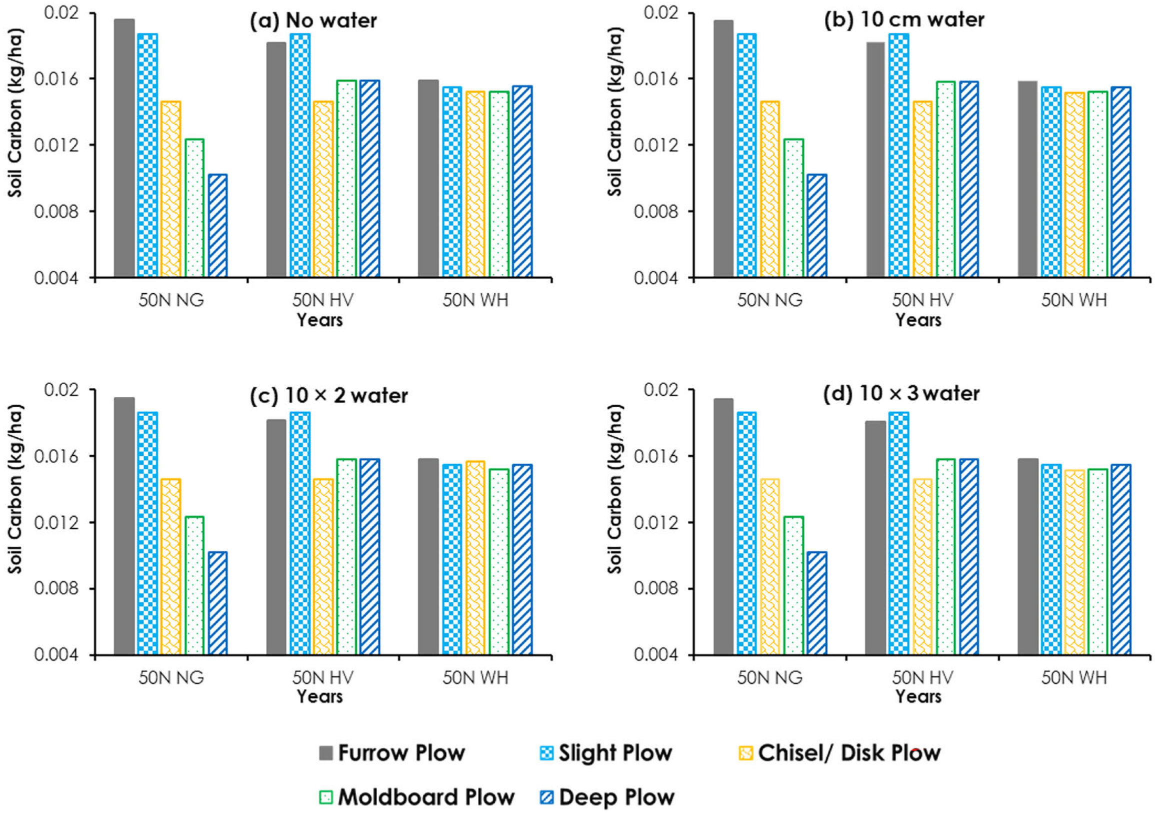

FIGURE 8 Effects of tillage systems and irrigation on C sequestration under different cover crops; (b) 10 cm water = single irrigation, (c) 10 × 2 cm water = double application of 10 cm irrigation, (d)10 × 3 cm water = tripple application of 10 cm irrigation. Lint yield values are showing the average of 10 years. 50 N = 50 kg nitrogen/ha; HV, hairy vetch; NG, native grass; WH, winter wheat.

recognize the advantages and better utilize the NT system for effectively practicing CA with more confidence.

AUTHOR CONTRIBUTIONS

Janntul Ferdush: Data curation; writing—original draft; writing—review and editing. **Changyoon Jeong**: Conceptualization; data curation; funding acquisition; investigation; resources; supervision; validation; visualization; writing—review and editing. **Hwangju Jeon**: Resources; writing—review and editing. **Jim Wang**: Validation; visualization; writing—review and editing. **Kyoung Ro**: Writing—review and editing. **Xi Zhang**: Resources; validation; writing—review and editing. **Meesook Lee**: validation; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Changyoon Jeong https://orcid.org/0000-0001-7181-6750
Jim Wang https://orcid.org/0000-0001-5082-8234

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