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Modeling biogeochemical impacts of alternative management practices for a row-crop field in Iowa

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Abstract

The management of contemporary agriculture is rapidly shifting from single-goal to multi-goal strategies. The bottleneck of implementing the strategies is the capacity of predicting the simultaneous impacts of change in management practices on agricultural production, soil and water resources and environmental safety. Process-based models provide an opportunity to quantify the impacts of farm management options on various pools and fluxes of carbon and nitrogen (N) in agroecosystems. The denitrification–decomposition or DNDC model was recently modified for simulating N cycling for the U.S. Midwestern agricultural systems. This paper reports a continuous effort on applying the model for estimating the impacts of alternative management practices (e.g., no-till, cover crop, change in fertilizer rate or timing) on agro-ecosystems in the Midwestern U.S. A typical row-crop field in Iowa was selected for the sensitivity tests. The modeled results were assessed with a focus on four major indicators of agro-ecosystems, namely crop yield, soil organic carbon (SOC) sequestration, nitrate–N leaching loss and nitrous oxide (N_2O) emissions. The results indicated that no-till practice significantly increased SOC storage and reduced nitrate–N leaching rate, but slightly decreased crop yield and increased N_2O emissions. By modifying the methods of fertilizer application in conjunction with the no-till practice, the disadvantages of no-till could be overcome. For example, increasing the fertilizing depth and using a nitrification inhibitor could substantially reduce N_2O emissions and increase crop yield under the no-till conditions. This study revealed the complexity of impacts of the alternative farming management practices across different climate conditions, soil properties and management regimes. Process-based models can play an important role in quantifying the comprehensive effects of management alternatives on agricultural production and the environment.

Keywords: Agro-ecosystem management; Crop yield; DNDC model; Nitrate–N leaching; N_2O emission; Soil organic carbon sequestration

1. Introduction

Contemporary agriculture is in a transition from single-goal to multi-goal management systems. Optimum yield is not the sole criterion for assessing the success of agricultural production. Instead, concerns about the impacts of agricultural activities on soil fertility, water resources, and environmental safety are now included in assessments of best management practices (Tilman et al., 2002). A crucial task for implementing multi-goal management involves building the capacity to quantify the simultaneous impacts of any single or combined alternative practices on crop yield, soil carbon storage, nutrient leaching and greenhouse gas emissions. Most agro-ecosystems are complex systems, within which climatic, soil and management factors intricately interact. Field experiments play a key role in obtaining first-hand information about the effects of

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alternative management practices on crop yield and various carbon (C) or nitrogen (N) pools or fluxes in the concerned fields. However, most field experiments require extensive time and resources. To extrapolate the understanding gained at a limited number of field sites to regional scales, process-based models have been developed and adopted to assist the policy making process in agricultural studies (Ahuja et al., 2002). During the past decade a number of agro-ecosystem models were developed that incorporate the complex interactions among climate, soil, plant growth and management practices. The modeling efforts have provided opportunities to assess the best management practice strategies in a range of scales from individual farms to watersheds and regions (Tsuji et al., 1994; Ahuja et al., 2000; Zhang et al., 2002; Donner and Kucharik, 2003; Li et al., 2006). Among these modeling efforts, the process-based, biogeochemical model, denitrification–decomposition or DNDC, was developed originally for estimating greenhouse gas emissions from U.S. agricultural lands (Li et al., 1992). This model was recently modified to enhance its capacity in predicting crop growth and yield, simulating discharge flow from tile-drained fields, and quantifying nitrate leaching while accounting for the soil buffering effect of ammonium (Li et al., 2006). The new modifications, plus the existing features of soil organic carbon (SOC) turnover as well as N gas emissions in DNDC, have made the model capable of simultaneously predicting crop yield, SOC dynamics, nitrate–N leaching and trace gas emissions under a wide range of farm management conditions, especially for the row-crop fields in the U.S. Midwest. This new version of DNDC has been preliminarily tested against field data sets observed in Iowa and Illinois with encouraging results (Li et al., 2006; Tonitto et al., 2007a,b).

The study reported in this paper is a continuation of the modeling effort to provide new information about how the new model can be utilized to analyze the complex impacts of alternative management practices related to agricultural/environmental decision making. Generalized impact assessments of alternative management practices, such as no-till, planting of cover crop and changes in fertilizer rate or timing, based on published research literature have been done as to these practices' effects on N and P losses to Midwestern U.S. surface waters (Dinnes, 2004). But as pointed out by Dinnes (2004), a key area of research needed to advance efficient agricultural land management is the development of more accurate, predictive computer models to quantitatively account for factors (i.e., climate, management practices) that change over space and time.

Applications of some alternatives (e.g., no-till) have shown potential for soil conservation or soil carbon sequestration, although comprehensive assessments of the alternative practices regarding their impacts on production and the environment are still lacking. For example, several field or modeling studies reported in publications indicated that no-till could elevate nitrous oxide (N_2O) emissions that may offset the benefit gained from the SOC sequestration in no-till fields (Mummey et al., 1998), however, other practices such as the type and amount of fertilizer application could determine enhancement or mitigation of N_2O emission (Venterea et al., 2005). Since the DNDC model has incorporated a relatively complete set of biogeochemical processes for the most common farming management practices (e.g., tillage, fertilization, manure amendment, irrigation, flooding, drainage and grazing) for Midwestern U.S. croplands, the model was utilized in this study for a series of sensitivity tests to improve our understanding by addressing the following objectives: (1) tso determine how the selected alternative management practices may simultaneously affect crop yield, SOC dynamics, nitrate–N leaching and N_2O emissions, and (2) to determine how a best management practice could be composed by optimizing the combination of the alternatives based on the local climatic and soil conditions. A typical row-crop field with tile-drainage measuring facilities in Iowa, with a long-term database, was selected as a target site for the sensitivity testing of no-till, cover crop and reduced fertilizer rate and for their impacts on the crop yield, SOC storage, nitrate–N leaching and N gas emissions. The results from the tests were compared with observations collected from the literature to verify the acceptability of the modeled results.

2. Materials and methods

2.1. The DNDC model

The DNDC Model was originally developed for estimating greenhouse gas emissions from U.S. agro-ecosystems (Li et al., 1992, 1996). The model incorporates a suite of processes that describe soil hydrology, plant growth, and biogeochemical reactions governing transport and transformation of C, N and water in the plant–soil systems. DNDC consists of six submodels for simulating soil climate, crop growth, decomposition, nitrification, denitrification and fermentation, respectively (Li et al., 1992, 1994, 2006; Li, 2000; Zhang et al., 2002). For nearly the past 15 years, DNDC was tested against a number of observed datasets of crop yield, SOC dynamics and trace gas emissions (Li, 2000; Brown et al., 2002; Li et al., 2003a,b; Butterbach-Bahl et al., 2004; Grant et al., 2004; Saggar et al., 2004; Smith et al., 2004; Pathak et al., 2005, 2006; Jagadeesh Babu et al., 2006; Liu et al., 2006a; Neufeldt et al., 2006; Sleutel et al., 2006; Zhang et al., 2006).

The latest efforts in refining DNDC were carried out for Midwestern agriculture and focused on improving model parameters for the region's specific soil textures and hydrologic systems. Model applicability was tested using long-term measurement data of water and nitrate–N leaching from the row-crop farm fields in Iowa and Illinois (Li et al., 2006; Tonitto et al., 2007a,b). The efforts resulted in several modifications of the model. The one-dimensional

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water movement algorithm in DNDC was modified for the tile-drained soils by adopting a water discharge recession curve, based on Tallaksen (1995), where the depth of saturation decreases gradually with a decrease in precipitation. In addition, a virtual water pool was added to the modeled soil to track the water reserve in the space interval between the tile lines (usually >100 cm) and the bottom of the modeled soil profile (0–50 cm). The processes governing nitrate–N leaching were modified by adopting the Langmuir equation to quantify adsorption and desorption of ammonium ions on clay and organic matter (Li et al., 2006). The modified features of water flow and nitrate–N leaching, working in conjunction with the functions originally existing in DNDC, enhanced its capacity for predicting impacts of management practices on agricultural production and the environment simultaneously. The improved DNDC was utilized in this study to explore the mechanisms underlying the simultaneous impacts of alternative practices on crop yield, SOC storage, nitrate–N leaching and N gas emissions for the Midwestern agricultural lands.

2.2. Site specifications

The selected site was located in a row-crop farm field, near Story City in central Iowa (42.2°N latitude and 93.6°W longitude), with an annual precipitation that ranged from 490 to 1500 mm during the period of 1980–1999 (Table 1). The local soils are in Kossuth (fine-loamy, mixed, mesic Typic Endoaquolls)-Ottosen (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) association with a small area of Harps Loam (Fine-loamy, mixed, mesic Typic Calciaquolls) and Okoboji (silty clay loam, fine, smectitic, mesic Cumulic Vertic Endoaquolls). The soils are characterized by high clay and SOC content (sandy clay; soil pH 6.0; bulk density 1.15 g cm^{-3}; initial SOC content 0.025 kg C kg^{-1}at the 0–0.15 cm soil depth) and poor drainage capacity. Parallel drainage pipes or ''tiles'' were installed at an average depth of 1.45 m in 1992. Detailed soil specifications have been presented in Jaynes et al. (2001), and Brevik et al. (2003). The measured data at the site for water and nitrate–N leaching from 1996 through 1999 have been utilized for validating DNDC earlier (Li et al., 2006).

For the purpose of sensitivity analyses, climate and soil conditions of the study field were applied as initial conditions for the model simulations. The scenarios for management practices were designed in coordination with the Iowa Department of Natural Resources' recommendations for the management of non point source pollutants of Iowa's surface waters (Dinnes, 2004). The management scenarios included corn and soybean that were rotated each year with planting date on May 1 and harvest date on October 1. We assumed that all crop residues were left on the field after harvest and incorporated in the soil following the next tillage practice. Urea at the rate of 120 and 30 kg-N ha^{-1} was applied to corn and soybean, respectively, at the planting time. Table 1 summarizes baseline and alternative soil, climate and management scenarios that were tested for sensitivity analyses.

2.3. Baseline and alternative management practices scenarios

Alternative management practices have been widely discussed in regard to their potentials for limiting the negative environmental impacts of contaminant transport from Midwestern crop fields. One of the primary strategies that have been discussed to reduce the nitrate–N leaching is to improve the soil water and SOC storage (Dinnes, 2004). For example, no-tillage soil management has been steadily increasing during the period between 1994 and 2004 with the percentage of total U.S. cropland in no-till increasing from 14 to 23% (Conservation Technology Information Center, 2004). Field experiments were conducted to observe the impacts of the alternative practices on crop yields, SOC sequestration, N_2O emissions or other relevant environmental issues (Parkin and Kaspar, 2006; Venterea et al., 2005). However, due to the complexity of the interactions between the farming practices and the responses of the agro-ecosystems, the field measurements carried out at different sites sometimes resulted in inconsistent conclusions. For example, higher N_2O emissions in no-till than in conventionally tilled cropping systems have been reported (MacKenzie et al., 1997; Ball et al., 1999; Baggs et al., 2000), although some studies have found lower emissions in no-till soils or no difference between tillage systems (Robertson et al., 2000; Elmi et al., 2003; Venterea et al., 2005). In a recent review, Six et al. (2004) concluded that differences in N_2O fluxes between tilled and no-tillage change over time, with N_2O fluxes higher within the first 5 years after conversion to no-tillage but then declining after the first decade. The discrepancies shown in the literature should be understandable as the same practice could produce different results when it is applied at different sites with varied climatic, soil or other management conditions. To test this hypothesis, we designed a series of scenarios by varying and combining three major alternative management practices, namely no-till, cover crop and alternative fertilizer use, for a typical row-crop field in Story County, Iowa. To observe the long-term effect, we ran each scenario for 20 years using the actual daily weather data for Story County from 1980 to 1999.

Two baseline scenarios were mainly designed for conventional tillage (CT) and no-till practice (NT). The two scenarios shared similar climatic, soil and other management (crop rotation, fertilization) conditions, only with tillage methods differing from each other. For the CT scenario, the soil was tilled twice to depth 20 cm on May 1 (day of planting) and October 10 (after the harvest). For the NT scenario, the residue is left at the soil surface and the soil was not physically disturbed.

Alternative scenarios were composed to represent changes in fertilizer application, cover crop, soil properties and climatic conditions in conjunction with the applied no-till practice. (Tables 1 and 2). As soybean was a minor

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Table 1
Baseline and alternative climate, soil and management conditions for the tested field in Story County, Iowa

Scenario	Descriptions
CT (conventional tillage)	1980: 9.1 °C/564 mm[a] 1981: 9.6 °C/657 mm 1982: 8.1 °C/1150 mm 1983: 9.0 °C/l207 mm 1984: 9.0 °C/986 mm 1985: 7.9 °C/702 mm 1986: 9.4 °C/1114 mm 1987: 10.9 °C/922 mm 1988: 9.6 °C/493 mm 1989: 8.4 °C/615 mm 1990: 9.9 °C/1214 mm 1991: 9.3 °C/1039 mm 1992:9.0 °C/855 mm 1993:7.8 °C/1499 mm 1994: 8.7 °C/784 mm 1995: 8.6 °C/775 mm 1996:7.4 °C/876 mm 1997: 8.6 °C/722 mm 1998: 10.5 °C/859 mm 1999:9.8 °C/852 mm Soil: sandy clay; soil pH 6.0; bulk density 1.15 g cm^{-3}; initial SOC content 0.025 kg C kg^{-1} Crops: corn–soybean rotation; planted on May 1, harvested on October 1 for both corn and soybean Tillage: conventional tillage: disked to 20 cm depth on May 1 and chisel plowed on October 10 every year Fertilization: 120 and 30 kg urea-N ha^{-1} for corn and soybean, respectively; applied on soil surface on May 1 Others: no cover crop; no manure applied
NT (baseline no-till)	Same as CT except with no-till: only mulched on May 1 and October 10 every year
NT-60 kg N	No-till with 60 kg urea-N ha^{-1} used for corn[b]
NT-80 kg N	No-till with 80 kg urea-N ha^{-1} used for corn[b]
NT-100 kg N	No-till with 100 kg urea-N ha^{-1} used for corn[b]
NT-140 kg N	No-till with 140 kg urea-N ha^{-1} used for corn[b]
NT-160 kg N	No-till with 160 kg urea-N ha^{-1} used for corn[b]
NT-2 splits	No-till with 120 kg urea-N ha^{-1} split to 2 applications (May 1 and June 15) for corn[b]
NT-3 splits	No-till with 120 kg urea-N ha^{-1} split to 3 applications (May 1, June 15 and August 1) for corn[b]
NT-15 cm	No-till with 120 kg urea-N ha^{-1} injected to 15 cm depth for corn[b]
NT-coated	No-till with 120 kg coated urea-N ha^{-1} used for corn[b]
NT-inhibitor	No-till with 120 kg urea-N ha^{-1} in conjunction with nitrification inhibitor used for corn[b]
NT-LCC1	No-till with legume cover crop planted in the corn years
NT-LCC2	No-till with legume cover crop planted in the corn and soybean years
NT-LCCF	No-till with legume cover crop planted in the corn and soybean years with reduced fertilizer rate (80 kg N ha^{-1}) for corn years
Scenario	Descriptions
NT-NLCC2	No-till with non-legume cover crop planted in the corn and soybean years
NT-SOC 0.005	No-till with SOC content 0.005 kg C kg^{-1}
NT-SOC 0.01	No-till with SOC content 0.01 kg C kg^{-1}
NT-SOC 0.015	No-till with SOC content 0.015 kg C kg^{-1}
NT-SOC 0.02	No-till with SOC content 0.02 kg C kg^{-1}
NT-SOC 0.03	No-till with SOC content 0.03 kg C kg^{-1}
NT-SOC 0.035	No-till with SOC content 0.035 kg C kg^{-1A}
NT-loam	No-till with soil texture as loam
NT-silty clay loam	No-till with soil texture as silty clay loam
NT-clay	No-till with soil texture as clay
NT-P − 60%	No-till with average annual precipitation 358 mm (decrease by 60%)
NT-P − 40%	No-till with average annual precipitation 536 mm (decrease by 40%)
NT-P − 20%	No-till with average annual precipitation 715 mm (decrease by 20%)
NT-P + 20%	No-till with average annual precipitation 1073 mm (increase by 20%)
NT-P + 40%	No-till with average annual precipitation 1252 mm (increase by 40%)
NT-P + 60%	No-till with average annual precipitation 1430 mm (increase by 60%)

[a] Annual average daily temperature/annual precipitation.
[b] Fertilizer rate for soybean remained unchanged as 30 kg urea-N kg^{-1}.

fertilizer consumer, fertilizer rates for soybean production years was not changed in alternative scenarios. The fertilizer splitting practice was implemented only for the corn years. Scenario ''NT-15cm'' shifted the fertilizing depth from the soil surface (baseline) to 15 cm below the soil surface. ''NT-coated'' replaced the traditional urea with coated urea, which slowly release N into the soil within 120 days. ''NT-Inhibitor'' indicates a nitrification inhibitor was continuously applied to keep the effective period for 120 days. In cover cropping scenarios the cover crops were planted in the prior fall after the prior primary crop's harvest and terminated in the next spring.

Each of the scenarios listed in Table 1 was run for 20 years. The modeled annual crop yield, change in SOC content, nitrate–N leaching, N_2O flux and total denitrification rate were recorded for each year with each scenario. Twenty-year averages were also calculated for comparison among the scenarios.

3. Results and discussion

3.1. Biogeochemical effects of conventional tillage versus no-till

Conventional tillage improves soil aeration (albeit temporarily) as well as N availability for crops by introducing more oxygen into the soil profile through

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Table 2
Modeled 20-year average annual yields, SOC changes and relevant N fluxes for a corn–soybean rotated field with baseline and alternative management scenarios in Story County, Iowa

Tillage	Crop yield[a] (kg C ha^{-1})	dSOC (kg C ha^{-1})	N_uptake[a] (kg N ha^{-1})	N_leach (kg N ha^{-1})	N_2O (kg N ha^{-1})	NO (kg N ha^{-1})	N_2 (kg N ha^{-1})	Denitrification (kg N ha^{-1})
CT	4190	−86	140	47	19	2	17	35
NT	3830	415	127	20	28	2	24	54
Fertilizer amount								
NT-60 kg N	3040	276	98	13	23	2	21	45
NT-80 kg N	3310	323	108	15	25	2	22	48
NT-100 kg N	3590	369	118	17	26	2	23	51
NT-140 kg N	4030	459	134	23	30	2	25	57
NT-160 kg N	4120	479	137	28	31	2	27	59
Fertilizer application method								
NT-2 splits	3770	411	125	18	29	2	25	56
NT-3 splits	4010	460	133	16	27	2	26	55
NT-15 cm	4170	480	139	32	14	1	20	35
NT-coated	4090	471	136	14	26	2	27	55
NT-inhibitor	4180	486	139	24	17	1	22	40
Cover crop								
NT-LCC1	3980	763	133	18	32	2	28	61
NT-LCC2	3810	1060	127	16	44	2	32	78
NT-LCC-F	3390	957	113	11	39	2	31	72
NT-NLCC2	3550	786	118	9	29	2	21	51
Soil organic carbon variation								
NT-SOC 0.005	4030	955	134	10	5	1	7	14
NT-SOC 0.01	4070	871	136	14	6	1	10	17
NT-SOC 0.015	3700	676	122	12	21	1	16	38
NT-SOC 0.02	3750	553	124	16	24	2	20	45
NT-SOC 0.03	3910	260	130	24	32	2	29	64
NT-SOC 0.035	4120	123	137	51	13	1	33	47
Soil texture variation								
NT-loam	4190	163	140	39	21	2	31	54
NT-silty clay loam	3850	279	127	20	34	2	27	63
NT-clay	3770	616	125	16	21	1	23	45
Temperature variation								
NT-T + 2	3660	305	121	17	30	2	30	63
NT-T + 4	3500	212	115	11	34	2	37	73
NT-T − 4	3890	760	134	26	18	1	14	33
NT-T − 2	4050	577	135	23	23	2	17	42
Precipitation variation								
NT-P − 60%	3170	257	106	1	28	2	38	69
NT-P − 40%	3780	398	126	9	28	2	27	58
NT-P − 20%	3830	410	127	14	29	2	25	56
NT-P + 20%	3760	406	124	24	27	2	23	53
NT-P + 40%	3730	400	123	27	27	2	24	53
NT-P + 60%	3710	400	122	31	25	2	23	50

[a] Only for corn shown in the table.

physical disturbance. Conversion of conventional tillage to no-till practice will reduce the physical disturbance and increase the area of the soil surface covered by crop residues that help prevent soil erosion on one hand and reduces soil N mineralization rate on the other. The CT and NT scenarios shared similar climatic, soil and management practices (e.g., crop type, planting and harvest dates and method, crop rotation, fertilizer application rate).

The modeled results indicated that soil N mineralization rates with conventional tillage were higher than that with no-till during the simulated 20 years although the difference between CT and NT varied inter-annually driven by weather conditions (Fig. 1a). The 20-year average annual gross mineralization rates were 201 and 157 kg N ha^{-1} for CT and NT, respectively (Fig. 1a). Under the no-till conditions, reduction in the N mineralization rate directly resulted in increased SOC accumulation and less inorganic N available for crop uptake and leaching. The simulated large reductions in N mineralization rates in the first couple of years were caused by overestimation of the labile SOC pools set as the initial conditions (or boundary conditions) for the simulations. The inter-annual variation in N mineralization rates of

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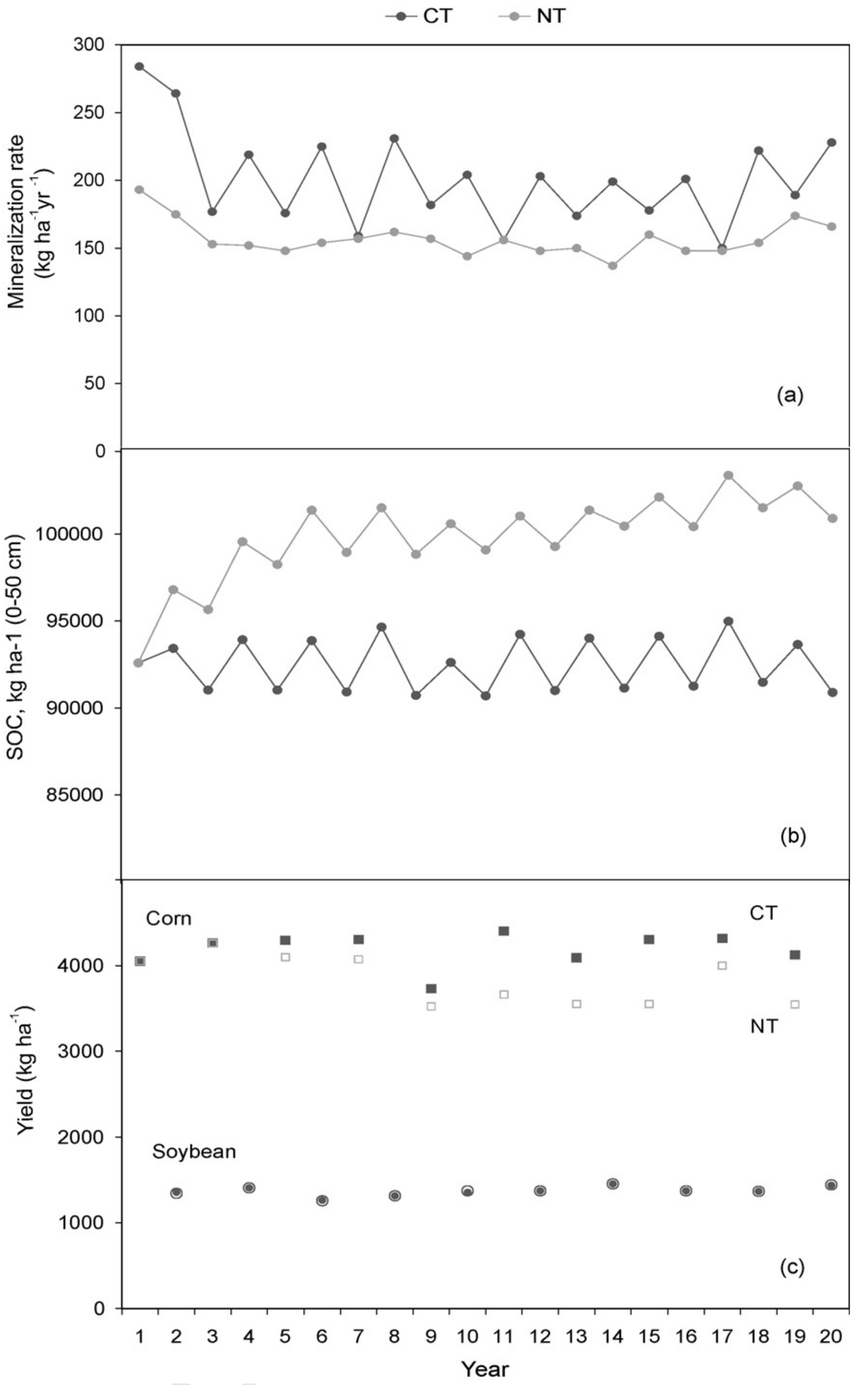

Fig. 1. Modeled 20-year soil mineralization rates (a), SOC dynamics (b), and crop yield (c), in a corn–soybean rotated field with conventional tillage (CT) and no-till (NT) scenarios in Story County, Iowa.

the CT system was greater than that of the NT system due to the stimulated decomposition rates in the CT system driven by the crop residue incorporation and the soil profile disturbance. The modeled SOC contents with CT were systematically lower than those with NT during the simulated 20 years (Fig. 1b). The 20-year average annual SOC change rates were −86 and 415 kg C ha^{-1} for CT and NT, respectively (Table 2). The results implied that the SOC contents in the CT system were relatively stable, and the SOC contents in the NT system continuously increased during the simulated 20 years. The simulated bi-annual SOC cycles in both systems were caused by the difference in crop litter production between the corn and soybean. The SOC increased during the corn production year and decreased during the soybean year.

Corn yields with NT (3830 kg C ha^{-1} or 9580 kg dry matter ha^{-1} as a 20-year average) were lower than that with CT (4190 kg C ha^{-1} or 10500 kg dry matter ha^{-1} as a

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20-year average). The conversion of tillage had little effect on the soybean yields since it, as a legume crop, required much less N from the soil (Table 3, Fig. 1c). The conversion of CT to NT significantly reduced nitrate–N loss from the soil through leaching processes (Fig. 2a). The modeled results also indicated that NT increased soil denitrification rates (Fig. 2b) due to the decreased redox potential under the suboptimum aeration conditions. A denser surface soil with consistently higher moisture content has been identified as the main reason for higher rates of denitrification in NT fields (Aulakh and Rennie, 1986). As an exclusive indicator of denitrification, the modeled 20-year average annual dinitrogen (N_2) production with NT was 1.4 times higher than that with CT (23.9 kg N ha^{-1} versus 17.0 kg N ha^{-1})(Table 3). Consequently, the modeled annual N_2O fluxes with NT were higher than that with CT (Fig. 2c). The 20-year average annual N_2O fluxes with NT and CT were 28 and 19 kg N ha^{-1}, respectively (Table 3). Based on the detailed mechanisms of denitrification embedded in DNDC, the N_2O/N_2 ratio is determined by the kinetics of the rates of nitrate, nitrite, nitric oxide and N_2O reductive reactions during denitrification processes. As an intermediate of the sequential denitrification reactions, the N_2O emission rate is controlled by both its production and consumption, which are governed by three direct factors, namely soil redox potential (Eh), availability of dissolved organic carbon (DOC) and concentrations of N oxides. Conversion of the CT system to the NT system can simultaneously alter the status of the three factors and, hence, cause variations in N_2O/N_2 ratio. The effect is variable depending on the local climate and soil and management conditions and therefore there is no linear relation between the N_2O/N_2 ratio and any of the three driving factors (Li et al., 1992).

In summary, under the baseline conditions for the simulated row-crop field in Iowa, the modeled results indicated that conversion of conventional tillage to no-till (1) slightly decreased the crop yield, (2) converted the soil from a weak source to a sink of atmospheric carbon dioxide (CO_2), (3) significantly reduced nitrate–N leaching loss, and (4) increased N_2O emissions.

Field N_2O measurements from row-crop systems are limited. Recent studies in Iowa have shown different results. Parkin and Kaspar (2006) reported no significant impact of tillage on N_2O emission from either corn or soybean plots, but significantly higher N_2O emission from the corn than the soybean plots. Venterea et al. (2005) reported higher N_2O emission under NT compared to CT following broadcast of urea on a corn–soybean rotation field; however, they concluded that emissions can be either enhanced or mitigated with NT depending on the type of fertilizer management employed and that fertilizer and tillage management effects may interact in affecting total greenhouse gas emissions.

Nitrate–N measurements have been more intensively carried out in comparison with gas measurements. Kanwar and Baker (1993) studied a corn–soybean field in Boone

Table 3
20-year average impacts of conventional tillage vs. no-till on the biogeochemistry of agroecosystem at a row-crop field in Iowa

	SOC change (kg C ha^{-1} yr^{-1})	Gross Mineralization (kg N ha^{-1} $year^{-1}$)	N uptake (corn) (kg C ha^{-1} $yearr^{-1}$)	N uptake[a] (soybean) (kg C ha^{-1} $year^{-1}$)	Yield (corn) (kg DM $ha^{-1}year^{-1}$)	Yield (soybean) (kg DM $ha^{-1}year^{-1}$)	Nitrate-N leaching (kg N ha^{-1} $year^{-1}$)	Denitrification (kg N ha^{-1} $year^{-1}$)	N_2O flux (kg N $ha^{-1}year^{-1}$)	NO flux N_2O flux (kg N ha^{-1} $year^{-1}$)	N_2 flux N_2O flux (kg N ha^{-1} $year^{-1}$)
Conventional tillage	−86	201	140	12	10500	1370	47	38	19	2	17
No-till	415	157	127	12	9580	1370	20	54	28	2	24

[a] N uptake from soil.

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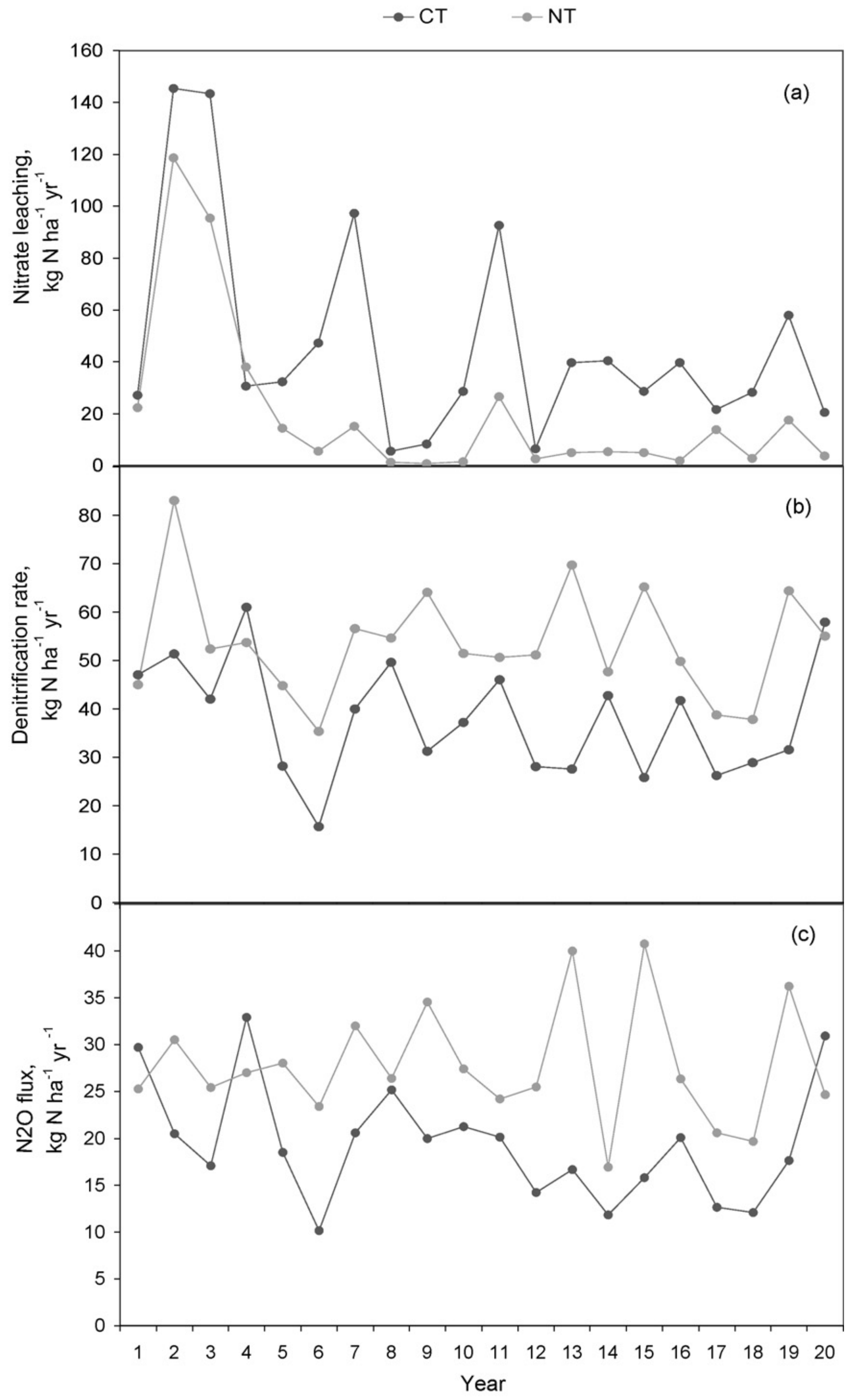

Fig. 2. Modeled 20-year nitrate-N leaching (a), denitrification ($N_2O + NO + N_2$) rates (b), and N_2O emission (c), in a corn–soybean rotated field with conventional tillage (CT) and no-till (NT) scenarios in Story County, Iowa.

County, Iowa and reported a consistently greater nitrate–N concentration under tilled systems due to higher N mineralization rates. Bakhsh et al. (2000) reported a higher residual nitrate–N in NT practices in a 6 year field study in Nashua, Iowa; however, majority of the field studies indicated that tillage systems alone would not significantly reduce N contamination of surface water if not combined with other conservation practices (Dinnes, 2004). Some studies have shown that reduced soil–N mineralization and fraction of soil water that percolates through the soil matrix that lessens nitrate–N transport tends to be offset with greater drainage volumes in conservation tillage systems. Factors such as rainfall patterns, fertilizer application rate and timing and type of cropping system may have a greater impact than tillage practices on N losses from agricultural production fields

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and therefore should be considered in studying N management methods (Dinnes, 2004).

3.2. Impacts of alternative fertilizing practices

Farmers in the initial processes of converting from tillage to no-till have been recommended by some agronomists to temporarily increase their N fertilizer application rates from their typical rates with tillage and to time the applications close to or within the crop's growing season to ensure the optimum yields (Dinnes et al., 2002). The recommended increased N application rate during the conversion from till to no-till management is due to the anticipated increase in SOC and the need to avoid shifting the C:N ratio of the field towards N immobilization (C:N ratios greater than ∼12:1). However, once a NT field SOC content has stabilized, N application rates may be reduced (Dinnes et al., 2002).

To estimate the impacts of changes in fertilizer use on crop yield, SOC storage, nitrate–N leaching and N_2O emissions, we designed 10 alternative practices by varying rate, timing and depth of fertilizer application and adoption of coated fertilizer (i.e., controlled-release fertilizer via urease enzyme inhibitor) or nitrification inhibitor. With the baseline scenario for conventional tillage (CT) or no-till (NT), urea was adopted as the N fertilizer, which was applied at rates 120 and 30 kg N ha^{-1} for corn and soybean, respectively. The fertilizer was surface applied once at the time of crop planting (May 1). As soon as the fertilizer is applied on the soil, DNDC begins to track the transformations of the fertilizer by simulating urea hydrolysis, ammonium–ammonia equilibrium, ammonia volatilization, nitrification, denitrification, N uptake by plants, ammonium adsorption by clay or organic matter, and nitrate–N leaching. The plant, soil microbes and leaching processes compete for available N. Any change in either the amount of fertilizer or the kinetics that affect conversion of fertilizer to available N will directly or indirectly alter the crop yield, SOC dynamics, nitrate–N leaching and N gas emissions. With the baseline fertilizer rate (120 kg N ha^{-1}), corn yield with NT decreased by about 900 kg dry matter ha^{-1} in comparison with CT (Table 3). Increasing the fertilizer rate to 140 or 160 kg N ha^{-1} obviously elevated corn yield (Fig. 3a), but also increased nitrate–N leaching loss (Fig. 3b) and N_2O emissions (Fig. 3c). Splitting the fertilizer application to three applications of 40 kg N ha^{-1} for each application enhanced crop yield, slightly decreased N_2O emissions, and significantly decreased nitrate–N leaching rate (Fig. 3a–c). Shifting the application depth from soil surface to 15 cm greatly improved the fertilizer uptake efficiency and brought the yield to almost the conventional level (Fig. 3a) and substantially reduced N_2O emissions (Fig. 3c), but enhanced nitrate–N leaching (Fig. 3b). Adoption of coated fertilizer increased crop yield and reduced both nitrate–N leaching loss and N_2O emissions. Utilization of nitrification inhibitor improved crop yield, decreased N_2O emission, but increased nitrate–N leaching due to the timing relation between nitrification and the rainfall events.

In summary, simply increasing fertilizer rate may not be the best option to optimize yields due to its negative effects on nitrate–N leaching and N_2O emissions. Applying urea below the soil surface or adoption of controlled-release fertilizer or nitrification inhibitor can also elevate crop yield with reduced impact of the environmental issues. For all the no-till alternatives, the soil remained as a sink of atmospheric CO_2. But in comparison with N_2O emissions, the differences in SOC sequestration (Fig. 3d) with the alternative fertilizer scenarios may not be very important as N_2O has a much higher atmospheric warming potential than CO_2. For example, applying the fertilizer at 15 cm depth reduced N_2O flux by 13.5 kg N ha^{-1} $year^{-1}$, which is equivalent to 6500 kg CO_2 ha^{-1} $year^{-1}$ sequestered in the soil.

A field experiment in northeastern Colorado indicated that N_2O emissions decreased linearly with increased depth of N placement in a corn field (Liu et al., 2006b). Also, NT greatly increased N_2O emissions compared with CT. This study suggested that N placement at 10 cm could be the effective option for reducing trace gaseous emissions from fertilized CT and NT soils (Liu et al., 2006b). Increase of N_2O in NT compared with CT in Colorado was in agreement with the simulations results for this Iowa field.

3.3. Impacts of cover crop

A cover crop can be planted after harvest of the main crop to protect the surface soil from erosion. A variety of plants such as clover, winter wheat, oat and barley can be used as a cover crop. In this study, we simulated the effects of fall legume and non-legume cover crops that shared the same sets of physiological and phenology parameters except their respective N fixation capacities. The legume cover crop could potentially fix 105 kg of atmospheric N; the non-legume cover crop did not have any N fixation capacity. Both crops had a maximum biomass production 3600 kg C ha^{-1}, consisting of 685 kg root-C ha^{-1} and 2915 kg shoot-C ha^{-1}. Four scenarios were simulated to test the impact of the alternative cover crop practices on crop yield, SOC storage, nitrate–N leaching and N_2O emissions for the row-crop field in Iowa (Table 1). In comparison with the baseline no-till (NT) scenario, as well as the conventional tillage (CT) scenario, all cover crop scenarios further increased SOC sequestration and reduced nitrate–N leaching loss (Fig. 4a and b). Planting the legume cover crop every year (NT-LCC2) gained the most SOC accumulation (a 20-year average annual increase of 1055 kg C), which was more than two times higher than that generated by the baseline no-till (NT) (Fig. 4a). By planting the non-legume cover crop every year (NT-NLCC2), the nitrate–N leaching rate reduced to 9 kg N ha^{-1} $year^{-1}$, which was less than a half of that (20 kg N ha^{-1} $year^{-1}$) with the baseline no-till scenario (NT) (Fig. 4b). However, the disadvantage of all the

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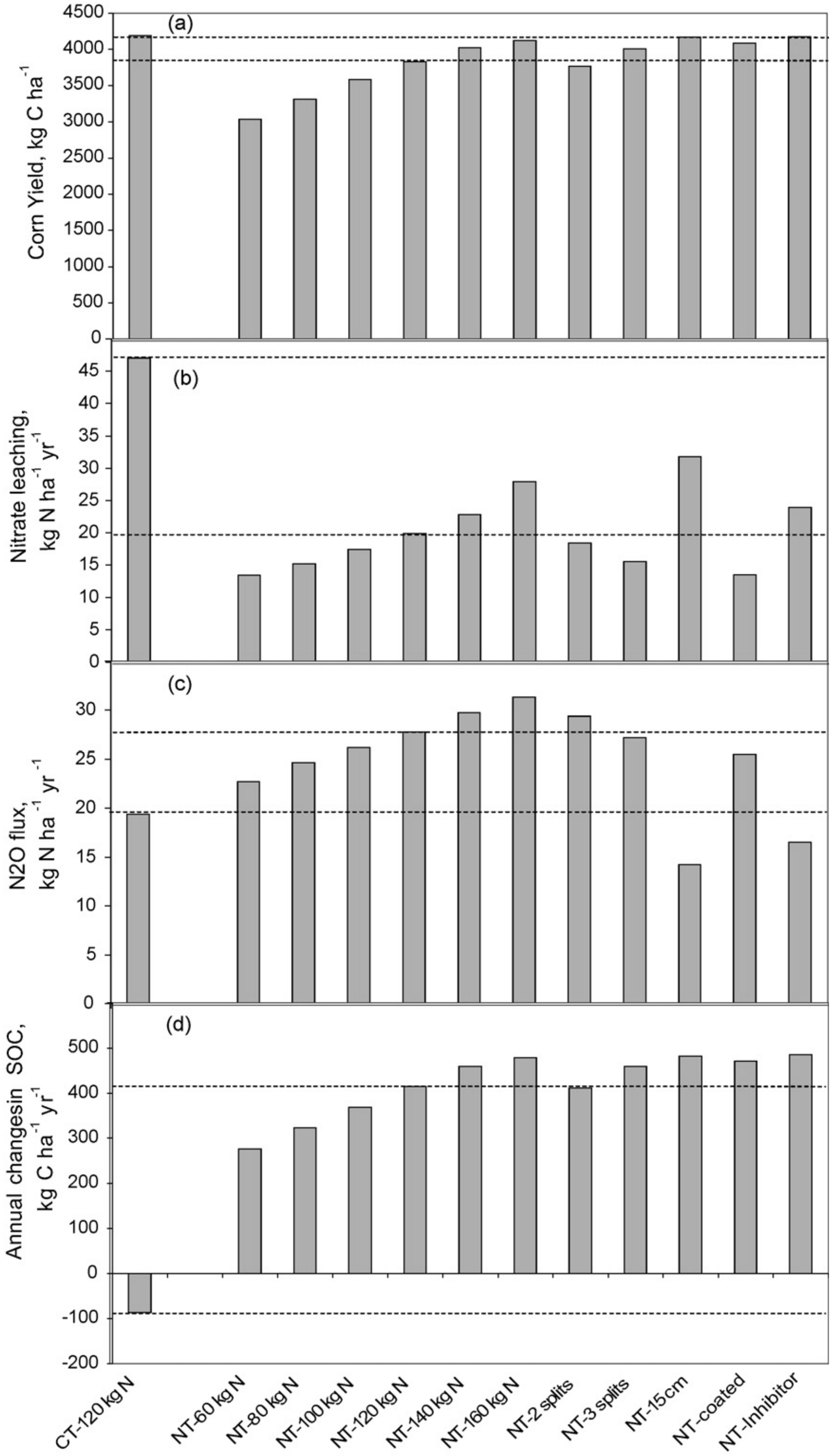

Fig. 3. Modeled 20-year average corn yields (a), annual nitrate–N leaching rates (b), N_2O emission (c), and SOC change (d), in a corn–Soybean rotated field with conventional tillage (CT) and no-till (NT) with varied fertilizing practices (60–160 kg N ha^{-1}). NT-2 splits and NT-3 splits = no-till with splitting the baseline fertilization into two and three applications for corn years. NT-15 cm = fertilizing application depth of 15 cm below the soil surface. NT-coated = application of coated urea, which slowly release N into the soil. NT-inhibitor = application of nitrification inhibitor.

scenarios with legume cover crop practices was an increase in N_2O emissions. Only the non-legume cover crop (NT-NLCC2) maintained the N_2O emission rate close to that of NT, but it was still higher than that of CT (Fig. 4c). In comparison with NT, NT-LCC1 slightly increased corn yield; but NT-LCCF and NT-NLCC2 decreased corn yield (Fig. 4d). The results could imply that under no-till conditions, application of synthetic fertilizer may still be

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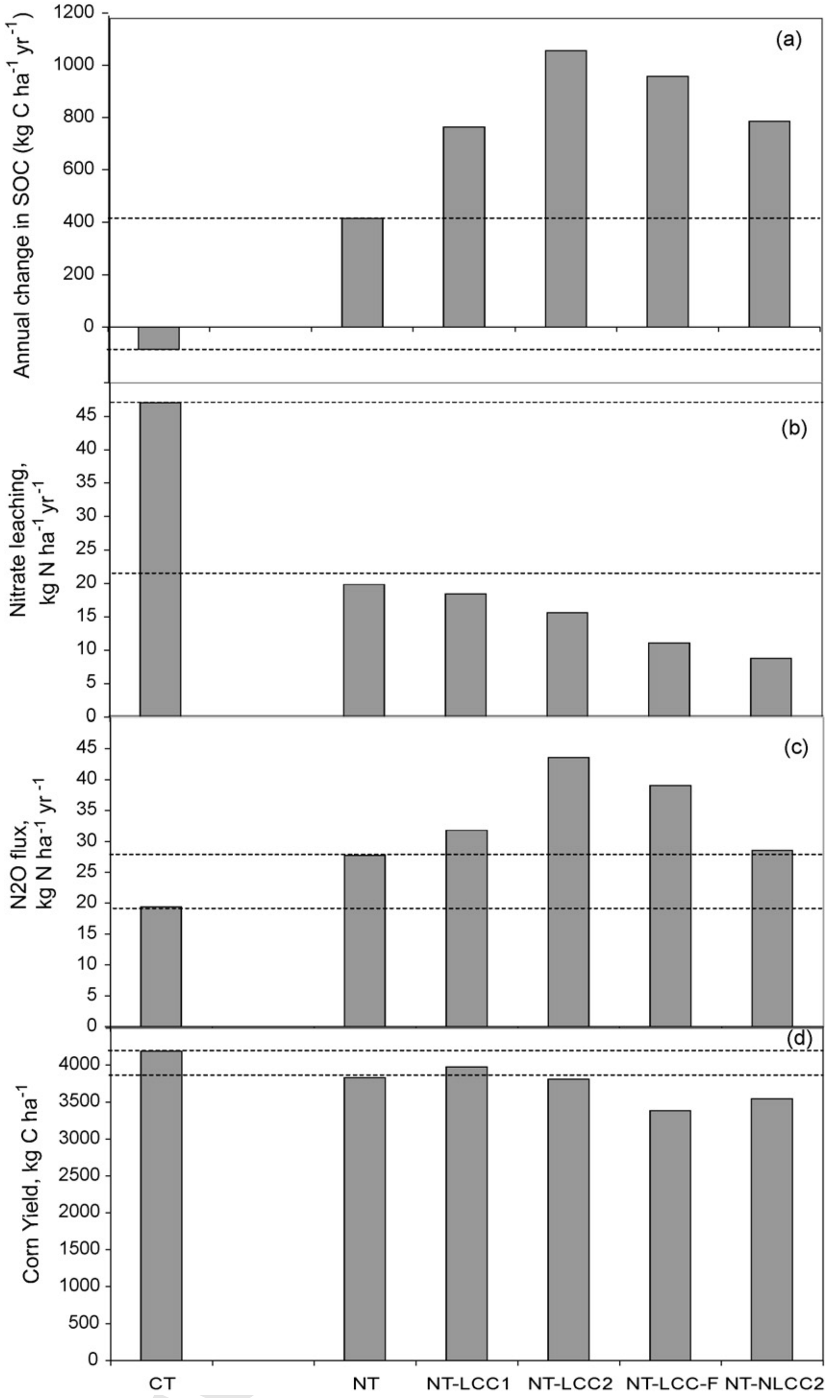

Fig. 4. Modeled 20-year average annual SOC change (a), nitrate–N leaching (b), N_2O emission (c), and corn yield (d), in a corn–soybean rotated field with conventional tillage (CT) and no-till (NT) with varied cover crop practices in Story County, Iowa. NT-LCC1 = legume cover crop in only corn years, NT-LCC2 = legume cover crop in both corn and soybean years, NT-LCCF = legume cover crop in both corn and soybean years with reduced fertilizer rate (80 kg N ha^{-1}) for corn and NT-NLCC2 = non-legume cover crop for both corn and soybean years.

needed to maintain the optimum yields even when legume cover crop is planted. The modeled data indicated that the rapidly accumulated soil organic matter might become a sink for N.

Observations of cover crop impacts on N cycling have been reported in a few Iowa field studies. Jaynes et al. (2004) showed a 13 mg l^{-1} decrease in nitrate–N in tile drainage when a rye cover crop was used. Another study with a rye cover crop after application of swine lagoon slurry showed that rye had a lower cumulative N_2O emission than the no-rye treatment. Nitrate–N leaching of the cover cropped field, however, was less than the fallow plots regardless of the manure rate (Kaspar et al., 2006). Singer and Kaspar (2006) recommended that yield reduction could be minimized by

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terminating cover crop growth more than 14 days prior to corn planting and use of a starter fertilizer. They also indicated that corn yields, following an oat cover crop or a legume that did not overwinter, was not reduced (Singer and Kaspar, 2006).

A recent study reports the impacts of varied management practices that included CT and NT, cover crops and split application of fertilizer urea ammonium nitrate (UAN), on green house gas emissions in a corn–soybean rotation field in Indiana (Stott et al., 2006). The results showed that for corn, N_2O emissions that peaked 4–6 weeks after fertilizer application were least in the CT treatment, and in an increasing trend were followed by split fertilizer application, single fertilizer application, NT, and cover crop exhibiting higher emissions, due to the decaying plant material. Soybean, with no fertilizer applications, had lower emissions. They attributed the highest emission rates of the cover crop treatment to the presence of the decaying rye residue (Stott et al., 2006). These results are in agreement with our model results that showed N_2O emissions were least in CT treatment followed by split fertilizer application (NT-3-splits), NT-2-splits and NT cover crop application (Figs. 3c and 4c).

3.4. Impacts of soil properties

Midwestern agricultural lands possess a wide range of soil types with various soil textures and SOC contents. These soil properties play an important role in governing C and N biogeochemical cycles in these agro-ecosystems. By varying soil texture and SOC content, we created nine alternative soil conditions for the field in Iowa to represent the ranges of soil texture and SOC contents commonly observed in Midwestern agricultural areas.

When soil texture shifted from the baseline (sandy clay) to a coarser texture soil (e.g., loam), the SOC sequestration rate significantly decreased from 410 to 160 kg C ha^{-1} $year^{-1}$ (Fig. 5a), the nitrate–N leaching rate increased from 20 to 39 kg N ha^{-1} $year^{-1}$ (Fig. 5b), and corn yield slightly increased (Fig. 5c). When the soil texture shifted to a finer texture (e.g., clay), the trends were reversed. The modeled data indicated that the mechanism driving the impacts was improved soil aeration in coarser textured soil under the no-till conditions that elevated the soil N mineralization rate. The effect of soil texture on N_2O emissions showed a rather complex pattern (Fig. 5d). Earlier studies indicated this complexity, e.g., soils with higher overall effective diffusivity (sandy soil) release N_2O faster than more compacted soils (e.g., clay and transitional) (Pérez et al., 2000). Other studies showed that high soil moisture contents in the fine-textured soil resulted in higher N_2O emission rates by denitrification than the coarse-textured soil. It was concluded that the fine-textured soil became anoxic at lower soil moisture content than the coarse-textured soil (Bollmann and Conrad, 1998).

When SOC content increased, the 20-year average annual change in SOC decreased (Fig. 6a), nitrate–N leaching loss increased (Fig. 6b), and N_2O emission increased except for the highest SOC scenario (SOC 0.035 kg C kg^{-1}) (Fig. 6c). The modeled data indicated that the high SOC content converted more N_2O to N_2, the end product of denitrification. Based on the mechanisms embedded in DNDC, DOC is the sole energy source for all the denitrifiers to compete. The higher SOC content produced more DOC that drove the sequential denitrification reactions to go through all the way to the end product, N_2. The simulated results also demonstrated that the relation between corn yields and SOC contents was non-linear (Fig. 6d).

Field data from row crop fields in Boone County, Iowa showed that the impact of SOC on crop yield is complex and inter-related with other climatic and environmental factors such as rainfall and terrain (Kaspar et al., 2003; Li et al., 2006). Other studies in row crop fields in Southwest Michigan showed that a number of soil properties were significantly correlated with peak plant biomass, which included soil nitrate pools, microbial biomass, gravel content, elevation, bulk density, clay content, and total carbon content (Robertson et al., 1996).

3.5. Impacts of climate

Four scenarios of alternative temperatures were run for the selected field in Iowa for 20 years. The modeled results indicated that an increase in temperature decreased crop yield (Fig. 7a), substantially decreased SOC sequestration (Fig. 7b), decreased nitrate–N leaching loss (Fig. 7c), and increased N_2O emissions (Fig. 7d). The simulated data indicated that the increased denitrification rate under higher temperature conditions was the primary factor that drove the higher N_2O flux and lower nitrate–N leaching rate.

Six precipitation scenarios were set by decreasing or increasing precipitation by 20%, 40% and 60%. The decreasing or increasing proportion was applied for each rainfall event at daily time step. The baseline rainfall amounts are presented in Table 1. Increasing precipitation almost linearly increased nitrate–N leaching rate (Fig. 8a), although not significantly affecting crop yield or SOC sequestration (except for the driest scenario; NT-P-60%) (Fig. 8b and c). The driest scenario reduced the average annual precipitation to 360 mm, which substantially decreased the crop yields and biomass production. Increased losses of nitrate–N leaching from leaching caused by higher levels of precipitation also led to slightly decreased N_2O emissions (Fig. 8d).

Variability of the annual rainfall, including both inter-and intra-annual pattern of rainfall, has been recognized as an important source influencing the discharge of nitrate–N to subsurface drainage and later to surface waters. Dinnes et al. (2002), Dinnes (2004), and Schilling and Zhang (2004) described the circumstances in which the risk for nitrate–N leaching is high, being: (1) when high rainfall occurs in early spring months or in fall and is not accompanied by plant growth, and (2) when nitrate–N accumulates in soils during years when conditions limit crop growth and yield, followed by a year with above-average rainfall.

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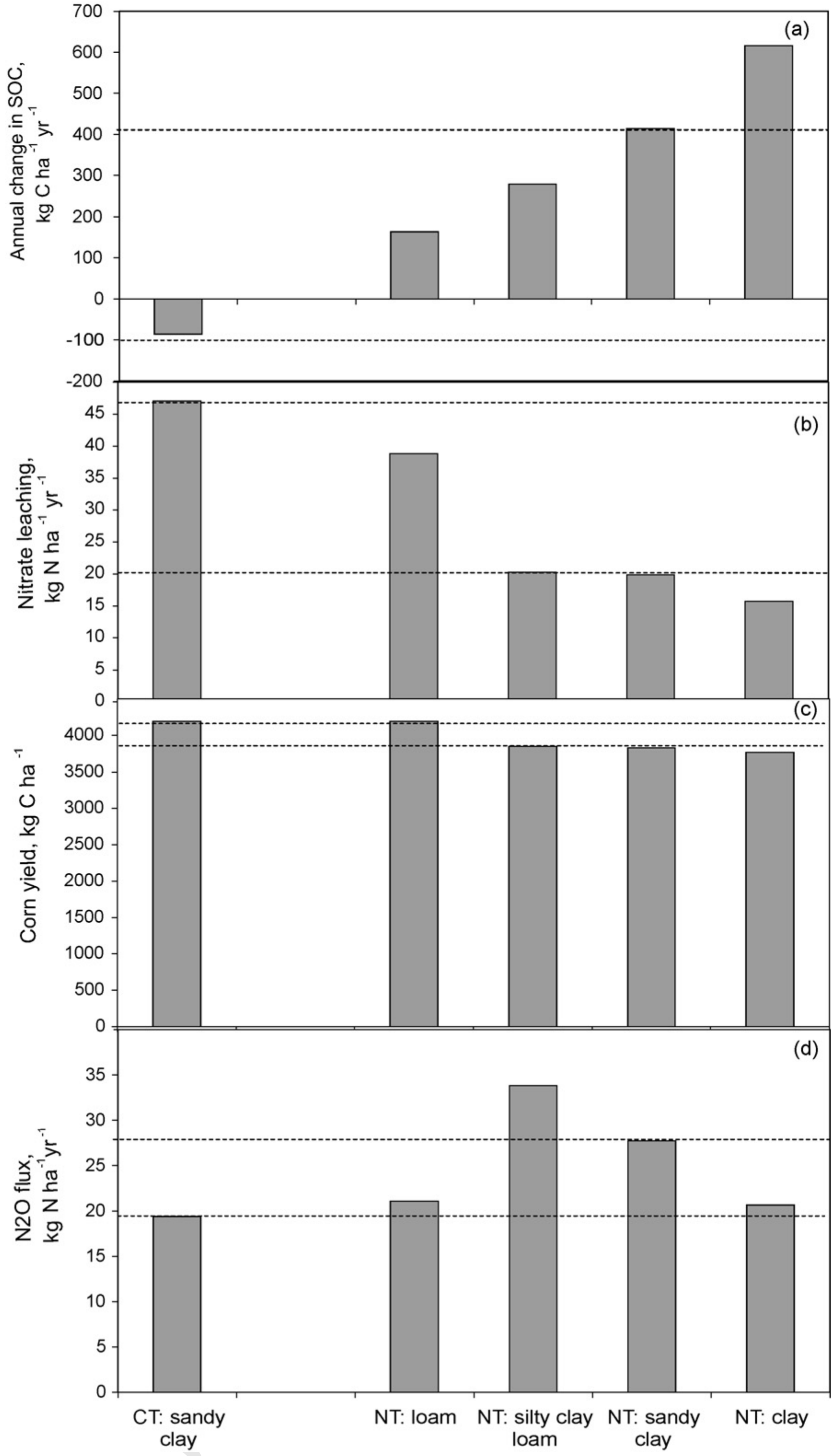

Fig. 5. Modeled 20-year average annual SOC change (a), nitrate–N leaching (b), corn yield (c), and N_2O emission (d), in a corn–soybean rotated field with conventional tillage (CT) and no-till (NT) with varied soil texture from the baseline (sandy clay) to loam, silty clay loam and clay, in Story City, Iowa.

3.6. Composition of best management practices

Based on the above-described sensitivity tests by varying a single factor while keeping all other factors constant, we determined the following impacts: under no-till conditions for the tested field, shifting the depth of fertilizer application from the surface to 15 cm reduced N_2O emissions (Fig. 3c) and elevated yield (Fig. 3a); splitting the baseline fertilizer

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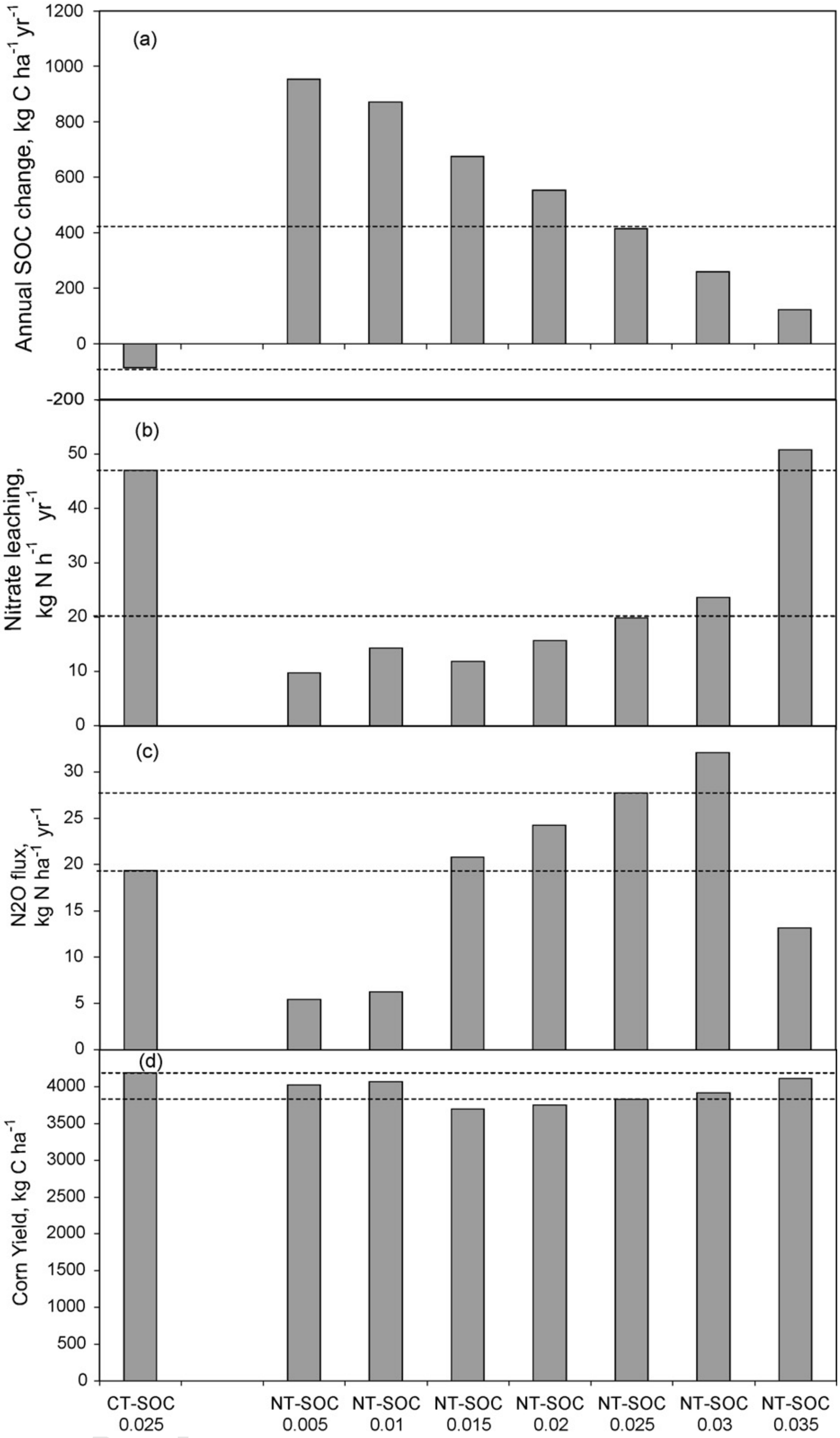

Fig. 6. Modeled 20-year average annual SOC change (a), nitrate–N leaching (b), N_2O emission (c), and corn yield (d), in a corn–soybean rotated field with conventional tillage (CT) and no-till (NT) with varied SOC contents (0.005, 0.01, 0.015, 0.02, 0.025, 0.03 and 0.035 kg C kg^{-1}) in Story County, Iowa.

application into three applications reduced nitrate–N leaching loss (Fig. 3b); and planting non-legume cover crop substantially increased SOC sequestration (Fig. 4a), decreased nitrate leaching (Fig. 4b) and caused the lowest N_2O emission increase (Fig. 4c). To achieve a best management scenario that could lead to a balance or gain in the production and environmental goals of a sound agricultural system (the four aspects of crop yield, SOC

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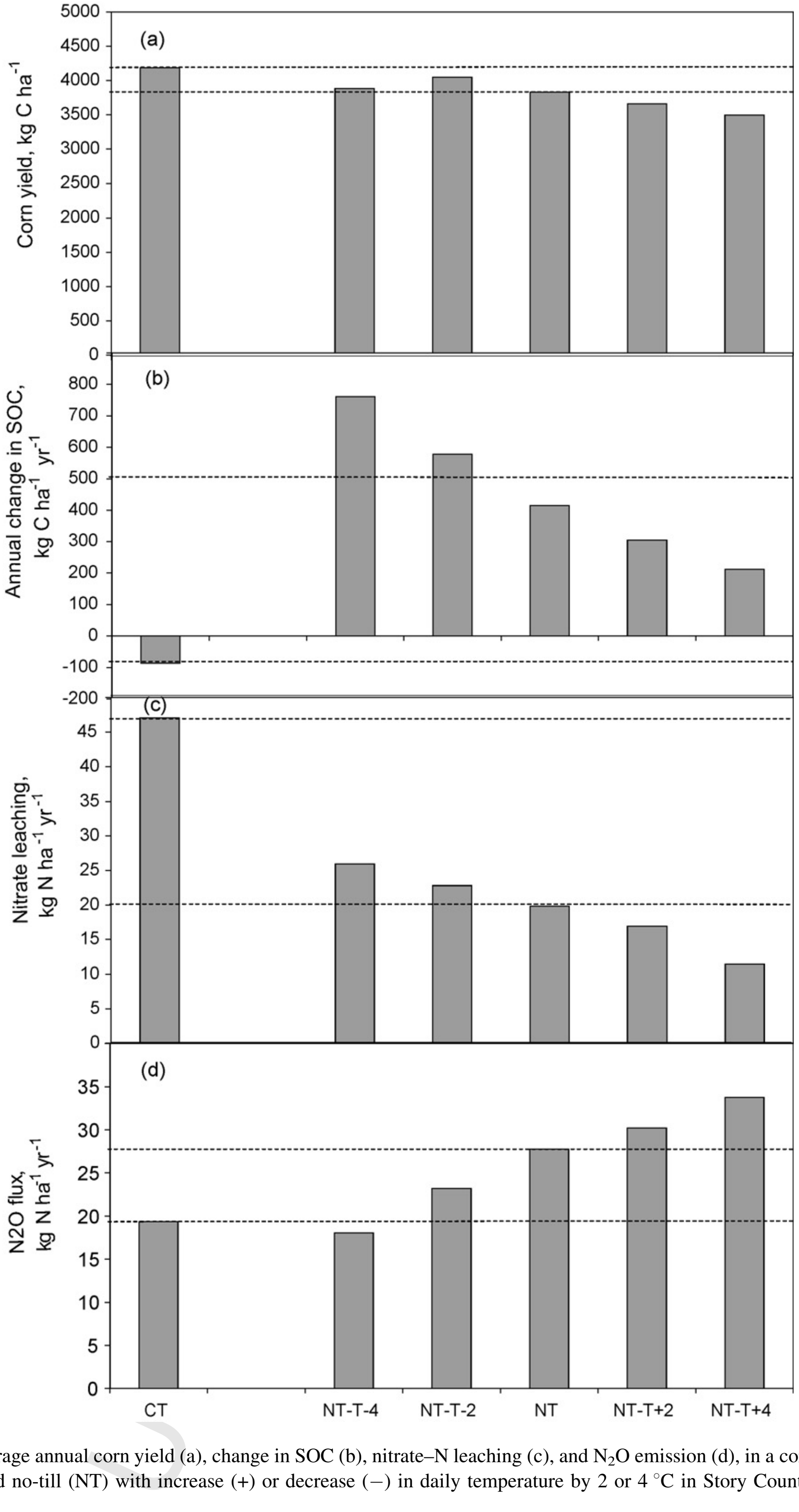

Fig. 7. Modeled 20-year average annual corn yield (a), change in SOC (b), nitrate–N leaching (c), and N_2O emission (d), in a corn–soybean rotated field with conventional tillage (CT) and no-till (NT) with increase (+) or decrease (−) in daily temperature by 2 or 4 °C in Story County, Iowa.

sequestration, nitrate–N leaching and N_2O emissions), we composed a new alternative management scenario, the best management practice (BMP) system, by combining the practices described above.

The modeled data shown in Table 4 explain how the BMP system gained the comprehensive benefits. Applying a cover crop significantly elevated transpiration rate and slightly decreased soil evaporation rate, which resulted in a net

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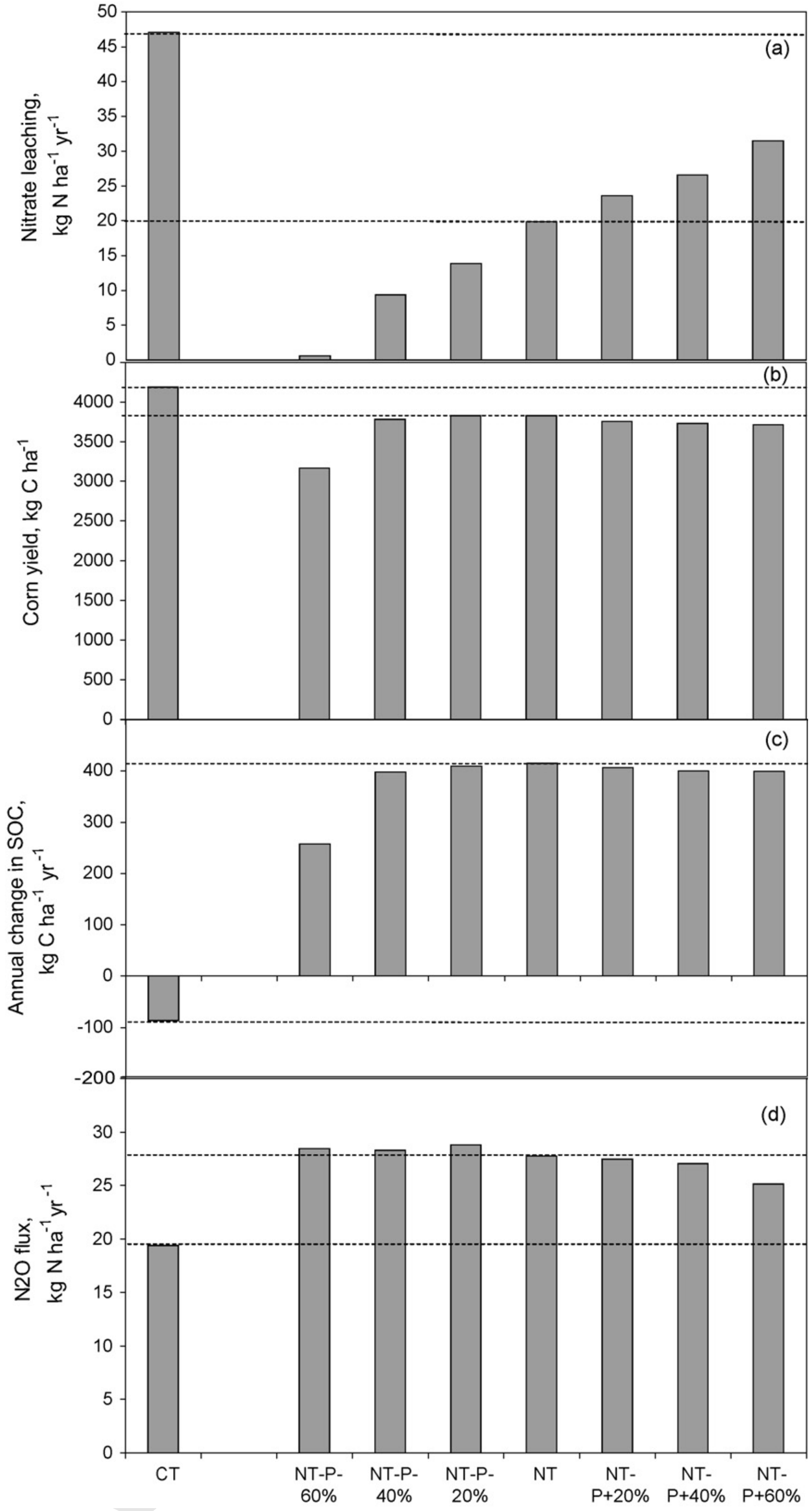

Fig. 8. Modeled 20-year average annual nitrate–N leaching (a), corn yield (b), change in SOC (c), and N_2O emission (d), in a corn–soybean rotated field with conventional tillage (CT) and no-till (NT) with increase (+) or decrease (−) in daily precipitation by 20%, 40% and 60% in Story County, Iowa.

decrease in leached water flow. Meanwhile, the amount of N assimilated by crops – including the main crops and cover crop – substantially increased. Both the change in water flow and soil available N drastically reduced the nitrate leaching loss from the soil. The split deep fertilizer applications also reduced the total denitrification rate resulting in a lower rate of N_2O fluxes. Because the main crops maintained high biomass production incorporation of cover crop biomass to

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Table 4
Modeled 20-year average annual C and N fluxes for a row-crop field under conventional tillage (CT), no-till (NT) and best management practices (BMP) conditions in Story County, Iowa

Average annual C, N or water flux	Unit	CT	NT	BMP
Transpiration	mm year^{-1}	123	122	224
Evaporation	mm year^{-1}	259	259	224
Water leaching flow	mm year^{-1}	297	297	236
N uptake by crop	kg C ha^{-1} year^{-1}	140	127	187
Nitrate leaching loss	kg N ha^{-1} year^{-1}	47	20	8
Denitrification rate	kg N ha^{-1} year^{-1}	38	54	35
N_2O flux	kg N ha^{-1} year^{-1}	19	28	16
NO flux	kg N ha^{-1} year^{-1}	2	2	1
N_2flux	kg N ha^{-1} year^{-1}	17	24	18
Fertilizer used[a]	kg N ha^{-1} year^{-1}	120	120	120
Crop biomass production	kg N ha^{-1} year^{-1}	11500	10500	12700
Crop yield[a]	kg C ha^{-1} year^{-1}	4190	3830	4140
Incorporated residue C	kg C ha^{-1} year^{-1}	5080	4780	6120
Soil respiration	kg C ha^{-1} year^{-1}	5170	4360	5120
Gross mineralization	kg N ha^{-1} year^{-1}	201	157	237
dSOC	kg N ha^{-1} year^{-1}	−86	415	996
dSON	kg N ha^{-1} year^{-1}	−8	7	37

[a] For corn years only.

the soil more than doubled the rate of SOC increase (dSOC) compared to the NT scenario. Along with the accumulation of SOC with the BMP system, much more N was also accumulated in organic forms in the soil (dSON), which could potentially increase the soil fertility. The modeled data in Table 4 present a typical picture of how the water, C and N cycles are tightly linked to each other in an agro-ecosystem and how alternative management practices can affect agricultural production and the environment by altering these interacting factors. The complexities between management and biogeochemical cycles provide challenges as well as opportunities for identifying and designing best management practices for specific agro-ecosystems.

4. Conclusions

No-till, as a dominant approach for soil conservation in the U.S., has been widely applied to Midwestern croplands. Numerous field measurements have been made to quantify the impacts of no-till on crop yields, SOC dynamics, nitrate leaching and trace gas emissions. These observations have provided first-hand information to understand the comprehensive effect of an alternative tillage method on agricultural production and the environment. However, field observations have indicated that the impacts of no-till on the Midwestern agro-ecosystems are highly variable in space and time due to the companion management practices (e.g., crop rotation, fertilization), as well as the climatic and soil conditions. To gain more understandings of the intricate interactions of no-till with other management and natural factors, we utilized the DNDC model to conduct 20-year simulations for a corn-soybean crop rotated field in Iowa with combinations of alternative management practices and varied soil and climate conditions. The modeled results indicated the following: (1) no-till practice has benefits and disadvantages in regard to its impacts on crop yield, and air and water quality; (2) the impacts of no-till on yield, SOC dynamics, nitrate leaching and N_2O emissions vary depending on the companion farming practices and climate and soil conditions; and (3) best management practices systems can be achieved by combining no-till with other management practices, in accord with local soil and climate conditions.

This study is an attempt to test how a process-based model can be used to identify best management practices for Midwestern agriculture. Since the sensitivity tests were conducted only for a specific field in Iowa, the values of the modeled results may not be specifically applicable to all other sites in the Midwest, but the general trends may still apply and help to guide more efficient agricultural land-use management practices.

Uncited references

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