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Comparing continuous-corn and soybean-corn rotation cropping systems in the U.S. central Midwest: Trade-offs among crop yield, nutrient losses, and change in soil organic carbon

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ABSTRACT

Soybean-corn (S-C) is the most common cropping sequence in the U.S. Midwest, known for improving corn yield compared with continuous corn (C-C). However, the underlying mechanisms and impacts on crop productivity, environmental sustainability, and economic returns are not fully understood. Using the agroecosystem model, *ecosys*, we simulated S-C and C-C systems under different nitrogen (N) fertilizer application rates, demonstrating good performance in capturing N rate-corn yield responses and CO_2 fluxes across 10 Illinois sites. Our analysis revealed: (1) under normal N rates (151 kg N/ha), soybean residues contributed an average of 36% less carbon but 47% more N than corn, resulting in higher early spring soil temperatures and net mineralization in the subsequent corn year, boosting corn yields for S-C relative to C-C. This yield benefit was reduced with higher N rates. (2) S-C reduced soil organic carbon (SOC) relative to C-C due to faster decomposition of soybean residue under normal N rates, but mitigated nitrous oxide (N_2O) and ammonia (NH_3) emissions. Effects on N leaching varied, with reductions during soybean years and increases in the following corn years. N rates shifted the relative differences of SOC and N losses between S-C and C-C. (3) Economically, S-C provided $1133/ha higher returns than C-C at low N rates (50 kg N/ha) under typical market conditions (soybean: $410/Mg, corn: $178/Mg, and N fertilizer: $193/Mg). However, this advantage diminished at higher N rates due to increased costs and smaller corn yield gains, especially under extreme market scenarios with high corn prices and lower soybean-to-corn and fertilizer-to-corn price ratios. These findings highlight trade-offs among crop yield, nutrient losses and soil carbon change by adopting S-C in the U.S. central Midwestern cropping systems.

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1. Introduction

The U.S. Midwest has been historically known as the Corn Belt for over 200 years due to its long history of corn (*Zea mays L.*)-based cropping systems. Growers historically incorporated organic nitrogen (N) sources such as manure and forage legumes like alfalfa (*Medicago sativa L.*) in rotation with corn (Olmstead and Brummer, 2008; Warntz, 1957). Starting from the 1920s, soybean (*Glycine max L.*) was promoted in the Midwest to produce animal feed and human food due to its high protein content, while synthetic inorganic N produced through the Haber-Bosch process gradually replaced organic sources for fertilizing corn (Frink et al., 1999; Hymowitz, 1990). Since the 1950s, growing a two-year sequence of soybean and corn over time (soybean-corn: S-C) with N fertilizer applied in the corn years has become an important practice (Bullock, 1992; McDaniel et al., 2014; Weber, 1981). Subsequent field experiments found that adopting S-C could improve both corn and soybean yields relative to continuous monocultures (Crookston and Kurle, 1989; Wilhelm and Wortmann, 2004). While studies in the mid-20th century suggested that yield benefits from crop rotation could be secured by replacing rotation with agrochemicals such as synthetic fertilizers (Aldrich, 1964; Shrader et al., 1966), this view has changed and crop rotation has been recognized for agronomic benefits leading to more stable and higher yields and allowing for sustainable production relative to a continuous single crop (Bullock, 1992; Mitchell et al., 1991; Sindelar et al., 2016; Bowles et al., 2020). Between 1970 and 2008, nearly 8% of corn yield gains in the U.S. Midwest have been attributed to increased S-C adoption (Farmaha et al., 2016). Today, S-C accounts for about 65% of Midwestern cropland, with continuous corn (C-C) making up the remaining 35% (Wang and Ortiz-Bobea, 2019; Socolar et al., 2021; Grassini et al., 2015). However, the underlying processes by which these two dominant cropping systems affect soil carbon (C) and N cycles are not fully understood.

Many studies have revealed that the N fertilizer required to achieve a given corn yield is lower in S-C compared with C-C, indicating corn yield benefits for S-C at equivalent N application rates (Crookston and Kurle, 1989; Meese et al., 1991; Wilhelm and Wortmann, 2004; Boincean et al., 2019). This rotation effect is generally found to improve corn yields by 2–19% (Strickling, 1951; Ta, 1989; Hauck, 1984; Pierce and Rice, 2015; Voss and Shrader, 2015; Welch, 1976) with reduced yield improvement under higher N fertilizer rates (Gentry et al., 2013; Kim et al., 2022; Sindelar et al., 2015). Although the mechanisms responsible for the rotational yield effect are not completely understood, three key reasons have been hypothesized, among which increased soil N supply is considered to be responsible for the vast majority of the benefits (Bullock, 1992; Russelle et al., 1987; Zhou et al., 2024). A second, abiotic benefit is improved soil physical conditions, such as increased soil temperature caused by the relatively lower soybean residue cover (Wilhelm and Wortmann, 2004; Seifert et al., 2017). The third entails biological benefits, including reduced weed, insect, and disease pressures (Benitez et al., 2021; Francis et al., 1986; Smith et al., 2023). In addition to corn yield benefits, the adoption of soybean with symbiotic N_2 fixation in S-C enables lower N fertilizer consumption by farmers than C-C (Schnitkey et al., 2021). However, the extent to which one cropping system outperforms the other in terms of net agronomic benefits depends on more than just corn yield and N fertilizer usage, but also needs to consider soybean yield and market-driven prices, including fertilizer, grain, and costs such as machinery (Schnitkey et al., 2021; Zulauf and Lines, 2021). Such comprehensive economic assessments can help farmers make informed decisions about crop sequences, especially in response to market fluctuations, and inform insurance products and conservation initiatives accordingly (Olmstead and Brummer, 2008). Additionally, coupling economic analyses with both agronomic and environmental benefits can increase farmer confidence in adopting a management practice (Al-Kaisi et al., 2015; Stanger et al., 2008).

Highly industrialized corn monoculture using synthetic N fertilizer has resulted in much higher corn yields compared to pre-industrialization, but its contribution to environmental degradation and climate change has often been overlooked (Smith et al., 2023, 2025). As an alternative to excessive N fertilizer usage, S-C is gaining attention for its potential to mitigate climate change relative to C-C, particularly through soil organic carbon (SOC) (Huggins et al., 2007; Deiss et al., 2021), N leaching (Pasley et al., 2021), and nitrous oxide (N_2O) emissions (Venterea et al., 2010). The reported effects on SOC involve conflicting findings, with some studies suggesting that S-C improves SOC due to greater corn residue resulting from improved corn growth under rotation (Dick et al., 1986). Others argue that S-C reduce SOC during the soybean phase due to (1) lower biomass production by soybean, resulting in less residue than under corn (Russell et al., 2009; Poffenbarger et al., 2017), and (2) higher residue N/C ratios from soybean N_2 fixation, which accelerate SOC decomposition (Hall et al., 2019). Differences in N losses between rotation systems have been previously quantified by some experiments, which report reductions in both N leaching and N_2O for S-C compared with C-C (Behnke et al., 2018; Zhu and Fox, 2003). These N loss reductions are mainly attributed to both reduced N fertilizer inputs with lower resulting soil inorganic nitrogen (SIN) levels (Behnke et al., 2018; Kim et al., 2022; Ochsner et al., 2018), and better developed roots during the corn growing seasons (Zhu and Fox, 2003). However, these studies are based on short-term experiments (<5 years), and the integrated long-term impact of crop rotations on soil C and N dynamics is still unclear.

Process-based models can simulate carbon-water-nutrient dynamics in soil-crop systems, helping to overcome challenges associated with field measurements (Bassu et al., 2014; Grant et al., 2015). Models, such as DNDC (Li et al., 2000), APSIM (McCown et al., 1996), EPIC (Williams et al., 1989), and DSSAT (Jones et al., 2003), have been applied to evaluate the impacts of different agricultural practices. Studies typically leverage experimental data to either calibrate or validate, and then use validated models to investigate the practice of interest (Kluger et al., 2022). These models have been used to assess crop rotation effects on specific processes, such as SOC (Jarecki et al., 2018), N leaching (Pasley et al., 2021), or N_2O (Jiang et al., 2021; Jia et al., 2023). For example, Jiang et al. (2021) used a validated DNDC model and found that S-C reduced N_2O emissions and improved corn yield relative to C-C. However, most studies focus on one or two specific processes, without examining the holistic impacts on soil C and N dynamics. Moreover, interactions between rotation and other practices (e.g. N fertilizer application) are often underexplored.

In this study, the overarching objective is to improve our understanding of how S-C rotation impacts crop production and environmental sustainability compared with C-C. This study aims to answer three questions using agroecosystem modeling: (1) How do crop rotations affect corn yield, and what is the impact of N fertilizer application on these effects? (2) How do crop rotations affect soil C and N dynamics? (3) To what extent do economic returns differ between soybean-corn and continuous-corn cropping systems? Although previous studies have examined some of these aspects, comprehensive assessments using process-based models remain limited. By synthesizing our modeling results, we summarize the major pathways of these impacts and describe the corresponding implications for the U.S. Midwestern corn-based agroecosystem (Fig. 1).

2. Data and methods

In this study, we leveraged an advanced process-based agroecosystem model, *ecosys*, to ensure its ability to reproduce a large amount of field-measured crop yield data under different crop rotations (S-C and C-C) along with N fertilizer application information collected from seven long-term experiment sites across Illinois. We also used flux measurements from three Illinois eddy-covariance (EC) flux tower sites under these two rotations. We then used the validated model to assess the impacts of different crop rotations on soil C and N status at seven Illinois sites and assessed the integrated outcomes using an economic

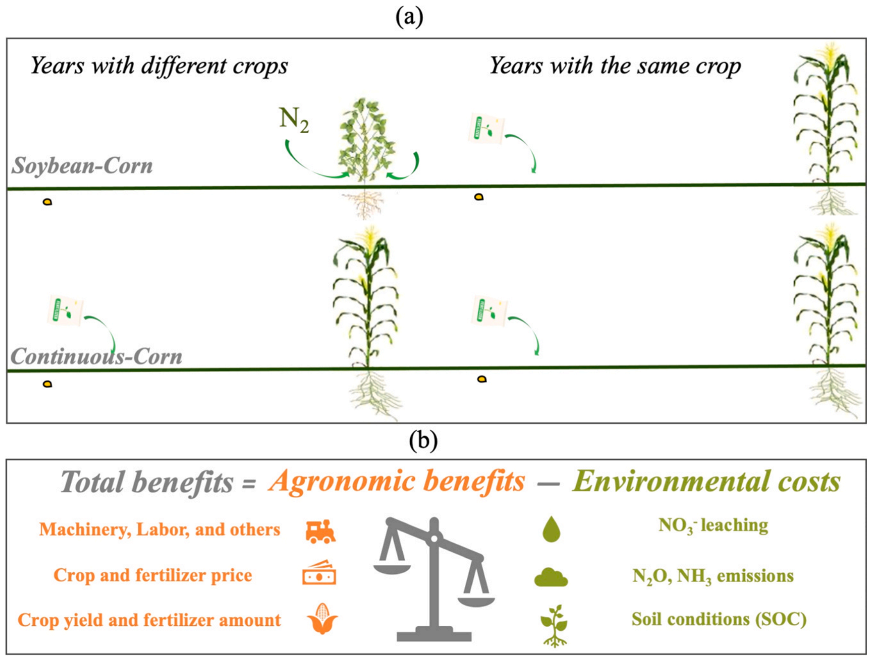

Fig. 1. A schematic diagram showing different crop rotations (a) and the framework to investigate the impact of different crop rotation and nitrogen application strategies on crop productivity and environmental sustainability in this study (b).

margin assessment.

2.1. Field trial data

Two datasets from 10 sites across Illinois under different cropping rotations were separately used to calibrate and validate *ecosys*, including data from N fertilizer-corn yield (N-yield) response experiments and ecosystem energy and C flux measurements (Fig. 2). 140 N-yield responses were collected from seven University of Illinois at Urbana-Champaign (UIUC) sites during 1999–2008 under S-C and C-C. To ensure N-yield responses for S-C were available every year, one corn plot and one soybean plot were included. Each N-yield dataset included six fertilizer rates (0, 50, 101, 151, 202, 252 kg N/ha) applied as banded urea ammonium nitrate (UAN 28–0–0, N-P-K) in the corn year, with four

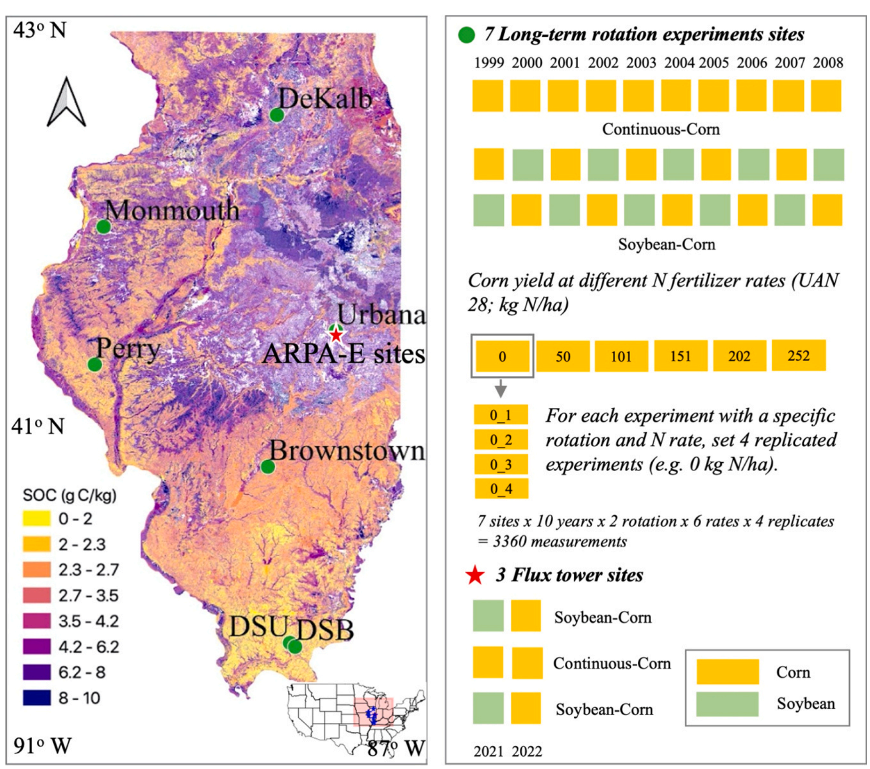

Fig. 2. The locations of seven long-term (1999–2008) field experiments (green dots) and three ARPA-E-founded flux tower sites (2021–2022, red stars) in Illinois, central USA, used in this study. At each long-term site, 10-year trials were conducted to measure N-yield responses.

replicate measurements obtained for each corn yield. Seven site-years in this dataset were filtered from measurements with either no yield responses (Brownstown-2000, Brownstown-2002, DSU-1999, and DSU-2000) or large yield differences between rotations (Urbana-2000, Monmouth-2003, and Brownstown-2004), following the detailed procedure described in Fig. A1. This dataset also includes soybean yield under S-C (see Fig. A2) but only contains one measurement for each site-year without distinguishing N fertilizer rates. Data from three EC flux towers (DOE The Advanced Research Projects Agency-Energy (ARPA-E) SMART-FARM project founded sites; AE1-AE3) were collected to validate the model performance in simulating both ecosystem energy and C fluxes under S-C and C-C. Methods used to measure EC fluxes and replace failed fluxes are described in Blanken et al. (2001) and Barr et al. (2002). Rotation and N fertilizer management are given in Table 1, while other detailed information can be found in Li et al. (2022).

2.2. Ecosys model and model validation

2.2.1. Ecosys model and its prior validation

Ecosys, an advanced process-based model built on classical biophysical and biochemical theories (Grant, 2001), has been used to simulate impacts of major agriculture management practices, including tillage (Grant, 1997), fertilization (Grant et al., 2020a, 2006), nitrification inhibitor (Grant et al., 2020b), tile drainage (Ma et al., 2024), and cover crop (Qin et al., 2023, 2021). These practices are incorporated into *ecosys* by improving model structures or parameterization of relevant submodules and are validated against corresponding field observations. For example, the effect of nitrification inhibitors is represented through an additional time-dependent algorithm that slows NH_4^+ oxidation in the biochemical submodule (Grant et al., 2020b). Tile drainage is simulated as a water sink within the hydrology submodule, defined by tile depth and spacing (Ma et al., 2024), while cover cropping is implemented by calibrating plant functional type parameters in the vegetation submodule and validating against measured biomass data (Qin et al., 2023, 2021).

Ecosys has been extensively validated and applied for crop growth and associated soil C and N dynamics in many North American agroecosystems, especially for U.S. Midwestern corn and soybean production (Li et al., 2022; Yang et al., 2022; Zhou et al., 2021). For example, Zhou et al. (2021) validated *ecosys* using data from seven EC flux towers across the U.S. Midwest and found good performance for daily net ecosystem exchange (NEE; R^2=0.59–0.88 and root-mean-square deviation (RMSD)=1.67–2.26 g C/m^2) and gross primary productivity (GPP; R^2=0.74–0.93 and RMSD=1.64–3.31 g C/m^2). Yang et al. (2022) further validated *ecosys* using both field measurements and EC flux tower data, achieving good agreement for crop yields (R^2=0.83 and RMSD=1.94 Mg/ha), annual N_2O flux (R^2=0.64 and RMSD=0.83 kg N/ha/yr), soil temperature (R^2=0.97–0.98 and RMSD=1.50–2.18 ℃), and soil water content (R^2=0.29–0.80 and RMSD=0.04–0.07 m^3/m^3). In this study, we incorporated additional field measurements under different N fertilization rates and crop rotation practices to further evaluate *ecosys* for simulating agroecosystem C and N interactions. We aimed to uncover new insights into the impacts from different crop rotations on annual SIN and SOC balances (Eq. 1- Eq. 2). Below, we briefly describe the key processes in *ecosys* related to our scientific questions, including SOC decomposition, soil N mineralization, crop N uptake and N_2 fixation, as well as crop growth and residue production. Detailed mathematical equations are provided in the appendix. A more comprehensive description of simulating other key processes including N losses through surface runoff, subsurface leaching, and gas emissions can be found in Grant et al. (2020a).

Soil temperature (T_{soil}) in each soil layer is determined by heat transfers driven by energy fluxes (Mekonnen et al., 2021). Surface energy flux is based on first-order closure of energy balances for surface litter and exposed soil for net radiation, latent and sensible heats, as well as soil heat (Grant et al., 2019; Grant, 2004a). Net radiation is calculated from shortwave and longwave radiations using fixed numerical values for albedo and emissivity of different surfaces. Latent and sensible heats are calculated based on the density of atmospheric water vapor and surface T_{soil} gradients, and from stomatal and soil surface resistances. T_{soil}, along with microbial nutrient concentrations, soil organic matter (SOM), soil moisture, and soil O_2 contents, collectively affect heterotrophic respiration (R_h; Eq. A1), which in turn controls the growth of microbes in each microbe-substrate complex (woody and non-woody litters, manure, humus, and particulate organic matter). The R_h rate is linked to O_2 consumption by aerobic microbes, and when O_2 is limited, it is instead associated with stepwise reductions of nitrate, nitrite, and N_2O by heterotrophic denitrifiers, as well as SOC consumption by fermentative microbes and methanogens (Grant, 2001). Additionally, autotrophic nitrifiers are involved in nitrification and denitrification, and autotrophic methanogens and methanotrophs are responsible for methane production and oxidation (Grant, 2001). R_h is then allocated to maintenance respiration (R_m), and the remainder is allocated to growth respiration (R_g). If R_m exceeds R_h, the gap is filled by decomposition of microbial structural C (Eq. A2), forcing senescence of corresponding non-structural C (Grant 2004a). The fate of microbial N depends on the N/C ratio. Mineralization occurs when N content exceeds the maintenance capability; otherwise, N becomes immobilized (Grant 2004b; Grant et al., 1993). Net mineralization is calculated as the difference between total mineralization and total immobilization across all microbes (Eqs. A3–4).

Besides being immobilized by microbes, SIN can also be taken up by crops, lost through runoff and discharge, or emitted as gases by microbes (Grant, 1995; Li et al., 2022) (Eq. 1). N uptake in *ecosys* is solved by coupling active uptake by root and mycorrhizal surfaces with radial transport by mass flow and ions diffusion (Eq. A5) from soil solutions to these surfaces (Grant, 1991). N uptake rate is affected by soil temperature, nutrient availability, water, and O_2 concentration (Grant, 1998). The root surface area and length available for N uptake are dynamically simulated, which is driven by the exchange of non-structural C and nutrients along concentration gradients established by the differential

Table 1
Field experiment data and *ecosys* model parameters used in this study. Larger values for the maturity group reflect a longer time to reach maturity.

Site name	Rotation	N Fertilizer	Tillage	Drainage	Maturity group in *ecosys* (corn)	Maturity group in *ecosys* (soybean)
DeKalb	continuous-corn and soybean-corn	Six fertilizer rates (kg N/ha) with the same increment (0, 50.45, …, 252.24)	√	√	17	15
Monmouth			√	√	18	16
Urbana			√	√	18	16
Perry			√		18	16
Brownstown			√		18	16
DSU					19	17
DSB			√		19	17
AE1	soybean-corn	Recorded N fertilizer rate	√	√	18	16
AE2	continuous-corn		√	√	18	16
AE3	soybean-corn		√	√	18	16

uptake and demand in shoots and roots (Grant, 1998). The absorbed N is then moved into root and different organs in shoot (e.g. stalk, sheath, leaf, and grain) based on their soluble C and nutrients pool sizes (Eq. A6) (Grant, 1989). R_g drives new biomass production using soluble C and N from these pools (Grant, 1998). Litter N from senescent leaves and residues after harvest decomposes into SOM (Eq. A7) and is then mineralized as SIN.

N_2 fixation serves as a critical mechanism for replenishing plant organic N, particularly in leguminous crops like soybean. Two types of N_2 fixation are considered in *ecosys* sharing the similar modeling method, including heterotrophic non-symbiotic diazotrophs and autotrophic symbiotic diazotrophs. Here we describe symbiotic N_2 fixation, which is constrained by R_g of diazotrophs, non-structural C, and non-structural N of nodule, reflecting an inhibition on N_2 fixation by its product (Eq. A8; Postgate, 1998). N_2 fixation is also constrained by the additional N needed to maintain microbial N that is not satisfied by other sources such as immobilization (Postgate, 1998).

$$\Delta SIN = Mineralization + Fertilizer - (Water_{SIN} + Uptake_{SIN} + Gas) \quad (1)$$

$$\begin{aligned} \Delta SOC &= (Litter_C + Root\ Exudates) - (Rh_{litter} + Rh_{soil}) - \xi_C \\ &= (GPP - Ra - Grain) - Rh - \xi_C \\ &= -NEE - Grain - \xi_C \end{aligned} \quad (2)$$

where ΔSIN and ΔSOC represent the change in SIN and SOC, respectively; $Water_{SIN}$ is the total SIN loss through surface runoff and subsurface discharge (i.e. leaching); Gas is gas emissions, including ammonia (NH_3), N_2O, and N_2 through processes including nitrification, denitrification, and volatilization; R_a and R_h are autotrophic and heterotrophic respirations, respectively; Grain is harvested C, and NEE is the net ecosystem exchange; ξ_C is the SOC leakage (e.g. methane emissions) which can be neglected due to its relatively smaller magnitude compared with other terms in Eq. 2.

2.2.2. Model calibration, validation, and simulation in this study

Inputs in *ecosys* included soil, weather, and management practices. Weather inputs included temperature, precipitation, wind speed, solar radiation, and humidity, which were obtained from the hourly North American Land Data Assimilation System (NLDAS-2 with a spatial resolution of 0.125°) meteorological data (Xia et al., 2012). Soil inputs (e.g. SOC, soil texture, and bulk density) were extracted from the USDA Gridded Soil Survey Geographic Database (gSSURGO, 2020). Management practices for each site were shown in Table 1. We ran *ecosys* in each of the 10 sites during their experimental periods, with the same spin-up settings (≥20 years starting from 1979) to ensure equilibrium was reached by the model before the experiments. To account for different cultivar of the same crop at different sites, one phenology-related parameter (i.e. maturity group) was calibrated using yield measurements (Table 1) (Qin et al., 2021; Li et al., 2022; Zhou et al., 2021). All other crop-specific parameters for corn and soybean such as morphology (e.g. root distributions) and photosynthesis (e.g. mesophyll carboxylation rate) were maintained as default values based on estimates from previous studies (Grant et al., 1999; Grant, 1998). We evaluated the performance of *ecosys* simulated corn yields against observations at seven long-term experimental sites under both C-C and S-C, utilizing R^2 and RMSD from regressions of modeled yield against measured yield (averaged over replicated experiments). We also compared RMSD with root-mean-square error (RMSE) to represent uncertainty in measured corn yield from replicated experiments. The corn yield differences between C-C and S-C for those seven sites and NEE and energy fluxes from three flux tower sites were then used as validation to compare with the corresponding model simulations.

The validated *ecosys* model with adjusted crop parameters at seven UIUC trial sites was then extended beyond the final experimental year through 2020 using the same settings as the original trials, such as the soil profiles and management practices as described in Table 1 with certain assumptions about planting, harvest, and N fertilization dates. For example, we continued to use six N fertilizer rates (0, 50, 101, 151, 202, and 252 kg N/ha) in the form of banded UAN under C-C and S-C rotations. During the extended simulation periods (2009–2020), weather data were obtained from the NLDAS-2 dataset, and May 5th and May 15th were selected as the corn and soybean planting dates and May 5th as the corn N fertilization date.

2.3. Economic analysis

We used the economic margin assessment to quantify agronomic benefits and environmental costs of S-C and C-C systems by incorporating simulated data from both corn and soybean phases as well as corresponding agronomic and environmental related prices. Agronomic benefit was defined as the difference between gross income calculated according to both crop yield and corresponding sales prices and costs including land and non-land costs such as fertilizer purchases, labor, and machinery (Eq. 3). We assumed land and other nutrients costs (e.g. phosphorus and potassium) to be the same between S-C and C-C, as they are not expected to affect the relative outcomes between two systems. Although there are specific operational differences between the two cropping systems such as the higher post-harvest drying costs for rotated corn due to increased yields (Katsvairo and Cox, 2000), we did not account for such differences as lacking related cost data. Instead, we used general non-land costs from typical corn and soybean fields in Illinois to estimate the costs between different cropping systems (Schnitkey et al., 2021) (Fig. A3). In this study, simulation results under S-C and C-C during 1999–2020 were analyzed for their impact on soil C and N cycles and were also combined with the contemporaneous public-available economic data to estimate the above-mentioned agronomic benefits. Specifically, the prices for corn, soybean and N fertilizer (i.e. urea) are from the global commodity prices of the World Bank dataset (World Bank Group, 2022). We then estimated the UAN prices by converting urea prices using a theoretical price ratio of 1.45 (urea:UAN) based on N content proportion (Kenkel, 2010). While some of these price-related assumptions contain uncertainties (e.g. the urea:UAN price ratio varied from 1.02 to 1.83 during 1991–2007 (Kenkel, 2010)), these impacts were considered by using different price scenarios, as described in Section 3.4.

Environmental costs considered the amount of SIN loss through surface and subsurface water flow ($Water_{SIN}$), N_2O emission, NH_3 emission, and C loss through CO_2 emission (estimated as -NEE - Grain (Eq. 2)) and the corresponding prices for each environmental loss (Eq. 4). The environmental price from N loss through water flow ($18.54/kg N) was quantified by considering different aspects of groundwater water contamination (Sobota et al., 2015). The price of N_2O emission ($16.18/kg N) reflected the ultraviolet light exposure from ozone (Jin et al., 2019). The price of NH_3 emission was set as $1.5/kg N by considering its role as a precursor to $PM_{2.5}$ formation (Gu et al., 2021). The price for net CO_2 emission is based on the social cost of C with values of $51/t CO_2 ($187/t C) (Chemnick, 2021). Finally, we calculated the relative difference in total economic return, by combining agronomic benefits and environmental costs between S-C and C-C to assess the net advantage of crop rotation.

$$Agronomic\ benefits = Yield \times Crop\ price - Fertilizer \times Fertilizer\ price - Other\ Costs \quad (3)$$

$$Environmental\ costs = Water_{SIN} \times Water_{SIN}\ prices + N_2O \times N_2O\ Emission\ prices + NH_3 \times NH_3\ Emission\ prices + CO_2 \times CO_2\ Emission\ prices \quad (4)$$

3. Results

3.1. Model performance evaluation with the field experiments

Ecosys adequately simulated the corn yield from the seven sites across Illinois by reproducing the corn yield for C-C (R^2=0.70, RMSD=2.03 Mg/ha, and RMSE=0.78 Mg/ha; Fig. 3a), S-C (R^2=0.66, RMSD=1.86 Mg/ha, and RMSE=0.78 Mg/ha; Fig. 3b), and the yield differences between these two cropping systems under different fertilizer rates (Fig. 3c). RMSD, which represented variation in measured yield not explained by *ecosys*, was slightly larger than the corresponding RMSE representing uncertainty in measured yield for both cropping systems. The larger RMSD relative to RMSE indicated some opportunity to improve agreement between the modeled and measured yield especially in certain site-years and will be further discussed in Section 4.1. Although our modeling performance for soybean yield simulations was worse than the corn yield, *ecosys* still achieved acceptable performance in capturing soybean yield under S-C with R^2=0.36 and RMSD=0.63 Mg/ha (Fig. 3d). The lower performance for soybean yields was partly due to data availability, as only one soybean yield was collected per site-year, and so it was difficult to distinguish the impacts of soil N content resulting from different N rates applied in corn years (Fig. A2; Section 2.1). This was the case for both our modeling results and other field experiments (Cordeiro and Echer, 2019; Salvagiotti et al., 2008). In addition, *ecosys* captured the measurements from the other three EC flux towers, with good alignment for both C fluxes (R^2=0.54–0.81 and RMSD=5.07–11.47 umol CO_2/m^2; Fig. 4 and Fig. A4) and energy fluxes (R^2=0.83–0.89 and RMSD=72.96–87.12 W/m^2; Fig. A5). The performance of *ecosys* in simulating processes related to agroecosystem C and N has been demonstrated across many sites. This model can reliably predict how soil available N and crop productivity respond to N fertilizer under various environmental conditions with acceptable accuracy.

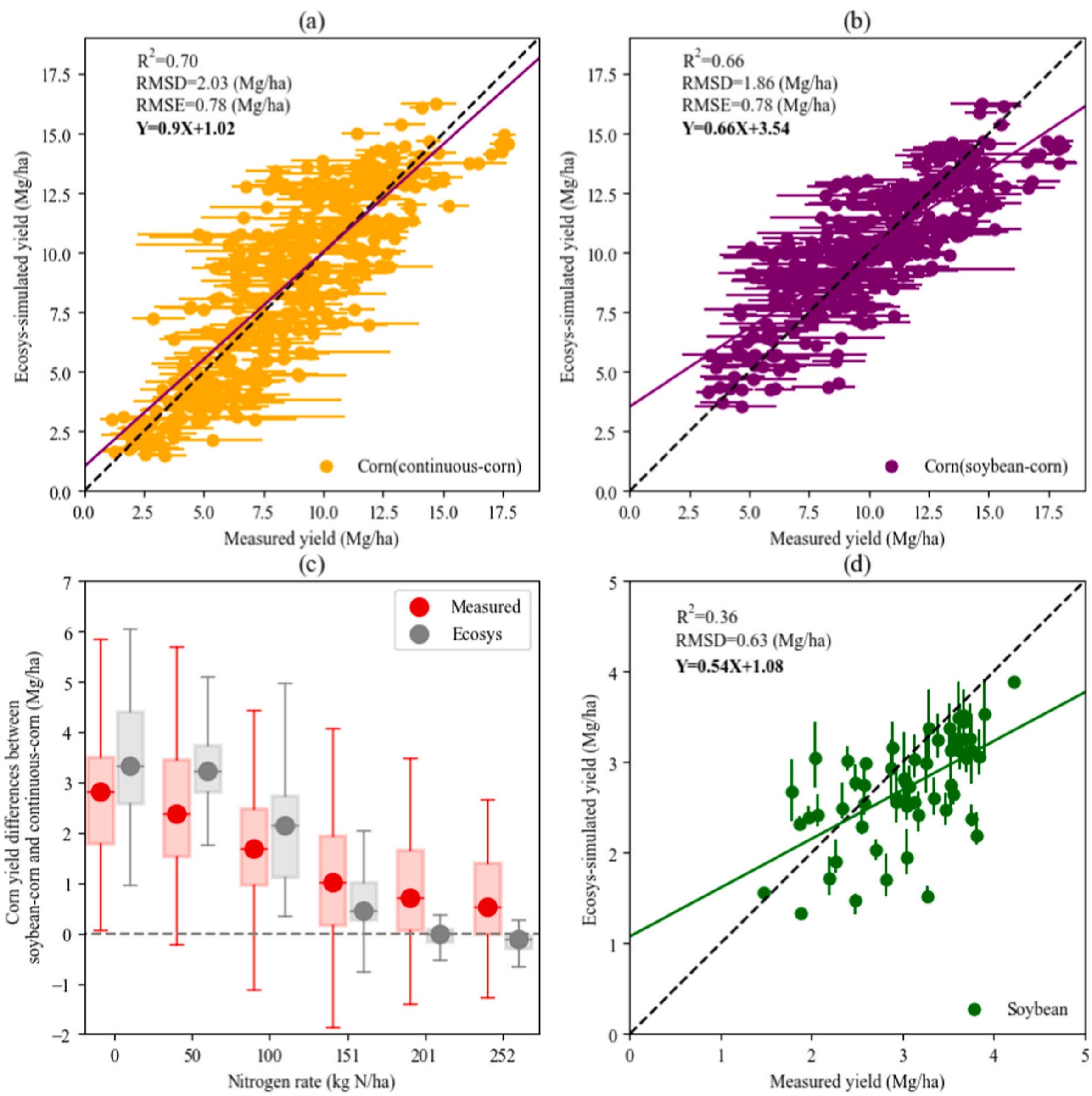

Fig. 3. Comparison of *ecosys* simulated and measured corn and soybean grain yield (15% moisture) at seven sites in Illinois (ranges and mean values of measured yield are respectively represented as lines and points; a: corn yield under continuous-corn (C-C); b: corn yield under soybean-corn (S-C)); c. corn yield differences between S-C and C-C under six different N fertilizer rates; d. soybean yield. Error bars in panels (a) and (b) show variability of corn yield measurements with four replicates, while those in panel (d) indicate variability of the modeled soybean yield, as only a single observation was available per site-year without N rate distinctions.

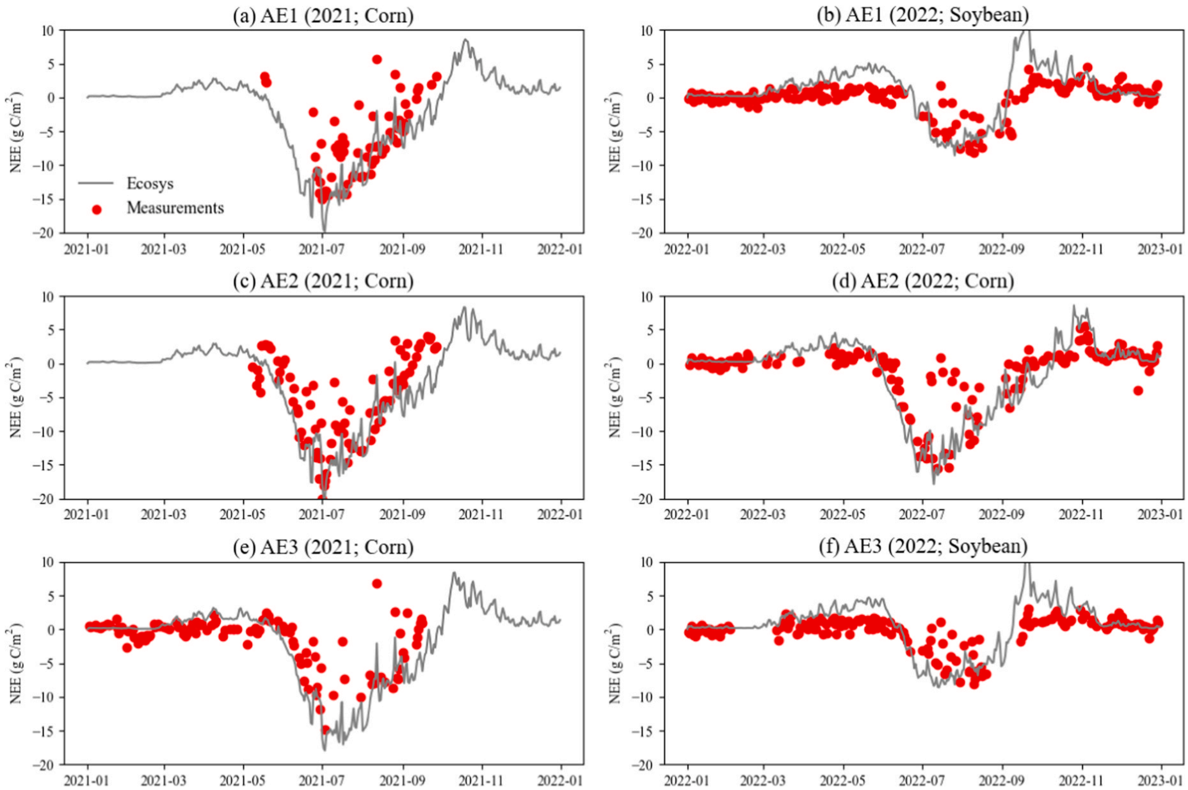

Fig. 4. Net Ecosystem Exchange (NEE) validation results for three ARPA-E founded sites during 2021–2022. The gray lines and red points in each subfigure represent *ecosys* simulations and measured data, respectively.

3.2. Model-simulated effect of crop rotations: trade-offs between SOC and SIN balances

Although S-C improved GPP and Grain C in years with the same crop (corn) compared with C-C under the normal N fertilizer rate, it led to lower systematic GPP, Grain C, ecosystem respiration, and ΔSOC across all seven Illinois sites. For example, at the Perry site during 1999–2020 with a typical fertilizer rate (151 kg N/ha; which is close to the average U.S. Midwestern corn N rate in 2018: 167 kg N/ha (USDA-NASS, 2020)), S-C induced 62 g C/m^2 more GPP, 32 g C/m^2 more R_a, 133 g C/m^2 less R_h, and 16 g C/m^2 more Grain C compared with C-C in years with the same crop (Fig. 5a and Fig. A6). In years with different crops, planting soybean (S-C) caused 586 g C/m^2 less GPP, 115 g C/ m^2 less corn R_a, 116 g C/m^2 less corn R_h, and 172 g C/m^2 less Grain C relative to planting corn in C-C (Fig. 5c). S-C contributed to overall decreases of 341 g C/m^2 in GPP, 219 g C/m^2 in ecosystem respiration, 94 g C/m^2 in Grain C, and 45 g C/m^2 in ΔSOC compared to C-C (Fig. 5c).

Under the same N fertilizer rate, S-C reduced total SIN balance inputs (the sum of mineralization and fertilizer) and certain outputs including N uptake and gas emissions (primarily N_2O), although the effect on N leaching varied across years (Fig. 5f and Fig. A7). For example, at the Perry site in years with the same crop, S-C increased total SIN inputs by 5.52 g N/m^2 through higher mineralization and raised N uptake by 5.38 g N/m^2 compared with C-C (Fig. 5b and Fig. A7), which was consistent with the increased Grain C observed in the SOC balance analysis mentioned above. The increased mineralization and higher soil O_2 from reduced R_h under S-C led to higher SIN (primarily nitrate) during the periods between planting and rapid crop uptake stages (May to June; Fig. A7). This elevated SIN in S-C also resulted in 1.56 g N/m^2 more N leaching, while N_2O emissions decreased by 0.01 g N/m^2, potentially due to higher soil O_2 under S-C, which inhibited denitrification compared to C-C (Fig. A7). In years with different crops, although adopting S-C resulted in 7.43 g C/m^2 more mineralization compared with C-C, it contributed to 7.68 g N/m^2 less total N input as no N fertilizer was applied to soybean (Fig. 5d). This reduced N input led to 7.32 g N/m^2 less N uptake, 1.09 g N/m^2 less N leaching, and 0.06 g N/ m^2 less N gas emissions (with over 88% as N_2O; Fig. 5d and Fig. A7). Similar trends in both SIN and SOC balances were observed across the other six study sites.

3.3. Model-simulated pathways of crop rotations affecting corn yield

As shown in previous sections, S-C improved corn N uptake and hence corn yield compared with C-C. However, these improved corn yields were reduced by adding more N fertilizer as shown by both field measurements and our simulations (Fig. 3c). Further analysis suggested that the improved corn yield was caused by both higher corn-year soil net mineralization and early spring (January-April) surface soil temperatures, which were respectively dominated by the quality (higher residue N driven by N_2 fixation) and quantity (less residue C) of soybean residues compared with corn residues (Fig. 6a). On average, across seven Illinois site from 1999 to 2020, soybean in S-C left 26.65 g N/m^2 more litter N and 263.19 g C/m^2 less litter C compared with the corresponding corn in C-C under the normal fertilizer rate (151 kg N/ha; Fig. 6b-c). These differences in crop residue quality and quantity between soybean and corn then caused 6.00 g N/m^2 more soil net mineralization and 1.03 °C higher early-spring soil temperature in the subsequent corn years of S-C compared with C-C (Fig. 6d-e). Consequently, the increased corn-year mineralization and early spring temperature under S-C led to 5.41 g N/m^2 more corn N uptake and 50.42 g C/m^2 more GPP relative to C-C (Fig. 7f-g).

3.4. Economic margin assessment of different crop rotation systems

By accounting for market-driven variability in crop and fertilizer prices, as well as differences in crop yield, fertilizer usage, and other non-land costs between S-C and C-C, our economic analysis indicated that S-C did not always produce higher agronomic benefits compared

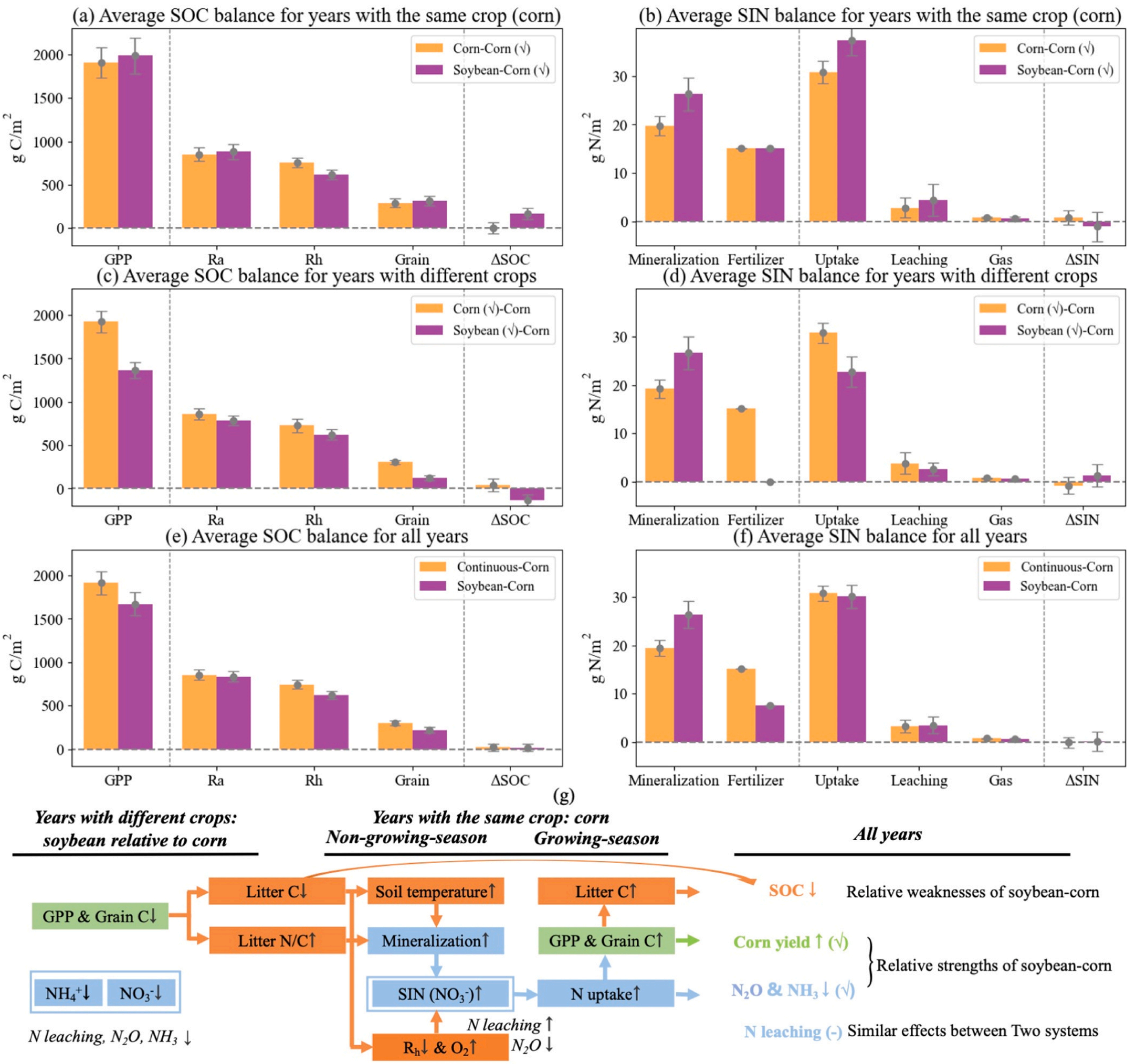

Fig. 5. Effects of crop rotation on modeled annual SOC (a, c, and e) and SIN (b, d, and f) balance for the Perry site during 1999–2020 with the fertilizer rate at 151 kg N/ha. Results are summarized for years with different crops (corn; a-b), years with the same crop (c-d), and all-years (e-f). Bar and error bars respectively represent mean values and standard deviations of the results. (f) is a scheme diagram to summarize the impact of soybean-corn (S-C) relative to continuous-corn (C-C) in different years in terms of SOC and SIN outcomes. (g) is a scheme diagram to illustrate the impact of S-C systems relative to C-C in different years in terms of SOC and SIN outcomes under the N fertilizer rate of 151 kg N/m^2.

with C-C under normal fertilizer rates. Using multi-year average non-land costs estimates for corn and soybean production from 2000 to 2022 and several representative prices scenarios for soybean, corn and N fertilizer (Section 2.3), we found that the relative profitability of S-C is highly sensitive to commodity price scenarios. Lower agronomic benefits for S-C relative to C-C were especially obvious under conditions with high corn prices together with lower soybean and fertilizer prices relative to corn prices. Taking the average results from all 154 site-year simulations (7 sites during 1999–2020) under 151 kg N/ha as an example (Fig. 7b), S-C had $467/ha less agronomic benefits under high corn price conditions ($280/Mg) with lower soybean/corn (2.00) and fertilizer/corn (1.00) price ratios. In contrast, S-C had $303/ha more agronomic benefits compared with C-C under low corn prices ($140/Mg) but with higher soybean/corn (2.75) and fertilizer/corn (1.50) prices ratios.

The relative agronomic benefits of S-C compared with C-C decreased and even became negative at higher N fertilizer application rates. This mainly occurred because the relative corn yield benefits of S-C decreased with higher N fertilizer rates (Section 3.3), while the soybean yield only slightly increased despite much higher fertilizer costs. For example, the relative agronomic benefits of S-C under normal corn ($178/Mg), soybean ($410/Mg), and fertilizer prices ($193/Mg) change from $1133/ha to −$206/ha when N fertilizer changed from low (50 kg N/ha; Fig. 7a) to very high rates (252 kg N/ha; Fig. 7c). In addition, we also found larger relative environmental benefits of S-C at higher N fertilizer rates, which will be further discussed in Section 4.2. For example, the relative

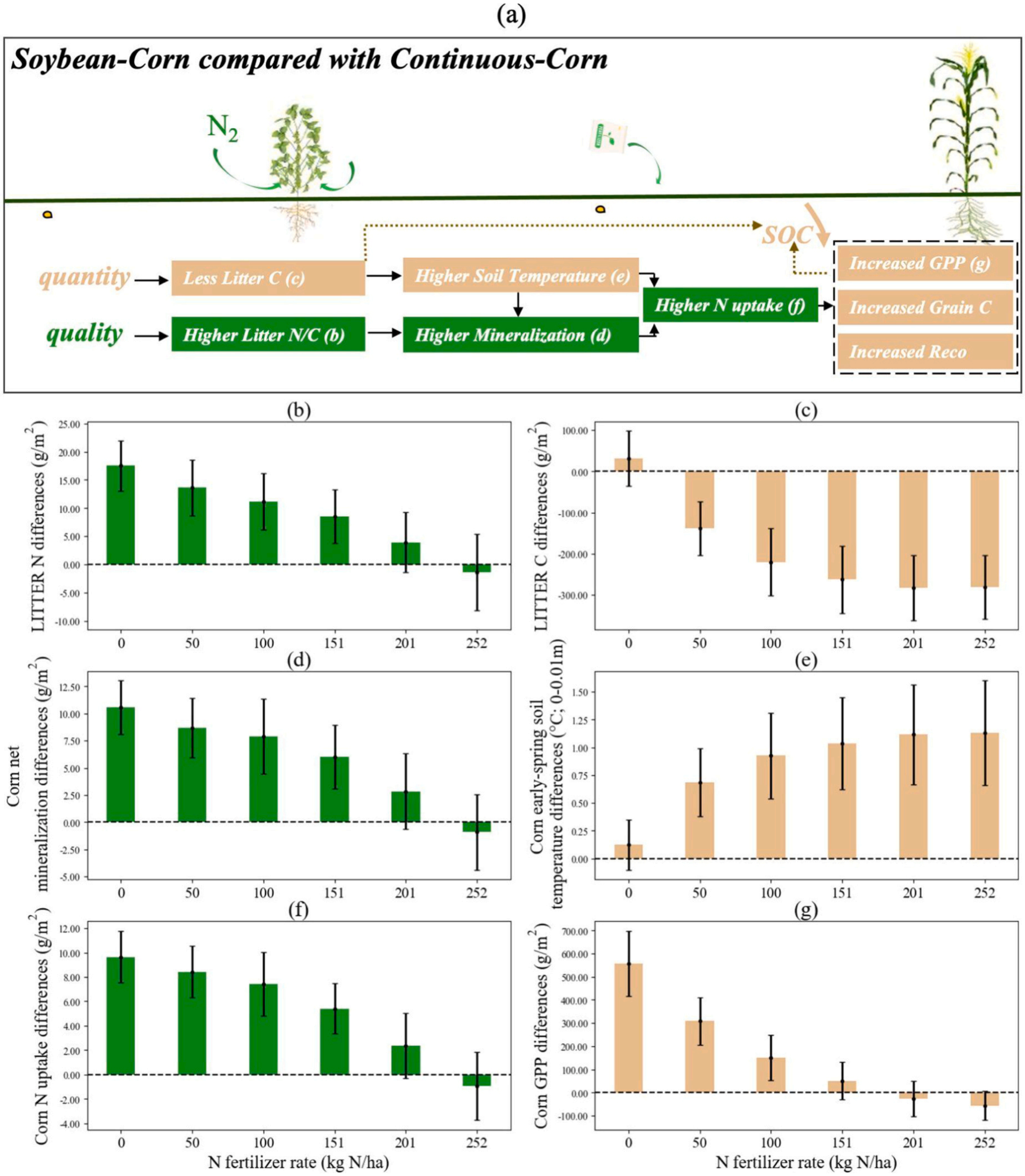

Fig. 6. (a) Schematic diagram illustrating the impacts of crop residues under soybean-corn rotation (S-C) relative to continuous-corn (C-C) system. Differences of previous-year litter N (b), litter C (c), and corn-year net mineralization (d), early-growing-season soil temperature (surface soil temperature at 0–0.01 m; e), N uptake (f), and GPP (g) between S-C and C-C. Results are based on the seven sites in Illinois during 1999–2020 with the fertilizer rates ranging from 0 to 252 kg N/ha. Bar and error bars respectively represent mean values and standard deviations of the results.

environmental benefits of S-C increased from −\$214/ha at low N rates to \$579/ha at high rates (Figs. 7d and 7f).

4. Discussion

We used N-corn yield responses from seven long-term experimental sites and NEE measurements from three flux tower sites under both S-C and C-C across Illinois to first validate *ecosys* and then used it to assess the impacts of adopting different rotation systems. Below, we summarized our findings to answer the three questions raised in the introduction.

4.1. How do crop rotations (S-C and C-C) affect corn yield, and what is the impact of N fertilizer application on these effects?

Our simulation results in Section 3.3 showed that S-C improved corn yield compared with C-C, primarily due to both higher residue N/C caused by symbiotic N_2 fixation by soybean and fewer residue C in soybean compared to corn. The fewer soybean residue C increased the reflection of solar radiation and reduced the insulating effects between soil surface and atmosphere, thereby raising early spring soil temperature (Suying et al., 2005). In combination, higher soil temperature and residue N/C of soybean accelerated soil net mineralization of the

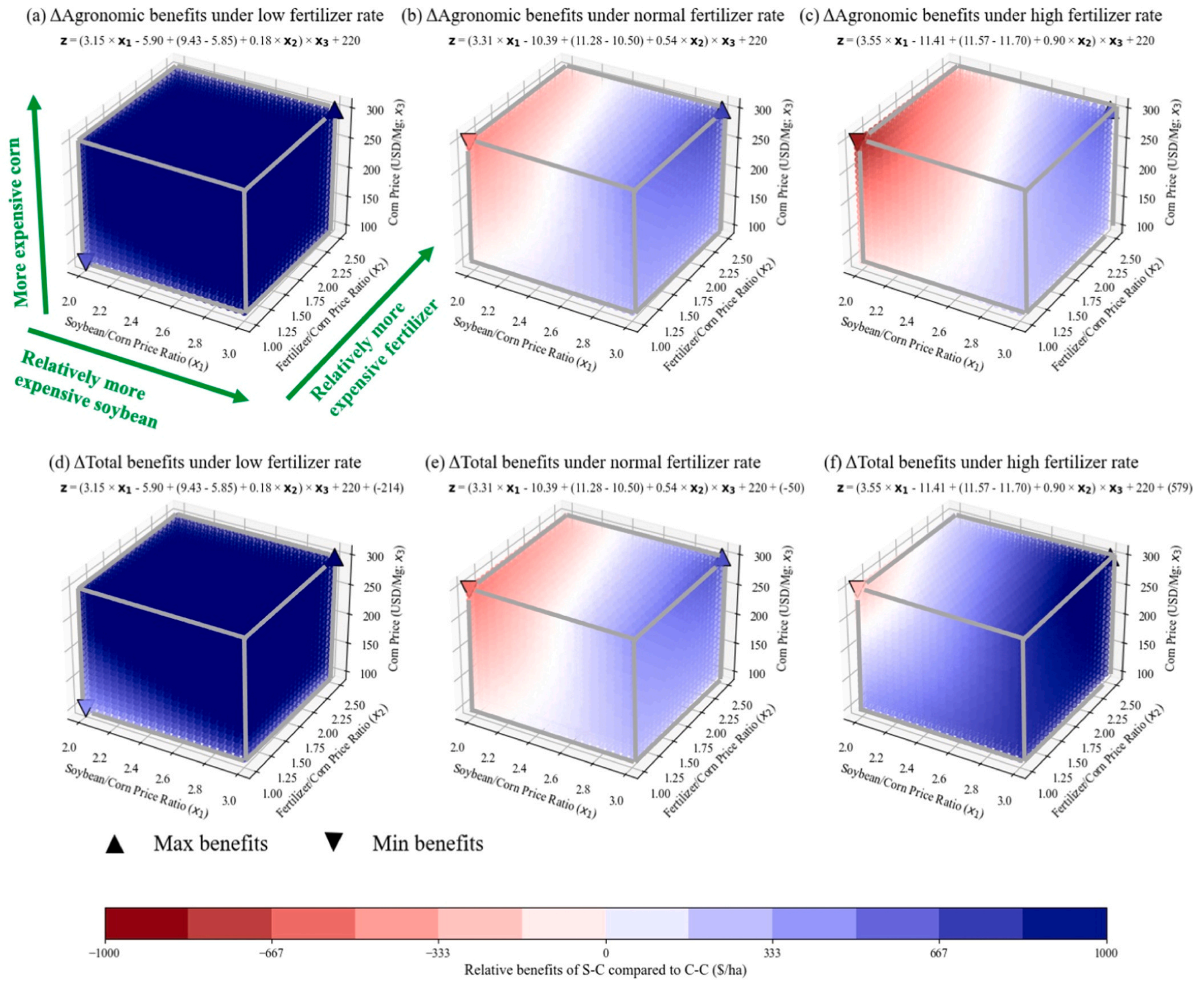

Fig. 7. Impact of different price terms (soybean/corn price ratio (x_1), fertilizer/corn price ratio (x_2), and corn price (x_3; \$/Mg)) on the relative benefits (\$/ha) of adopting soybean-corn (S-C) compared with continuous-corn (C-C) for all 154 site-year simulations (average results based on 7 Illinois sites during 1999–2020). (a), (b), and (c) represent agronomic benefits based on low (50 kg N/ha), normal (151 kg N/ha), and high fertilizer rates (252 kg N/ha). (d)-(f) represent results that consider both agronomic benefits and environmental costs under the same N rates. Ranges for x_1, x_1, and x_3 are based on the historical range of each price term (Fig. A3).

subsequent corn-years (Eqs. A3–5), and finally led to increases in corn N uptake and yield of S-C compared with C-C. Previous field (Green and Blackmer, 1995; Gentry et al., 2001; Breza et al., 2023) and modeling studies (Puntel et al., 2016) also indicated that less soybean residue quantity and higher residue N/C compared with corn residue contributed to the subsequent corn yield benefits of S-C through faster residue decomposition and increased plant available N through stimulating mineralization. However, the pathway of less residue cover improved soil temperature and N uptake received less attention (Wilhelm and Wortmann, 2004; Gentry et al., 2001).

Our simulations estimated an average corn yield increase of 0.62 Mg/ha (6.4%) under S-C compared with C-C under a normal fertilizer rate of 151 kg N/ha across 7 Illinois trials during 1999–2008. This yield benefit diminished at higher N fertilizer rates, which was also observed in our field observations and other studies (Fig. 2c; Kim et al., 2022). Although our simulations approximated the observations, our simulation was slightly smaller than our observed magnitude of 0.80 Mg/ha (10.3%) under the same N fertilizer rate. This underestimation of our simulations was potentially explained by the lack of considering other field-level benefits of rotation in *ecosys*, such as reduced pesticide and insecticide use, as well as improvements in soil physical properties (Kim et al., 2022; Neupane et al., 2021; Liu et al., 2024). For example, Liu et al. (2024) found S-C disrupts pest and weed cycles, enriches the corn rhizospheres with beneficial bacteria and fungi, and suppresses pathogenic fungi compared to C-C. Our simulated corn yield increases through adopting S-C compared with C-C were within estimates from other studies. Erickson (2008) summarized 28 U.S. trials showing 2–19% corn yield gains from S-C relative to C-C. Seifert et al. (2017) found a 4.5% average corn yield benefit using crop yield data from more than 700, 000 commercial fields across the U.S. Midwest. This highly variable corn yield benefit from adopting S-C may be affected by factors including different management practices (e.g. N fertilizer rates) and environmental conditions (Kim et al., 2022; Gentry et al., 2001; Seifert et al., 2017; Breza et al., 2023). Several studies have suggested that corn yield improvements under S-C relative to C-C were greater in dry environments than in normal conditions, potentially due to improved drought tolerance and resilience through better root development in rotated corn (Langer and Randall, 1981; Peterson and Varvel, 1989; Seifert et al., 2017; Zhou et al., 2024). Our results in the central Corn Belt were generally less than those values from locations with lower soil moisture (western Corn Belt states such as Nebraska) with a rotation effect in improving corn yield by over 20% (Wilhelm and Wortmann, 2004; Peterson and Varvel, 1989). The future impacts of S-C on corn yield may also be greater in the U.S. Midwest because of a higher frequency of drought as climate change is predicted (Dietzel et al., 2016). Although how historical environment conditions and future climates affect S-C impacts is beyond the scope of this study, future modeling studies should be explored at larger spatial scales with contrasting environmental conditions to discern interactions between soil and weather that respond to different cropping systems. Such efforts could help farmers better identify changes that may improve productivity, alter different environmental outcomes, and adapt practices based on location-specific conditions (Maaz et al., 2021).

4.2. How do crop rotations affect soil C and soil N dynamics?

Implementing more sustainable management practices is important for reducing environmental impacts, and crop rotation has emerged as a promising strategy to mitigate environmental challenges associated with monoculture while maintaining crop productivity (Kazula and Lauer, 2018). Results in Section 3.2 showed S-C reduced both SOC and other agricultural gas emissions (e.g. N_2O and NH_3) compared with C-C under normal N fertilizer rates, while N leaching varied across years (Fig. 5). N leaching was lower for S-C during soybean years because no N fertilizer was applied in soybean phases; however, the N_2 fixed by soybean was released to the soil after harvest and further mineralized in the following corn year, which elevated SIN levels and N leaching. Further analysis identified N fertilizer rates as a key controlling factor determining the relative relationship between S-C and C-C regarding SOC, N leaching and N gas emissions. Each of these environmental outcomes has a breakpoint (i.e. threshold of N fertilizer rate) above which the relative relationships between S-C and C-C shifted (Fig. 8c-f).

At low N fertilizer rates during the corn phase, soybean left similar or even greater litter C than corn (Fig. 8b; 8 g). The enhanced corn growth,

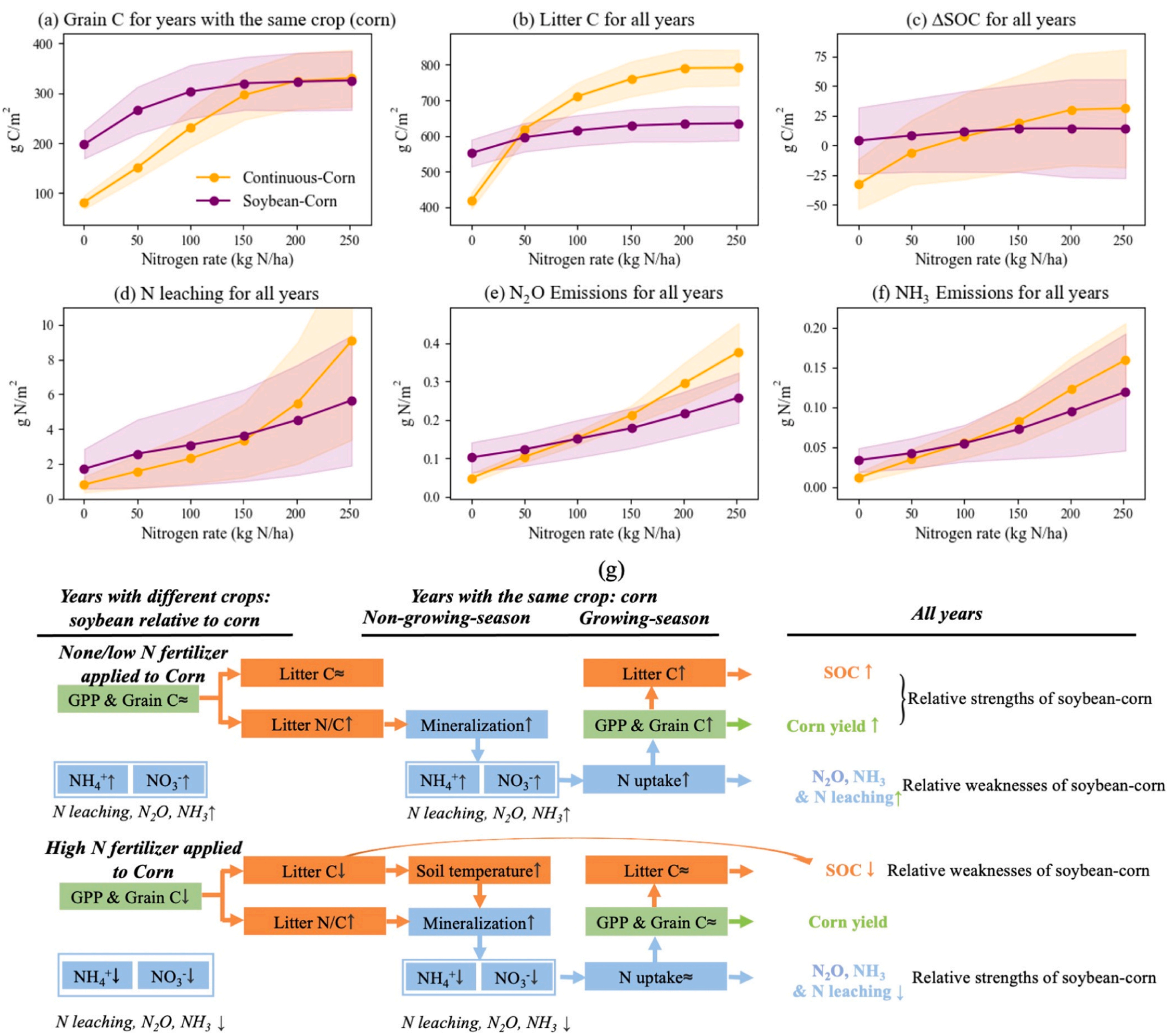

Fig. 8. Cropping system and N fertilizer rate effects on grain carbon in the corn phase (a), and effects on all-years average litter C (b), ΔSOC (c), N leaching (d), N_2O (e) and NH_3 (f) emissions based on results during 1999–2020 at 7 Illinois sites. Note that for litter C and ΔSOC, we use multi-year average results over each 2-year cycle. The orange and purple dots represent mean values for continuous-corn (C-C) and soybean-corn (S-C), respectively, while the shaded areas indicate standard deviations. (g) is a scheme diagram illustrating the impact of S-C systems relative to C-C in different years (i.e. years with different crops (corn), years with the same crop, and all-years) in terms of SOC and SIN outcomes under no/low or high N fertilizer rates (252 kg N/m^2).

with increased grain and stover production under S-C, contributed to greater SOC than C-C. As N fertilizer increased, the positive rotation effect on corn development diminished (as discussed in Section 4.1), and corn left over 30% more residue than soybean with slower residue decomposition, leading to lower SOC in S-C relative to C-C (Kazula and Lauer, 2018). Similar trends in residue C input and annual SOC change influenced by the cropping system and N fertilizer rate have been observed in other experimental studies (Poffenbarger et al., 2017; Deiss et al., 2021; Huggins et al., 2007). Most field experiments conducted under normal N fertilizer rates also observed reduced SOC in S-C compared with C-C (Wilson and Al-Kaisi, 2008; Huggins et al., 2007; Deiss et al., 2021), though a few studies found no significant SOC differences between rotation systems, potentially due to relatively shorter experimental periods (<5 years) (Hernandez-Ramirez et al., 2009).

In most field experiments, N leaching under S-C is typically found to be similar to or lower than that under C-C (Zhu and Fox, 2003; Attia et al., 2015; Ochsner et al., 2018). Our simulations (Fig. A8) were consistent with field experiments showing similar soil water dynamics regarding evapotranspiration and discharge between S-C and C-C (Ochsner et al., 2018; Hussain et al., 2019), suggesting that differences in N leaching are primarily driven by biogeochemical processes. Our simulation showed a N rate breakpoint above which S-C produced less N leaching compared with C-C (Fig. 8d). At low to normal fertilizer rates, N_2 fixed by soybean elevated soil N after residue decomposition, resulting in higher N leaching in S-C than in C-C (Fig. 8d, A6). As the N rate increased, conditions shifted toward lower SIN in S-C, leading to reduced N leaching compared to C-C. Similar N leaching breakpoints (between 151 and 202 kg N/ha) were also identified by another modeling study conducted in the central U.S. Midwest (Pasley et al., 2021). Gaseous N losses including N_2O and NH_3 also exhibited breakpoints, above which S-C produced less N gas emissions relative to C-C. While no previous studies have identified N_2O across different N rates, studies conducted at regular N rates have reported reduced N_2O emissions under S-C during corn phase (Jacinthe and Dick, 1997; Omonode et al., 2011), or across entire rotation cycles (Behnke et al., 2018). For instance, after accounting for N_2O emissions across both corn and soybean phases, S-C reduced annual N_2O by amounts ranging between 0.02 and 0.31 g N/m^2 compared with C-C (Venterea et al., 2010; Adviento-Borbe et al., 2006; Omonode et al., 2011; Behnke et al., 2018). Reductions of NH_3 by conducting S-C relative to C-C in this study should be tested by future field experiments.

Crop rotation is gaining interest in both research and policy settings as a way to achieve ecosystem services, such as improving soil health and breaking pest cycles, without compromising yield (Smith et al., 2023, 2025). As a predominant rotation strategy in the U.S. Midwest, S-C has been demonstrated to have benefits for soil biodiversity relative to monoculture systems (Zuber et al., 2015). However, its effects on soil C sequestration have rarely been linked to N fertilizer rates. Our modeling study bridged this gap, showing that S-C could enhance SOC and bring corn yield benefits compared with C-C, particularly at low N fertilizer rates due to improved corn growth and increased corn residue. However, it may also increase N losses since higher SIN from soybean residue decomposition (Fig. A7). As N fertilizer increases, the corn yield benefits diminish, with concerns about reduced SOC due to decreased total crop residues. These reduced SOC under S-C may further affect other soil properties such as soil aggregation, microbial communities, and erosion control (Fig. A9 and Fig. A10; Attia et al., 2015; Meki et al., 2013; Kim et al., 2022). For example, soil under S-C had a less stable structure and lower aggregation than under C-C, likely due to a lower presence of humic substances and rapid decomposition of soybean residue (Martens, 2000; Blanco-Canqui and Lal, 2004). Although shifts in the soil microbial community due to variations in crop sequencing remain unclear, studies have found more abundant microorganism populations in S-C than in C-C (Neupane et al., 2021; Liu et al., 2024; Chamberlain et al., 2020). On the other hand, the lower SIN associated with reduced N fertilizer inputs when adopting S-C may offer additional benefits, such as lowering risks of soil acidification (Kim et al., 2022; Rengel, 2011) as well as air and water pollution risks. Although our study characterized soils under typical U.S. Midwest cropping systems, its implications can be extended to similar productive regions, including the Northeast China and the Argentinean Pampas (Zhao et al., 2020).

4.3. *To what extent do economic returns differ between soybean-corn and continuous-corn cropping systems?*

With rising food commodity prices and expanded cultivated area in the U.S. Midwest over recent decades, improving crop yields in a cost-effective manner has become increasingly important for both farmers and agriculture-related industries (Mourtzinis et al., 2017). As an alternative to the excessive use of synthetic N fertilizers with C-C, S-C was also thought to increase farm income by improving corn yield and reducing N fertilizer cost during the soybean phase (Baum et al., 2025; Mourtzinis et al., 2017). However, comparisons of economic returns between S-C and C-C often overlook several critical factors such as soybean productivity and the variability of market prices for crops and fertilizer. For example, C-C has historically expanded in periods of high corn prices relative to soybean, such as during the ethanol boom in the early 2000s (Hendricks et al., 2014). In addition, farmers must select cropping systems based on expected market returns and risks associated with those returns (Young, 1996). While most studies report higher average economic returns for S-C relative to C-C (Al-Kaisi et al., 2015; Chase and Duffy, 1991; Karlen et al., 2013; Singer and Cox, 1998), these analyses often assume static prices (Stanger et al., 2008) and exclude other critical factors, such as varying fertilizer input levels (Katsvairo and Cox, 2000). Consequently, they may fail to identify cropping systems that maintain or increase profitability with reduced chemical inputs. Given the stochastic nature of commodity prices (Livingston et al., 2015), coupled with the agronomic effects of crop rotation versus monoculture as well as the monetized environmental risks, an economic analysis that accounts for both crop rotations and management inputs is essential for identifying better cropping systems under different market conditions (Katsvairo and Cox, 2000).

In this study, we adopted a systematic economic analysis by considering both agronomic and environmental outcomes of S-C relative to C-C under different N fertilizer rates. Agronomic benefits were assessed based on factors including yield, cost differences, and price variations, while environmental benefits were monetized through factors such as net CO_2 emissions, N leaching, N_2O, and NH_3 emissions. Under low to normal fertilizer rates, S-C generally provided higher agronomic returns than C-C due to better corn yields and lower fertilizer costs. However, under extreme market conditions characterized by high corn prices combined with low soybean/corn and fertilizer/corn price ratios, the agronomic advantage of S-C diminished or even reversed, demonstrating its sensitivity to market fluctuations. Increasing N fertilizer rates further reduced the relative agronomic benefits of rotation, as higher rates led to smaller corn yield gains and only modest soybean yield improvements. Although higher N fertilizer rates improved the environmental performance of S-C by reducing N losses relative to C-C, accurately monetizing these benefits remains challenging due to significant uncertainties in environmental cost valuation, and the fact that both S-C and C-C still exhibit substantial absolute N losses. To preserve S-C's agronomic benefits while maintaining or even elevating SOC, adopting normal or lower N fertilizer rates is recommended, because the potential increases in N losses are insignificant in absolute terms relative to C-C. Policy interventions should focus on providing subsidies to incentivize sustainable practices and mitigate the risks of lower agronomic benefits, especially under extreme market conditions, while also imposing taxes to address potential environmental degradation.

5. Conclusion

This study used a process-based model, *ecosys*, to evaluate the long-term impacts of S-C and C-C cropping systems on soil C and N dynamics in the U.S. Midwest. After validating the model using multi-site-year trial data across Illinois, including N fertilizer rate–corn yield responses and ecosystem flux measurements, we conducted simulations to assess both the agronomic and environmental outcomes through an integrated economic margin analysis. We found (1) compared to corn, soybean residue contributed to less residue C but more N, leading to elevated early spring soil temperature and net mineralization for the coming corn year. These effects increased corn-year N uptake and yield in S-C relative to C-C. However, this advantage diminished with additional N fertilizer input, which could compensate for the difference in N uptake between systems. (2) Under typical N fertilizer rates (151 kg N/ha), S-C reduced SOC but mitigated N_2O and NH_3 emissions relative to C-C. During soybean years, the absence of N fertilizer led to lower N leaching, but mineralized N from soybean residues in the following corn year elevated leaching compared to C-C. Thresholds in N fertilizer rate shifted the system dynamics of SOC and N losses between the two systems, with S-C offering yield and SOC benefits but increasing N loss risks at low N rates (50 kg N/ha), whereas this trend reversed at high N rates (252 kg N/ha). (3) S-C offered higher economic returns ($1133/ha) at low N rates (50 kg N/ha) under typical price conditions (soybean: $410/Mg; corn: $178/Mg; N fertilizer: $193/Mg) relative to C-C. But this profitability advantage was reduced at higher N rates due to increased fertilizer costs and smaller corn yield benefits, and further diminished under extreme market conditions (e.g. high corn prices with lower soybean/corn and fertilizer/corn price conditions). Overall, our findings provide key insights to understand different crop rotations in the U.S. Midwestern agroecosystems.

CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare that there are **no financial or personal relationships** with other people or organizations that could **inappropriately influence or bias** the research findings presented in this manuscript.

The authors have received **no employment, consultancies, stock ownership, honoraria, paid expert testimony, patent applications, or any other financial interests** that could be perceived as a potential competing interest in relation to this study.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2025.109739.

Data availability

Data will be made available on request.

References

Adviento-Borbe, M.A.A., Doran, J.W., Drijber, R.A., Dobermann, A., 2006. Soil electrical conductivity and water content affect nitrous oxide and carbon dioxide emissions in intensively managed soils. J. Environ. Qual. 35, 1999–2010. https://doi.org/10.2134/jeq2006.0109.

Aldrich, S.R. (1964). Are crop rotations out of date. Proc. 19th Annual Hybrid Corn Industry-Research Conference.

Al-Kaisi, M.M., Archontoulis, S.V., Kwaw-Mensah, D., Miguez, F., 2015. Tillage and crop rotation effects on corn agronomic response and economic return at seven Iowa locations. Agron. J. 107, 1411–1424. https://doi.org/10.2134/agronj14.0470.

Attia, A., Shapiro, C., Kranz, W., Mamo, M., Mainz, M., 2015. Improved yield and nitrogen use efficiency of corn following soybean in irrigated sandy loams. Soil Sci. Soc. Am. J. 79, 1693–1703. https://doi.org/10.2136/sssaj2015.05.0200.

Barr, A.G., Griffis, T.J., Black, T.A., Lee, X., Staebler, R.M., Fuentes, J.D., Chen, Z., Morgenstern, K., 2002. Comparing the carbon budgets of boreal and temperate deciduous forest stands. Can. J. For. Res. 32, 813–822. https://doi.org/10.1139/x01-131.

Bassu, S., Brisson, N., Durand, J.-L., Boote, K., Lizaso, J., Jones, J.W., Rosenzweig, C., Ruane, A.C., Adam, M., Baron, C., Basso, B., Biernath, C., Boogaard, H., Conijn, S., Corbeels, M., Deryng, D., De Sanctis, G., Gayler, S., Grassini, P., Hatfield, J., Hoek, S., Izaurralde, C., Jongschaap, R., Kemanian, A.R., Kersebaum, K.C., Kim, S.-H., Kumar, N.S., Makowski, D., Müller, C., Nendel, C., Priesack, E., Pravia, M.V., Sau, F., Shcherbak, I., Tao, F., Teixeira, E., Timlin, D., Waha, K., 2014. How do various maize crop models vary in their responses to climate change factors. Glob. Change Biol. 20, 2301–2320. https://doi.org/10.1111/gcb.12520.

Baum, M.E., Sawyer, J.E., Nafziger, E.D., Castellano, M.J., McDaniel, M.D., Licht, M.A., Hayes, D.J., Helmers, M.J., Archontoulis, S.V., 2025. The optimum nitrogen fertilizer rate for maize in the US Midwest is increasing. Nat. Commun. 16. https://doi.org/10.1038/s41467-024-55314-7.

Behnke, G.D., Zuber, S.M., Pittelkow, C.M., Nafziger, E.D., Villamil, M.B., 2018. Long-term crop rotation and tillage effects on soil greenhouse gas emissions and crop production in Illinois, USA. Agric., Ecosyst. Environ. 261, 62–70. https://doi.org/10.1016/j.agee.2018.03.007.

Benitez, M.-S., Ewing, P.M., Osborne, S.L., Lehman, R.M., 2021. Rhizosphere microbial communities explain positive effects of diverse crop rotations on maize and soybean performance. Soil Biol. Biochem. 159, 108309. https://doi.org/10.1016/j.soilbio.2021.108309.

Blanco-Canqui, H., Lal, R., 2004. Mechanisms of carbon sequestration in soil aggregates. Crit. Rev. Plant Sci. 23 (6), 481–504. https://doi.org/10.1080/07352680490886842.

Blanken, P.D., Black, T.A., Neumann, H.H., den Hartog, G., Yang, P.C., Nesic, Z., Lee, X., 2001. The seasonal water and energy exchange above and within a boreal aspen forest. J. Hydrol. 245, 118–136. https://doi.org/10.1016/S0022-1694(01)00343-2.

Boincean, B., Dent, D., Boincean, B., Dent, D., 2019. Crop rotation. Farming Black earth: Sustain. Clim. -smart Manag. chernozem Soils 89–124.

Bowles, T.M., Mooshammer, M., Socolar, Y., Calderón, F., Cavigelli, M.A., Culman, S.W., Deen, W., Drury, C.F., Garcia y Garcia, A., Gaudin, A.C.M., Harkcom, W.S., Lehman, R.M., Osborne, S.L., Robertson, G.P., Salerno, J., Schmer, M.R., Strock, J., Grandy, A.S., 2020. Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in north America. One Earth (Camb., Mass.) 2 (3), 284–293. https://doi.org/10.1016/j.oneear.2020.02.007.

Breza, L.C., Mooshammer, M., Bowles, T.M., Jin, V.L., Schmer, M.R., Thompson, B., Grandy, A.S., 2023. Complex crop rotations improve organic nitrogen cycling. Soil Biol. Biochem. 177 (108911), 108911. https://doi.org/10.1016/j.soilbio.2022.108911.

Bullock, D.G., 1992. Crop rotation. Crit. Rev. Plant Sci. 11, 309–326. https://doi.org/10.1080/07352689209382349.

Chamberlain, L.A., Bolton, M.L., Cox, M.S., Suen, G., Conley, S.P., Ané, J.-M., 2020. Crop rotation, but not cover crops, influenced soil bacterial community composition in a

corn-soybean system in southern Wisconsin. Appl. Soil Ecol.: A Sect. Agric., Ecosyst. Environ. 154 (103603), 103603. https://doi.org/10.1016/j.apsoil.2020.103603.
Chase, C.A., Duffy, M.D., 1991. An economic analysis of the Nashua tillage study: 1978-1987. J. Prod. Agric. 4, 91–98. https://doi.org/10.2134/jpa1991.0091.
Chemnick, J., 2021. Cost of carbon pollution pegged at $51 a ton. Scientific American.
Cordeiro, C.F.D.S., Echer, F.R., 2019. Interactive effects of nitrogen-fixing bacteria inoculation and nitrogen fertilization on soybean yield in unfavorable edaphoclimatic environments. Sci. Rep. 9 (1), 15606. https://doi.org/10.1038/s41598-019-52131-7.
Crookston, R.K., Kurle, J.E., 1989. Corn residue effect on the yield of corn and soybean grown in rotation. Agron. J. 81, 229–232. https://doi.org/10.2134/agronj1989.00021962008100020018x.
Deiss, L., Sall, A., Demyan, M.S., Culman, S.W., 2021. Does crop rotation affect soil organic matter stratification in tillage systems. Soil Tillage Res. 209 (104932), 104932. https://doi.org/10.1016/j.still.2021.104932.
Dick, W.A., Van Doren, D.M., Triplett, G.B., Henry, J.E., 1986. Influence of long-term tillage and rotation combinations on crop yields and selected soil parameters II. ResultObtained for a typic fragiudalf soil.
Dietzel, R., Liebman, M., Ewing, R., Helmers, M., Horton, R., Jarchow, M., Archontoulis, S., 2016. How efficiently do corn- and soybean-based cropping systems use water? A systems modeling analysis. Glob. Change Biol. 22, 666–681. https://doi.org/10.1111/gcb.13101.
Erickson, B., 2008. Corn/soybean rotation literature summary. Purdue Univ., West Lafayetter, IN.
Farmaha, B.S., Eskridge, K.M., Cassman, K.G., Specht, J.E., Yang, H., Grassini, P., 2016. Rotation impact on on-farm yield and input-use efficiency in high-yield irrigated maize–soybean systems. Agron. J. 108 (6), 2313–2321. https://doi.org/10.2134/agronj2016.01.0046.
Francis, C.A., Harwood, R.R., Parr, J.F., 1986. The potential for regenerative agriculture in the developing world. Am. J. Altern. Agric. 1, 65–74. https://doi.org/10.1017/S0889189300000904.
Frink, C.R., Waggoner, P.E., Ausubel, J.H., 1999. Nitrogen fertilizer: retrospect and prospect. Proc. Natl. Acad. Sci. 96, 1175–1180. https://doi.org/10.1073/pnas.96.4.1175.
Gentry, L.E., Below, F.E., David, M.B., Bergerou, J.A., 2001. Source of the soybean N credit in maize production. Plant Soil 236, 175–184. https://doi.org/10.1023/A:1012707617126.
Gentry, L.F., Ruffo, M.L., Below, F.E., 2013. Identifying factors controlling the continuous corn yield penalty. Agron. J. 105, 295–303. https://doi.org/10.2134/agronj2012.0246.
Grant, B.B., Smith, W.N., Campbell, C.A., Desjardins, R.L., Lemke, R.L., Kröbel, R., McConkey, B.G., Smith, E.G., Lafond, G.P., 2015. Comparison of DayCent and DNDC models: Case studies using data from long-term experiments on the Canadian prairies. In: Synthesis and Modeling of Greenhouse Gas Emissions and Carbon Storage in Agricultural and Forest Systems to Guide Mitigation and Adaptation. American Society of Agronomy and Soil Science Society of America, pp. 21–57. https://doi.org/10.2134/advagricsystmodel6.2013.0035.
Grant, R., 2001. A Review of the Canadian Ecosystem Model — ecosys. In: A Review of the Canadian Ecosystem Model — ecosys. Modeling Carbon and Nitrogen Dynamics for Soil Management. https://doi.org/10.1201/9781420032635.ch6.
Grant, R.F., 1989. Simulation of carbon assimilation and partitioning in maize. Agron. J. 81, 563–571. https://doi.org/10.2134/agronj1989.00021962008100040004x.
Grant, R.F., 1991. The distribution of water and nitrogen in the soil-crop system: A simulation study with validation from a winter wheat field trial. Fertil. Res. 27, 199–213. https://doi.org/10.1007/bf01051128.
Grant, R.F., 1995. Salinity, water use and yield of maize: Testing of the mathematical model ecosys. Plant Soil 172, 309–322.
Grant, R.F., 1997. Changes in Soil Organic Matter under Different Tillage and Rotation: Mathematical Modeling in ecosys. Soil Sci. Soc. Am. J. 61, 1159–1175. https://doi.org/10.2136/sssaj1997.03615995006100040023x.
Grant, R.F., 1998. Simulation in ecosys of root growth response to contrasting soil water and nitrogen. Ecol. Model. 107, 237–264. https://doi.org/10.1016/S0304-3800(97)00221-4.
Grant, R.F., 2004a. Modeling topographic effects on net ecosystem productivity of boreal black spruce forests. Tree Physiol. 24, 1–18. https://doi.org/10.1093/treephys/24.1.1.
Grant, R.F., 2004b. Modelling changes in nitrogen cycling to sustain increases in forest productivity under elevated atmospheric CO2 and contrasting site conditions. Biogeosciences 10, 7703–7721.
Grant, R.F., Juma, N.G., McGill, W.B., 1993. Simulation of carbon and nitrogen transformations in soil: Mineralization. Soil Biol. Biochem. 25, 1317–1329. https://doi.org/10.1016/0038-0717(93)90046-E.
Grant, R.F., Wall, G.W., Kimball, B.A., Frumau, K.F.A., Pinter, P.J., Hunsaker, D.J., Lamorte, R.L., 1999. Crop water relations under different CO2 and irrigation: testing of ecosys with the free air CO2 enrichment (FACE) experiment. Agric. For. Meteorol. 95, 27–51. https://doi.org/10.1016/S0168-1923(99)00017-9.
Grant, R.F., Pattey, E., Goddard, T.W., Kryzanowski, L.M., Puurveen, H., 2006. Modeling the effects of fertilizer application rate on nitrous oxide emissions. Soil Sci. Soc. Am. J. 70, 235–248. https://doi.org/10.2136/sssaj2005.0104.
Grant, R.F., Mekonnen, Z.A., Riley, W.J., 2019. Modeling climate change impacts on an arctic polygonal tundra: 1. Rates of permafrost thaw depend on changes in vegetation and drainage. J. Geophys. Res.: Biogeosciences 124, 1308–1322. https://doi.org/10.1029/2018jg004644.
Grant, R.F., Lin, S., Hernandez-Remirez, G., 2020b. Modelling nitrification inhibitor effects on N2O emissions after fall- and spring-applied slurry by reducing nitrifier NH4+ oxidation rate. Biogeosciences 17 (7), 2021–2039. https://doi.org/10.5194/bg-17-2021-2020.
Grant, R.F., Dyck, M., Puurveen, D., 2020a. Nitrogen and phosphorus control carbon sequestration in agricultural ecosystems: modelling carbon, nitrogen, and phosphorus balances at the Breton Plots with ecosys under historical and future climates. Can. J. Soil Sci. 100, 408–429. https://doi.org/10.1139/cjss-2019-0132.
Grassini, P., Specht, J.E., Tollenaar, M., Ciampitti, I., Cassman, K.G., 2015. High-yield maize–soybean cropping systems in the US Corn Belt. Crop Physiology, pp. 17–41. https://doi.org/10.1016/b978-0-12-417104-6.00002-9.
Green, C.J., Blackmer, A.M., 1995. Residue decomposition effects on nitrogen availability to corn following corn or soybean. Soil Sci. Soc. Am. J. 59, 1065–1070. https://doi.org/10.2136/sssaj1995.03615995005900040016x.
gSSURGO, 2020. The Gridded Soil Survey Geographic (gSSURGO).
Gu, B., Zhang, L., Van Dingenen, R., Vieno, M., Van Grinsven, H.J., Zhang, X., Zhang, S., Chen, Y., Wang, S., Ren, C., Rao, S., Holland, M., Winiwarter, W., Chen, D., Xu, J., Sutton, M.A., 2021. Abating ammonia is more cost-effective than nitrogen oxides for mitigating PM2.5 air pollution. Science 374, 758–762. https://doi.org/10.1126/science.abf8623.
Hall, S.J., Russell, A.E., Moore, A.R., 2019. Do corn-soybean rotations enhance decomposition of soil organic matter. Plant Soil 444, 427–442. https://doi.org/10.1007/s11104-019-04292-7.
Hauck, R.D., 1984. Nitrogen in Crop Production: Proceedings of a Symposium. American Society of Agronomy.
Hendricks, N.P., Sinnathamby, S., Douglas-Mankin, K., Smith, A., Sumner, D.A., Earnhart, D.H., 2014. The environmental effects of crop price increases: Nitrogen losses in the U.S. Corn Belt. J. Environ. Econ. Manag. 68, 507–526. https://doi.org/10.1016/j.jeem.2014.09.002.
Hernandez-Ramirez, G., Brouder, S.M., Smith, D.R., Van Scoyoc, G.E., 2009. Carbon and nitrogen dynamics in an eastern corn belt soil: Nitrogen source and rotation. Soil Sci. Soc. Am. J. 73, 128–137. https://doi.org/10.2136/sssaj2007.0381.
Huggins, D.R., Allmaras, R.R., Clapp, C.E., Lamb, J.A., Randall, G.W., 2007. Corn-soybean sequence and tillage effects on soil carbon dynamics and storage. In: Soil Science Society of America Journal, 71. Soil Science Society of America, pp. 145–154. https://doi.org/10.2136/sssaj2005.0231.
Hussain, M.Z., Hamilton, S.K., Bhardwaj, A.K., Basso, B., Thelen, K.D., Robertson, G.P., 2019. Evapotranspiration and water use efficiency of continuous maize and maize and soybean in rotation in the upper Midwest U.S. Agric. Water Manag. 221, 92–98. https://doi.org/10.1016/j.agwat.2019.02.049.
Hymowitz, T., 1990. Soybeans: the success story, advances in new crops. Portland, OR: Timber Press.
Jacinthe, P.-A., Dick, W.A., 1997. Soil management and nitrous oxide emissions from cultivated fields in southern Ohio. Soil Tillage Res. 41, 221–235. https://doi.org/10.1016/S0167-1987(96)01094-X.
Jarecki, M., Grant, B., Smith, W., Deen, B., Drury, C., VanderZaag, A., Qian, B., Yang, J., Wagner-Riddle, C., 2018. Long-term trends in corn yields and soil carbon under diversified crop rotations. J. Environ. Qual. 47, 635–643. https://doi.org/10.2134/jeq2017.08.0317.
Jia, M., Lapen, D.R., Su, D., Mayer, K.U., 2023. Modeling of dual-permeability gas and solute reactive transport in macroporous agricultural soils with a focus on GHG cycling and emissions. J. Hydrol. 620, 129408. https://doi.org/10.1016/j.jhydrol.2023.129408.
Jiang, R., Yang, J.Y., Drury, C.F., He, W., Smith, W.N., Grant, B.B., He, P., Zhou, W., 2021. Assessing the impacts of diversified crop rotation systems on yields and nitrous oxide emissions in Canada using the DNDC model. Sci. Total Environ. 759, 143433. https://doi.org/10.1016/j.scitotenv.2020.143433.
Jin, Z., Archontoulis, S.V., Lobell, D.B., 2019. How much will precision nitrogen management pay off? An evaluation based on simulating thousands of corn fields over the US Corn-Belt. Field Crops Res. 240, 12–22. https://doi.org/10.1016/j.fcr.2019.04.013.
Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. Eur. J. Agron. 18, 235–265. https://doi.org/10.1016/S1161-0301(02)00107-7.
Karlen, D.L., Kovar, J.L., Cambardella, C.A., Colvin, T.S., 2013. Thirty-year tillage effects on crop yield and soil fertility indicators. Soil Tillage Res. 130, 24–41. https://doi.org/10.1016/j.still.2013.02.003.
Katsvairo, T.W., Cox, W.J., 2000. Economics of cropping systems featuring different rotations, tillage, and management. Agron. J. 92, 485–493. https://doi.org/10.2134/agronj2000.923485x.
Kazula, M.J., Lauer, J.G., 2018. The influence of crop rotation on corn total biomass production. J. Soil Water Conserv. 73 (5), 541–548.
Kenkel, P., 2010. Managing fertilizer price risk.
Kim, N., Behnke, G.D., Villamil, M.B., 2022. Characterization of Mollisols after Long-Term N Fertilization at Successive Rates in Continuous and Rotated Corn Systems. Agronomy 12, 625. https://doi.org/10.3390/agronomy12030625.
Kluger, D.M., Owen, A.B., Lobell, D.B., 2022. Combining randomized field experiments with observational satellite data to assess the benefits of crop rotations on yields. Environ. Res. Lett. 17, 044066. https://doi.org/10.1088/1748-9326/ac6083.
Langer, D.K., Randall, G.W., 1981. Corn production as influenced by previous crop and N rate. American Society of Agronomy Meeting.
Li, C., Aber, J., Stange, F., Butterbach-Bahl, K., Papen, H., 2000. process-oriented model N2O emissions from forest soils: 1. Model development. J. Geophys. Res.: Atmospheres D4, 4369–4384.
Li, Z., Guan, K., Zhou, W., Peng, B., Jin, Z., Tang, J., Grant, R.F., Nafziger, E.D., Margenot, A.J., Gentry, L.E., DeLucia, E.H., Yang, W.H., Cai, Y., Qin, Z., Archontoulis, S.V., Fernández, F.G., Yu, Z., Lee, D., Yang, Y., 2022. Assessing the

impacts of pre-growing-season weather conditions on soil nitrogen dynamics and corn productivity in the U.S. Midwest. Field Crops Res. 284, 108563. https://doi.org/10.1016/j.fcr.2022.108563.
Liu, C., Wang, J., Wang, Y., Li, L., Feng, Z., Xian, Y., Jiang, Y., Yu, J., Tong, T., Li, X., Yao, M., 2024. Crop rotation and fertilization shape the microbiomes of maize rhizosphere soil with distinct mechanisms. Plant Soil. https://doi.org/10.1007/s11104-024-06847-9.
Livingston, M., Roberts, M.J., Zhang, Y., 2015. Optimal sequential plantings of corn and soybeans under price uncertainty. Am. J. Agric. Econ. 97, 855–878. https://doi.org/10.1093/ajae/aau055.
Ma, Z., Guan, K., Peng, B., Zhou, W., Grant, R., Tang, J., Jin, Z., 2024. Impacts tile drainage hydrology, soil biogeochemistry, crop yield US Midwestern agroecosystems. Hydrology Earth System Sciences Discussions, pp. 1–39.
Maaz, T.M., Sapkota, T.B., Eagle, A.J., Kantar, M.B., Bruulsema, T.W., Majumdar, K., 2021. Meta-analysis of yield and nitrous oxide outcomes for nitrogen management in agriculture. Glob. Change Biol. 27, 2343–2360. https://doi.org/10.1111/gcb.15588.
Martens, D.A., 2000. Management and crop residue influence soil aggregate stability. J. Environ. Qual. 29 (3), 723–727. https://doi.org/10.2134/jeq2000.00472425002900030006x.
McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P., Freebairn, D.M., 1996. APSIM: a novel software system for model development, model testing and simulation in agricultural systems research. Agric. Syst. 50, 255–271. https://doi.org/10.1016/0308-521X(94)00055-V.
McDaniel, M.D., Grandy, A.S., Tiemann, L.K., Weintraub, M.N., 2014. Crop rotation complexity regulates the decomposition of high and low quality residues. Soil Biol. Biochem. 78, 243–254. https://doi.org/10.1016/j.soilbio.2014.07.027.
Meese, B.G., Carter, P.R., Oplinger, E.S., Pendleton, J.W., 1991. Corn/soybean rotation effect as influenced by tillage, nitrogen, and hybrid/cultivar. J. Prod. Agric. 4, 74–80. https://doi.org/10.2134/jpa1991.0074.
Meki, M.N., Kemanian, A.R., Potter, S.R., Blumenthal, J.M., Williams, J.R., Gerik, T.J., 2013. Cropping system effects on sorghum grain yield, soil organic carbon, and global warming potential in central and south Texas. Agric. Syst. 117, 19–29. https://doi.org/10.1016/j.agsy.2013.01.004.
Mekonnen, Z.A., Riley, W.J., Grant, R.F., Romanovsky, V.E., 2021. Changes in precipitation and air temperature contribute comparably to permafrost degradation in a warmer climate. Environ. Res. Lett. 16, 024008. https://doi.org/10.1088/1748-9326/abc444.
Mitchell, C.C., Westerman, R.L., Brown, J.R., Peck, T.R., 1991. Overview of long-term agronomic research. Agron. J. 83, 24–29. https://doi.org/10.2134/agronj1991.00021962008300010010x.
Mourtzinis, S., Marburger, D., Gaska, J., Diallo, T., Lauer, J.G., Conley, S., 2017. Corn, soybean, and wheat yield response to crop rotation, nitrogen rates, and foliar fungicide application. Crop Sci. 57, 983–992. https://doi.org/10.2135/cropsci2016.10.0876.
Neupane, A., Bulbul, I., Wang, Z., Lehman, R.M., Nafziger, E., Marzano, S.-Y.L., 2021. Long term crop rotation effect on subsequent soybean yield explained by soil and root-associated microbiomes and soil health indicators. Sci. Rep. 11 (1), 9200. https://doi.org/10.1038/s41598-021-88784-6.
Ochsner, T.E., Schumacher, T.W., Venterea, R.T., Feyereisen, G.W., Baker, J.M., 2018. Soil water dynamics and nitrate leaching under corn–soybean rotation, continuous corn, and Kura clover. Vadose Zone J. 17, 1–11. https://doi.org/10.2136/vzj2017.01.0028.
Olmstead, J., Brummer, C., 2008. Benefits and barriers to perennial forage crops in Iowa corn and soybean rotations. Renew. Agric. Food Syst. 23, 97–107. https://doi.org/10.1017/S1742170507001937.
Omonode, R.A., Smith, D.R., Gál, A., Vyn, T.J., 2011. Soil nitrous oxide emissions in corn following three decades of tillage and rotation treatments. Soil Sci. Soc. Am. J. 75, 152–163. https://doi.org/10.2136/sssaj2009.0147.
Pasley, H., Nichols, V., Castellano, M., Baum, M., Kladivko, E., Helmers, M., Archontoulis, S., 2021. Rotating maize reduces the risk and rate of nitrate leaching. Environ. Res. Lett. 16, 064063. https://doi.org/10.1088/1748-9326/abef8f.
Peterson, T.A., Varvel, G.E., 1989. Crop yield as affected by rotation and nitrogen rate. I. soybean. Agron. J. 81, 727–731. https://doi.org/10.2134/agronj1989.00021962008100050005x.
Pierce, F.J., Rice, C.W., 2015. Crop rotation and its impact on efficiency of water and nitrogen use, in: Cropping Strategies for Efficient Use of Water and Nitrogen. American Society of Agronomy Meeting 21–42. https://doi.org/10.2134/asaspecpub51.c3.
Poffenbarger, H.J., Barker, D.W., Helmers, M.J., Miguez, F.E., Olk, D.C., Sawyer, J.E., Six, J., Castellano, M.J., 2017. Maximum soil organic carbon storage in Midwest U.S. cropping systems when crops are optimally nitrogen-fertilized. PLOS One 12, e0172293. https://doi.org/10.1371/journal.pone.0172293.
Postgate, J.R., 1998. Nitrogen Fixation. Cambridge University Press.
Puntel, L.A., Sawyer, J.E., Barker, D.W., Dietzel, R., Poffenbarger, H., Castellano, M.J., Moore, K.J., Thorburn, P., Archontoulis, S.V., 2016. Modeling Long-Term Corn Yield Response to Nitrogen Rate and Crop Rotation. Front. Plant Sci. 7, 1630. https://doi.org/10.3389/fpls.2016.01630.
Qin, Z., Guan, K., Zhou, W., Peng, B., Villamil, M.B., Jin, Z., Tang, J., Grant, R., Gentry, L., Margenot, A.J., Bollero, G., Li, Z., 2021. Assessing the impacts of cover crops on maize and soybean yield in the U.S. Midwestern agroecosystems. Field Crops Res. 273, 108264. https://doi.org/10.1016/j.fcr.2021.108264.
Qin, Z., Guan, K., Zhou, W., Peng, B., Tang, J., Jin, Z., Grant, R., Hu, T., Villamil, M.B., DeLucia, E., Margenot, A.J., Umakant, M., Chen, Z., Coppess, J., 2023. Assessing long-term impacts of cover crops on soil organic carbon in the central US Midwestern agroecosystems. Glob. Change Biol. 29, 2572–2590. https://doi.org/10.1111/gcb.16632.
Rengel, Z., 2011. Soil pH, Soil Health and Climate Change, in: {C}{C}Singh, B.P., Cowie, A.L., Chan, K.Y.{C}{C}, Soil Health and Climate Change Meeting 69–85. https://doi.org/10.1007/978-3-642-20256-8_4.
Russell, A.E., Cambardella, C.A., Laird, D.A., Jaynes, D.B., Meek, D.W., 2009. Nitrogen fertilizer effects on soil carbon balances in midwestern U.S. agricultural systems. Ecol. Appl. 19, 1102–1113. https://doi.org/10.1890/07-1919.1.
Russelle, M.P., Hesterman, O.B., Sheaffer, C.C., Heichel, G.H., 1987. Estimating nitrogen and rotation effects in legume-corn rotations.
Salvagiotti, F., Cassman, K.G., Specht, J.E., Walters, D.T., Weiss, A., Dobermann, A., 2008. Nitrogen uptake, fixation and response to fertilizer N in soybeans: A review. Field Crops Res. 108 (1), 1–13. https://doi.org/10.1016/j.fcr.2008.03.001.
Schnitkey, G., Zulauf, C., Swanson, K., Paulson, N., 2021. 2022 Planting Decisions. Nitrogen Fertil. Prices., Corn. Soybean Prices. Farm. Dly. 11.
Seifert, C.A., Roberts, M.J., Lobell, D.B., 2017. Continuous corn and soybean yield penalties across hundreds of thousands of fields. Agron. J. 109 (2), 541–548. https://doi.org/10.2134/agronj2016.03.0134.
Shrader, W.D., Fuller, W.A., Cady, F.B., 1966. Estimation of a common nitrogen response function for corn (*Zea mays*) in different crop rotations. Agron. J. 58, 397–401. https://doi.org/10.2134/agronj1966.00021962005800040010x.
Sindelar, A.J., Schmer, M.R., Jin, V.L., Wienhold, B.J., Varvel, G.E., 2015. Long-term corn and soybean response to crop rotation and tillage. Agron. J. 107 (6), 2241–2252. https://doi.org/10.2134/agronj15.0085.
Sindelar, A.J., Schmer, M.R., Jin, V.L., Wienhold, B.J., Varvel, G.E., 2016. Crop rotation affects corn, grain sorghum, and soybean yields and nitrogen recovery. Agron. J. 108 (4), 1592–1602. https://doi.org/10.2134/agronj2016.01.0005.
Singer, J.W., Cox, W.J., 1998. Economics of different crop rotations in New York. J. Prod. Agric. 11, 447–451. https://doi.org/10.2134/jpa1998.0447.
Smith, M.E., Vico, G., Costa, A., Bowles, T., Gaudin, A.C.M., Hallin, S., Watson, C.A., Alarcòn, R., Berti, A., Blecharczyk, A., Calderon, F.J., Culman, S., Deen, W., Drury, C. F., Garcia, A.G. y, García-Díaz, A., Plaza, E.H., Jonczyk, K., Jäck, O., Lehman, R.M., Montemurro, F., Morari, F., Onofri, A., Osborne, S.L., Pasamón, J.L.T., Sandström, B., Santín-Montanyá, I., Sawinska, Z., Schmer, M.R., Stalenga, J., Strock, J., Tei, F., Topp, C.F.E., Ventrella, D., Walker, R.L., Bommarco, R., 2023. Increasing crop rotational diversity can enhance cereal yields. Commun. Earth Environ. 4. https://doi.org/10.1038/s43247-023-00746-0.
Smith, M.E., Bommarco, R., Vico, G., 2025. Rethinking crop rotational benefits under climate change: Beyond the growing season. Glob. Change Biol. 31 (1), e70012. https://doi.org/10.1111/gcb.70012.
Sobota, D.J., Compton, J.E., McCrackin, M.L., Singh, S., 2015. Cost of reactive nitrogen release from human activities to the environment in the United States. Environ. Res. Lett. 10, 025006. https://doi.org/10.1088/1748-9326/10/2/025006.
Socolar, Y., Goldstein, B.R., de Valpine, P., Bowles, T.M., 2021. Biophysical and policy factors predict simplified crop rotations in the US Midwest. Environ. Res. Lett. 16, 054045. https://doi.org/10.1088/1748-9326/abf9ca.
Stanger, T.F., Lauer, J.G., Chavas, J.-P., 2008. The profitability and risk of long-term cropping systems featuring different rotations and nitrogen rates. Agron. J. 100, 105–113. https://doi.org/10.2134/agronj2006.0322.
Strickling, E., 1951. The effect of soybeans on volume weight and water stability of soil aggregates, soil organic matter content, and crop yield. Soil Sci. Soc. Am. J. 15, 30–34. https://doi.org/10.2136/sssaj1951.036159950015000c0006x.
Suying, C., Zhang Xiying, C.S., Dong, P., Sun Hongyong, P.D., 2005. Effects corn straw mulching soil temperature soil evaporation winter wheat field.
Ta, P., 1989. Crop yield as affected by rotation and nitrogen rate: III. Agron. J. 81, 735–738.
USDA-NASS, 2020. Crop Production; USDA-NASS.
Venterea, R.T., Dolan, M.S., Ochsner, T.E., 2010. Urea decreases nitrous oxide emissions compared with anhydrous ammonia in a Minnesota corn cropping system. Soil Sci. Soc. Am. J. 74, 407–418. https://doi.org/10.2136/sssaj2009.0078.
Voss, R.D., Shrader, W.D., 2015. Rotation effects and legume sources of nitrogen for corn, in: Organic Farming. American Society of Agronomy Meeting pp. 61–68. https://doi.org/10.2134/asaspecpub46.c5.
Wang, H., Ortiz-Bobea, A., 2019. Market-Driven Corn Monocropping in the U.S. Midwest. Agric. Resour. Econ. Rev. 48, 274–296. https://doi.org/10.1017/age.2019.4.
Warntz, W., 1957. An Historical Consideration of the Terms “Corn” and “Corn Belt” in the United States. Agric. Hist. 31, 40–45.
Weber, E.J., 1981. Compositions of commercial corn and soybean lecithins. J. Am. Oil Chem. ’ Soc. 58, 898–901. https://doi.org/10.1007/BF02659654.
Welch, L.F., 1976. Morrow plots: hundred years of research. Annals of Agricultural Sciences.
Wilhelm, W.W., Wortmann, C.S., 2004. Tillage and rotation interactions for corn and soybean grain yield as affected by precipitation and air temperature. Agron. J. 96, 425–432. https://doi.org/10.2134/agronj2004.4250.
Williams, J.R., Jones, C., Kiniry, J., Spanel, D., 1989. The EPIC crop growth model. Trans. ASABE 32, 497–0511. https://doi.org/10.13031/2013.31032.
Wilson, H.M., Al-Kaisi, M.M., 2008. Crop rotation and nitrogen fertilization effect on soil CO2 emissions in central Iowa. Appl. Soil Ecol. 39, 264–270. https://doi.org/10.1016/j.apsoil.2007.12.013.
World Bank Group, 2022. Commodity Markets Outlook, April 2022: The Impact of the War in Ukraine on Commodity Markets. World Bank.
Xia, Y., Mitchell, K., Ek, M., Sheffield, J., Cosgrove, B., Wood, E., Luo, L., Alonge, C., Wei, H., Meng, J., Livneh, B., Lettenmaier, D., Koren, V., Duan, Q., Mo, K., Fan, Y., Mocko, D., 2012. Continental-scale water and energy flux analysis and validation for the North American Land Data Assimilation System project phase 2 (NLDAS-2): 1. Intercomparison and application of model products. J. Geophys. Res. 117. https://doi.org/10.1029/2011jd016048.

Yang, Y., Liu, L., Zhou, W., Guan, K., Tang, J., Kim, T., Grant, R.F., Peng, B., Zhu, P., Li, Z., Griffis, T.J., Jin, Z., 2022. Distinct driving mechanisms of non-growing season N2O emissions call for spatial-specific mitigation strategies in the US Midwest. Agric. For. Meteorol. 324, 109108. https://doi.org/10.1016/j.agrformet.2022.109108.

Young, C.E., 1996. 1996 US Farm Act increases market orientation.

Zhao, J., Yang, Y., Zhang, K., Jeong, J., Zeng, Z., Zang, H., 2020. Does crop rotation yield more in China? A meta-analysis. Field Crops Res. 245 (107659), 107659. https://doi.org/10.1016/j.fcr.2019.107659.

Zhou, J., Zhu, P., Kluger, D.M., Lobell, D.B., Jin, Z., 2024. Changes in the yield effect of the preceding crop in the US corn belt under a warming climate. Glob. Change Biol. 30, e17556. https://doi.org/10.1111/gcb.17556.

Zhou, W., Guan, K., Peng, B., Tang, J., Jin, Z., Jiang, C., Grant, R., Mezbahuddin, S., 2021. Quantifying carbon budget, crop yields and their responses to environmental variability using the ecosys model for U.S. Midwestern agroecosystems. Agric. For. Meteorol. 307, 108521. https://doi.org/10.1016/j.agrformet.2021.108521.

Zhu, Y., Fox, R.H., 2003. Corn–soybean rotation effects on nitrate leaching. Agron. J. 95, 1028–1033. https://doi.org/10.2134/agronj2003.1028.

Zuber, S.M., Behnke, G.D., Nafziger, E.D., Villamil, M.B., 2015. Crop rotation and tillage effects on soil physical and chemical properties in Illinois. Agron. J. 107 (3), 971–978. https://doi.org/10.2134/agronj14.0465.

Zulauf, C., Lines, A., 2021. Soybean–Corn. Ratios 1974. Farm. Dly. 11.