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Assessing the impacts of cover crops on maize and soybean yield in the U.S. Midwestern agroecosystems

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ABSTRACT

Growing cover crops is one of the most promising conservation practices with multiple benefits. However, the impacts of cover crops on the productivity of the maize-soybean [*Zea mays* L. - *Glycine max* (L.) Merr.] rotation system in the U.S. Midwest still have large uncertainties based on results obtained from field experiments, specifically across different soil properties, climate conditions, and land management practices. Process-based models fully validated with data from field experiments across these diverse conditions provide an effective tool to quantify cover crop impacts on cash crop productivity and optimize the management of cover crops accordingly. In this study, we aim to answer the following questions: (1) What are the impacts of cover crops on cash crop yield in the U.S. Midwest agroecosystems? (2) What are the mechanistic pathways of cover crop to affect cash crop yield (e.g. through influencing soil water, nitrogen and O_2 dynamics)? (3) What management practices can be used to mitigate the negative impacts on cash crop yield caused by cover crops? To address these questions, we calibrated and validated a sophisticated process-based agroecosystem model, *ecosys*, using field experimental data from 2013 to 2018 across Illinois, and then used *ecosys* to assess the impacts of winter cover crops on maize and soybean yield under different management practices. Our study revealed the following findings: (1) planting non-legume cover crops can cause 3.9 ± 3% yield reduction for maize and no significant impacts on soybean yield, while planting legume cover crops has no significant impact on the yield of either maize or soybean; (2) the maize yield reduction caused by planting cover crops can be mainly explained by nitrogen deficiency induced by increased immobilization, water competition in dry areas, cooler soil surface and oxygen competition; (3) later termination of non-legume cover crops before maize can result in larger maize yield loss due to intensive competition for resources (e.g. water and nitrogen), and the impacts of non-legume cover crops on maize yield reduction can be minimized by optimizing cover crop termination time in the spring. Overall, in the U.S. Midwestern maize-soybean rotation system, we found that although non-legume cover crops cause yield reduction for maize through resource competition, this yield reduction can be minimized through management practices, such as controlling termination time of cover crop and proper fertilizer management.

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1. Introduction

Cover crops are planted during the non-growing season to benefit the soils in the U.S. Midwestern maize-soybean rotation system. Winter cover crops are usually seeded in autumn, growing during the winter and terminated in the early spring before planting cash crops. Integrating cover crops into the agroecosystem have multiple benefits, including reducing N leaching (Kaye et al., 2019; Thapa et al., 2018) especially in tile-drained fields (David et al., 2015), increasing soil organic carbon (SOC) (Lal, 2015, 2004), suppressing weeds (Florence et al., 2019; Nichols et al., 2020), reducing soil erosion (Schütte et al., 2020), and helping break up soil compaction (Jian et al., 2020a; Wheeler et al., 2008). However, though the adoption rate of cover crops has increased 50 % in 2017 compared with 2012 (USDA NASS, 2019), the overall croplands planted with cover crops is still low in the U.S. Midwest (about 5%) (USDA NASS, 2019), partly due to concerns on potential yield losses caused by planting cover crops. Improving the understanding of cover crop impacts on cash crop yield as well as designing effective management practices to minimize the negative impacts could help increase the adoption of cover crops.

Despite their assumed benefit, the quantitative impacts of cover crops on cash crop yield are still uncertain (Abdalla et al., 2019). Generally, when cover crops have a long growing window in the winter, large cover crop biomass could be achieved, which assures the benefits on soil health. However, it might cause competition for nutrients and water with subsequent cash crops and reduce cash crop yield (Noland et al., 2018). A meta-study of 372 experiment sites around the world from 106 studies (Abdalla et al., 2019) showed that planting non-legume cover crops could significantly decrease cash crop yield by competing water and nutrients with cash crops. Similarly, a meta-study focusing on the Argentine Pampa showed that, with non-legume cover crops, the maize yield decreased by an average of 8% (Alvarez et al., 2017). However, a meta-study in the U.S. and Canada showed that non-legume winter cover crops had no significant impact on maize yield (Marcillo and Miguez, 2017). Thus, a better quantification tool is needed to quantify the impacts of cover crops on cash crop yield under different soils, climates conditions, and management practices; these quantifications can help guiding cover crop management to minimize the negative impacts and maximize the benefits from cover crops.

To study the impacts of cover crops on cash crop yield, process-based models validated with distributed ground truth data have multiple advantages compared to field trial experiments alone. Trial studies provide the actual ground truth data to study cover crops (Jian et al., 2020b; Poeplau and Don, 2015). However, limitations exist in the trial approach alone, as trial-based studies usually need multiple years to conduct experiments and replicates, and most field experiments only focus on final variables (e.g. cash crop yield and cover crop biomass), which cannot provide mechanistic understanding due to the lack of measurements of intermediate processes (Kaye et al., 2019; Thapa et al., 2018). Therefore, combining field experiments with agroecosystem models, which explicitly simulate crop growth and carbon-water-nutrient balance in the soil-plant systems, may provide a complementary approach to assess the impact of cover crops on crop productivity. Process-based modeling methods can be especially useful as they enable the understanding of mechanistic pathways by simulating intermediate variables which are difficult to measure in field experiments, and they can also provide guidance on how to optimize crop management (e.g. planting time, termination time) through scenario simulations.

There were some studies using the process-based models to simulate impacts of cover crops on soil health and cash crop yield (e.g. DSSAT, CENTURY, APSIM, DLEM-Ag, DNDC, WAVE, and RZWQM2) (Alonso-Ayuso et al., 2018; Basche et al., 2016a; Chatterjee et al., 2020; Huang et al., 2020; Qi et al., 2011; Soldevilla Martínez et al., 2014; Tonitto et al., 2007). However, previous studies remain relatively vague in illustrating mechanistic pathways of how cover crops impact cash crop yield, which calls for further studies. One of the biggest challenges of model-based studies is to ensure that models can reproduce reality with the right mechanisms. In our case, ideally models should demonstrate its ability to correctly simulate processes of how cover crops affect cash crops, and models should be evaluated by not only simulating the values of interested variables (e.g. cash crop yield and cover crop biomass), but also reproducing the internal relationships that lead to these observed values (i.e. the process). To achieve this goal, a process-based model needs to be rigorously validated by reliable and spatially-distributed measurements (Peng et al., 2020).

In this study, we aim to answer the following three questions: (1) What are the impacts of cover crops on cash crop yield in the U.S. Midwest agroecosystems? (2) What are the mechanistic pathways of cover crop to affect cash crop yield (e.g. through influencing soil water, nitrogen and O_2 dynamics)? (3) What management practices can be used to mitigate the negative impacts on cash yield caused by cover crops? To answer these questions, we used a sophisticated mathematical agro-ecosystem model, *ecosys*, to quantify the impacts of winter cover crops on cash crop yield. *Ecosys* has comprehensive process representations for simulating water, energy, carbon, and nutrient cycles simultaneously at the hourly step (Grant, 2001), and has been extensively validated for its simulation of water, nitrogen (N), and carbon (C) cycles in various ecosystems and soil and climate conditions (Grant et al., 2011, 2007c; Mezbahuddin et al., 2020). We first calibrated and validated *ecosys* using ground truth data of maize and soybean yield and cover crop biomass. Then, we used the *ecosys* model to investigate cover crop impacts on cash crop yield with different management practices (e.g. different cover crop types and different growing windows).

2. Materials and methods

2.1. Field experiments

Seven cover crop field experiment sites across Illinois (Fig. 1 and Table 1) were used to evaluate the performance of the *ecosys* model (Villamil and Nafziger, 2019). The annual precipitation of these sites ranges from 910 to 1319 mm, with annual mean temperature ranges from 8.9 to 13.7 °C. The SOC concentration is lower in the southern sites and higher in the northern sites, ranging from 2% to 5%. Six of the seven sites were maize-soybean rotations with cash crops during the summer and different cover crops (i.e. annual ryegrass [*Lolium multiflorum* Lam.], cereal rye [*Secale cereale* L.], and hairy vetch [*Vicia villosa* Roth]) during the winter at different plots from 2013 to 2018 (Behnke et al., 2020; Dozier et al., 2017). Each plot is 12 m long and 3 m wide with 4 replicates. The other site is at Urbana with continuous maize during summer,

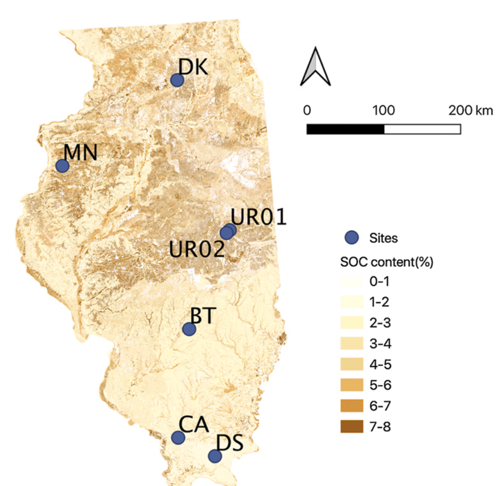

Fig. 1. The locations of cover crop experimental sites and SOC distribution map in Illinois (IL).

Table 1
Soil properties and weather conditions at 7 experimental sites in Illinois.

Site_ID	Location	Latitude ()	Longitude ()	Mean annual precipitation (mm)	Mean annual temperature (C)	SOC concentration (0–0.3 m) g C/kg
DK	Dekalb	41.84	−88.85	1001.5	10.4	29.50
MN	Monmouth	40.93	−90.73	910.2	11.8	29.60
UR01	Urbana01	40.06	−88.23	1002.9	12.4	21.40
UR02	Urbana02	40.03	−88.28	1002.9	12.4	33.00
BT	Brownstown	38.95	−88.96	1183.9	13.7	11.40
DS	Dixon Springs	37.46	−88.72	1319.3	14.7	10.50
CA	Carbondale	37.70	−89.24	1211.5	14.8	12.50

and with cover crops (i.e. cereal rye) during winter from 2016 to 2019 with tile drainage. We used experimental data from these sites (Villamil and Nafziger, 2019) to evaluate the performance of *ecosys* in simulating cover crops and their impacts on cash crops under three different rotation strategies (i.e. maize-cover crop-soybean-cover crop, maize-cover crop-maize-cover crop, and maize-(fallow)-soybean-(fallow)).

For field experiments, 190 kg N/ha as urea ammonium nitrate (UAN 28 %) was applied before maize planting, and no fertilizer before soybean planting for the six maize-soybean rotation sites. No tillage was applied to the plots. There were two types of cover crops in the maize-soybean rotation sites: (1) maize-annual ryegrass-soybean-annual ryegrass, and (2) maize-cereal rye-soybean-hairy vetch. Maize and soybean were

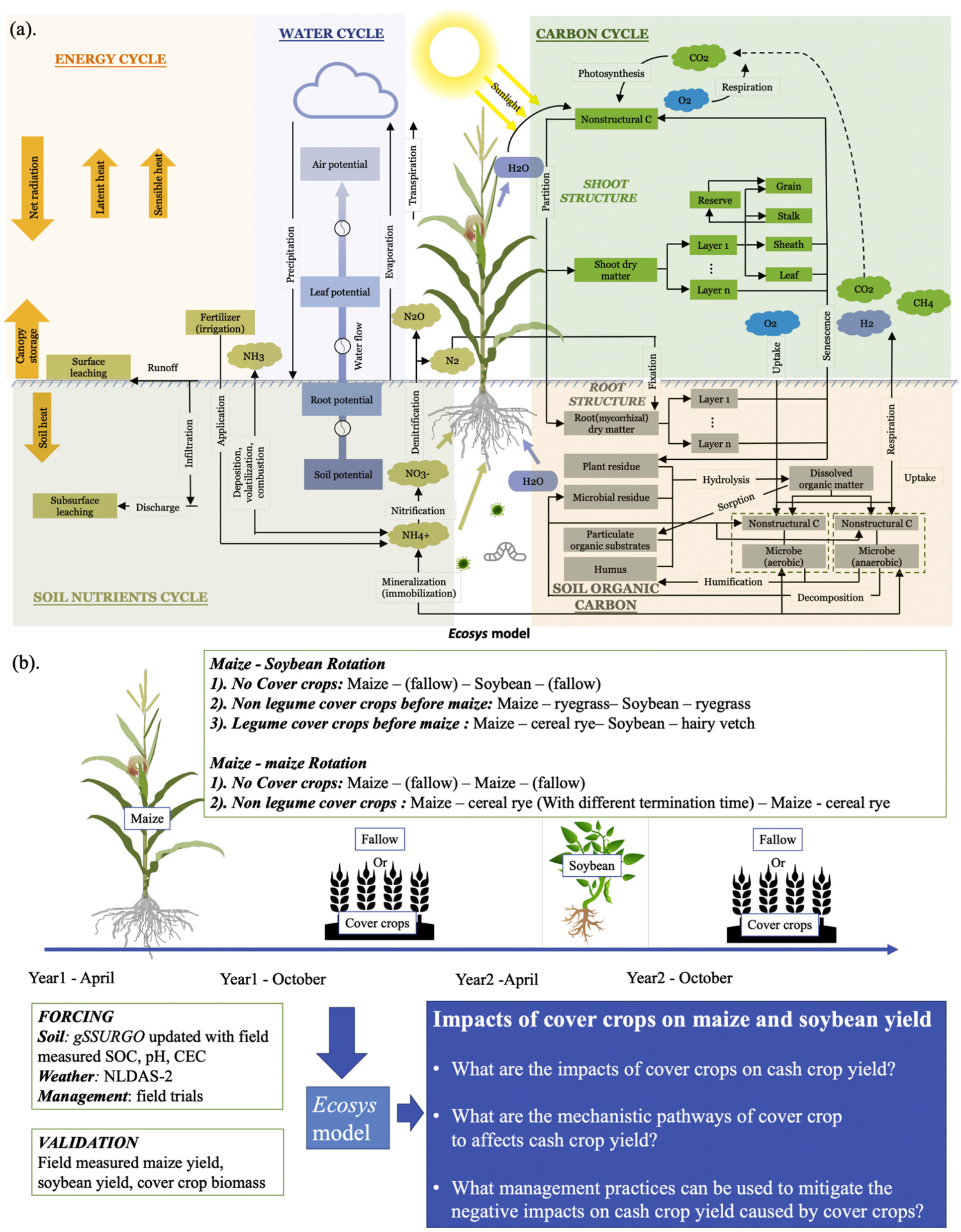

Fig. 2. (a) Major processes in the *ecosys* model (Revised from Grant, 2001; Grant et al., 1993a, 1993b). (b) Framework of this study.

planted with the seeding rate of 79–91,000 seeds/ha and 370–395,000 seeds/ha. As for cover crops, seeding rates were 16.8 kg/ha for annual ryegrass, 22.4 kg/ha for hairy vetch, and 100 kg/ha for cereal rye (Blaser et al., 2007; Casey, 2012; Lawson et al., 2015). Cover crops were planted by aerial seeding 1–2 weeks before cash crops harvested each year (Behnke et al., 2020). The aboveground biomass of cover crops was measured (not removed) in April, and cash crops were harvested in September or October. For the maize-(cereal rye)-maize rotation site with tile drainage in Urbana (UR02), 50 kg/ha N was applied before maize planted in the spring and 150 kg/ha N was side-dressed one month after maize planted. Tillage was applied in 2017 to 2018. Cereal rye as a cover crop was seeded before maize harvested from 2017 to 2018. There were 3 paired experiments with different termination time for cover crops in UR02 (e.g., terminated four weeks, two weeks and one day before maize planted).

2.2. Ecosys modeling

Ecosys is a sophisticated process-based mathematical model with comprehensive physical and chemical process representations to simulate the water-energy-carbon-nutrient balance within the ecosystem (Fig. 2a) (Grant, 2001). *Ecosys* has been applied and validated for cropland carbon budget simulations in the U.S. Midwestern corn-soybean rotation system (Zhou et al., 2021). Since cover crops may strongly influence the ecosystem carbon (C), nitrogen (N) and water cycle processes, we here focus our analysis on how the C, N and water cycles are simulated in *ecosys*. For C cycle, we described the plants C fixation and plants and soil respiration; for N cycle, we focused on plant N uptake, legume plants N fixation, and soil mineralization; for water cycle, we described plants water uptake, and soil water flow. More processes of *ecosys* are described in the supplement of Grant et al. (2020).

2.2.1. Carbon balance of plant and soil in ecosys

In the *ecosys* model, C fixation is simulated by calculating carboxylation rates, which is based on ribulose bisphosphate carboxylation (Grant, 1989). After hourly calculation of carboxylation rates, *ecosys* simulates CO_2 fixation of the whole canopy by aggregating all leaf surfaces as nonstructural carbohydrates. *A*utotrophic respiration (Ra) is simulated by adding maintenance respiration (Rm) and growth respiration (Rg) together (Grant, 1989). In the model simulation, plants continue accumulating dry matter until maturity, which is presumed to occur when the maximum kernel mass is reached or when kernel growth is stopped due to inclement weather. Grain yield in *ecosys* is modeled by sink-driven filling of the grain sink capacity determined by the maximum seed number, the final seed number, and the final seed size (Grant et al., 2011).

C cycle processes in *ecosys* have been previously calibrated under various soils and plant types in the past studies (Grant, 1989; Grant et al., 2011, 2007a). The sensitivity of the C fixation algorithm has been tested at the leaf level against phytotron (Grant, 1989; Grant and Hesketh, 1992) and field data (Grant et al., 2007b, 1999) under wide ranges of weather conditions (i.e. irradiance, temperature) and shows high consistency with field data. *Ecosys*-simulated biomass and grain yield were compared with observed values at various sites with small bias (Grant et al., 2011). The decomposition parts of *ecosys* were tested against C and N mineralization in different soils (Grant et al., 1993a, 1993b).

2.2.2. Water balance in ecosys

Ecosys simulates plant water flow hourly through coupled transfers of water through soil–root–canopy, and canopy–atmosphere pathways (Grant et al., 2011). Root and mycorrhizal water uptake is calculated from the difference between a canopy and soil water potentials across the soil and root hydraulic resistances in each rooted soil layer. A root system submodel is used to calculate root resistances from root radial and primary and secondary axial resistivities using root lengths and surface areas. Soil water flow in *ecosys* is separated into surface flow and subsurface flow. Surface flow is modeled from runoff velocity multiplied by the width of the flow path and depth of mobile surface water. Subsurface water flow through soil matrices within the modeled grid cells is calculated by multiplying hydraulic conductance and soil water potential (ψs) (matric + osmotic + gravimetric) differences (Grant, 2004).

2.2.3. Nitrogen balance in ecosys

Root and mycorrhizal N uptake are calculated by solving for solution NH_4^+ and NO_3^- concentrations at surfaces of root and mycorrhizal. Active inorganic N uptake by these surfaces equals radial N transport through mass flow and diffusion from the soil solution to these surfaces. In *ecosys*, a root and mycorrhizal growth submodel is used to calculate surface areas for N uptake. Nonstructural N exchanges between roots and mycorrhizae are calculated through concentration gradients which is from the difference between uptake and consumption of N in shoots and roots. A product inhibition function is included to avoid uptake in excess of nutrient requirements (Grant et al., 1993a, 1993b). *Ecosys* simulates N fixation by legume plants through simulating root nodules which could reduce N_2 to storage N by following energetics in Schubert (1982). The products of N uptake and N fixation are added to nonstructural pools in each root and mycorrhizal layer, concentrations of which drive transfer to nonstructural pools in the shoot. Plant growth respiration drives the combination of N from these pools with nonstructural C to support plant biomass growth (Grant, 1991). Grain biomass growth is sustained by nonstructural N accumulated in the stalk via translocation.

Simulated soil NH_4^+ and NO_3^- concentrations driving root N uptake are controlled by thermodynamically driven precipitation, adsorption and microbial mineralization-immobilization. During growth and decay, microbial populations in each complex seek to maintain set ratios of biomass N:C in the presence of varying N:C ratios in the dissolved decomposition products of diverse litter, POC and humus substrates. When the N:C ratio in each microbial population is larger than this ratio, excess biomass N is released as NH_4^+ by mineralization. If this ratio is smaller, microbial N deficits are reduced by NH_4^+ and NO_3^- uptake through immobilization (Grant, 2001; Grant et al., 2020). Therefore, net N mineralization-immobilization is driven by dynamic N:C ratios in the microbial populations of all substrate complexes.

2.2.4. Model inputs and simulation setup

The weather data to drive the *ecosys* model is from the North American Land Data Assimilation System (NLDAS-2) forcing data and the soil data is from the Gridded Soil Survey Geographic Database (gSSURGO) updated with field soil samples information. For six maize-soybean rotation sites, SOC, pH, bulk density, cation exchange capacity and inorganic N were measured at the beginning of each field experiment in 2012. We ran the e*cosys* model from 1987 to 2019, with 1987–2012 as the model spin-up period to assure the model reached equilibrium under the experimental site conditions and 2013–2019 as the analysis period. During the spin-up period, we used the maize-soybean rotation and applied 150 kg/ha UAN fertilizer in the spring before maize. No tillage and no cover crops were implemented during the spin-up period. Following field practices, each model run was set with no-till and winter cover crops vs. no winter cover crops (Fig. 2b). For the maize-maize rotation site at UR02, we ran the e*cosys* model from 1987 to 2019, with 1987–2015 as the model spin-up period. Spin-up period settings were the same with maize-soybean rotation sites. During the analysis period, different management practices were applied according to the actual field experiment setup as described above.

2.2.5. Model calibration and evaluation

The field measurements were collected at the seven experimental sites in Illinois from 2013 to 2018 as previously described in Section 2.1. Detailed sampling method and sampling date can be found in Behnke et al. (2020). In order to take the differences among cultivars at different sites into account, we calibrated the *ecosys* model at each study site with multi-year averaged yield and cover crop biomass by calibrating two plant species parameters: plant maturity group and rubisco carboxylation activity. After calibrating the model with the multi-year averaged cash crop yield and cover crop biomass, we used each year's measured data to evaluate the *ecosys* model performance in capturing yearly variation of cash crop yield and cover crop biomass. We selected four statistical criteria to indicate model performance: *r* (Pearson coefficient), geometric mean standard deviation in the measurement ($\overline{sd}$), root mean square error (RMSE) and simulation bias (Eq.1~4) (Ku, 1966; Chai and Draxler, 2014).

$$\overline{sd} = \sqrt{\frac{\sum_{i=1}^{n}\left(\sum_{j=1}^{k}\left(O_{ij} - \overline{O_i}\right)^2\right)}{k*n}} \tag{1}$$

$$\text{RMSE} = \sqrt{\frac{\sum\left(P_i - \overline{O_i}\right)^2}{n}} \tag{2}$$

$$\text{bias} = \frac{\sum\left(P_i - \overline{O_i}\right)}{n} \tag{3}$$

$$\text{Relative bias} = \frac{bias}{\overline{O_i}} \tag{4}$$

where n is the number of observations, k is the number of replicating samplings of each observation, O_{ij} is observed value at each sampling, $\overline{O_i}$ and P_i is the mean of observed and predicted values. If RMSE is comparable and even smaller than $\overline{sd}$, closer agreement between modeled and predicted values is achieved.

3. Results

3.1. The performance of ecosys in simulating cash crop yield and cover crop biomass

3.1.1. The performance of ecosys in simulating cash crop yield

We found that *ecosys* provided satisfactory results in the simulation of cash crop yield by capturing the interannual and spatial variation for different locations at a regional level in maize and soybean yield under with and without cover crops treatments (Fig. 3). The $\overline{sd}$, RMSE and bias of the model are 17.57, 17.29 and -0.41 bu/ac (1.17, 1.15 and -0.02 t/ha) for maize, and 8.21, 7.43 and 3.21 bu/ac (0.54, 0.49 and 0.2 t/ha) for soybean, respectively, which proves that the *ecosys* model is able to predict maize and soybean yield under different soil, weather, and crop rotation conditions with small RMSE and bias, and can be used to assess the impacts of cover crops on cash crop yield.

3.1.2. The performance of ecosys in simulating cover crop biomass

The *ecosys* simulation of cover crop above ground C biomass was consistent with field measurements for different cover crop types, including annual ryegrass, cereal rye and hairy vetch (Fig. 4). The *r*, $\overline{sd}$, bias, and relative bias of the model in simulating cover crop biomass were 0.9, 0.29 Mg C/ha, 0.28 Mg C/ha, -0.08 Mg C/ha, and -7.4 % respectively. This high *r* and low bias of the *ecosys*-simulated cover crop biomass built the foundation for using *ecosys* to further evaluate cover crop impacts on cash crop yield.

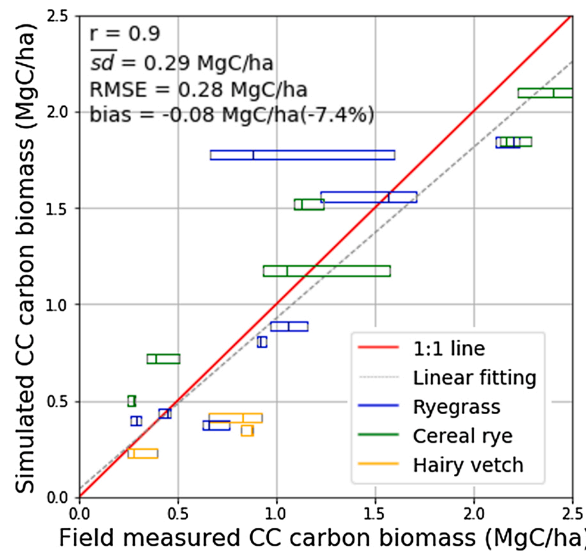

Fig. 4. Comparison of *ecosys*-simulated and field-measured cover crop above-ground biomass at maize-soybean rotation sites in IL from 2013 to 2018 (CC: cover crop). The middle, upper, and lower parts of the boxplots indicate 25 %, 50 % and 75 % quantile of the measured values.

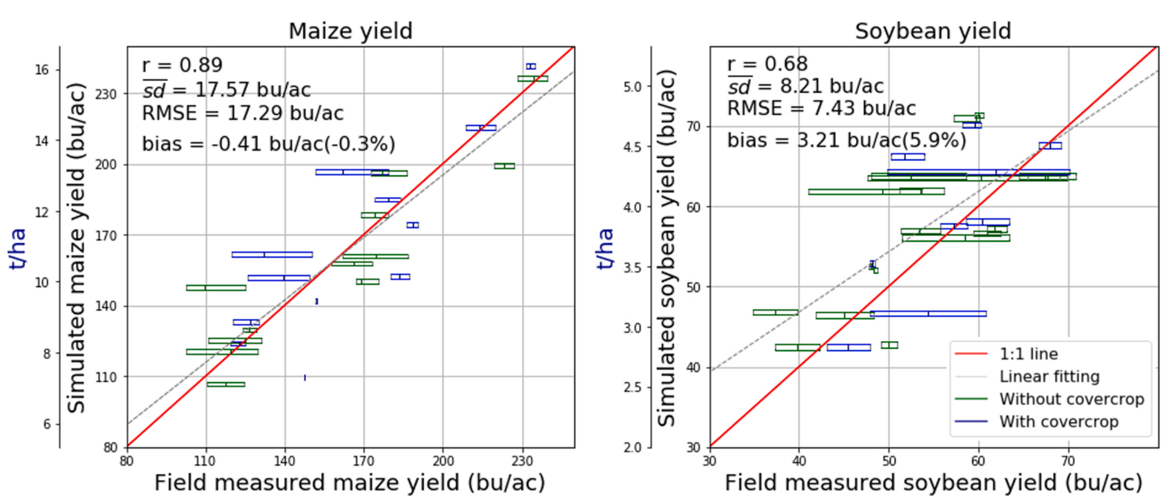

Fig. 3. Comparison of *ecosys*-simulated and ground measured maize (15 % moisture) and soybean (13 % moisture) yield in Illinois with vs. without cover crop under no tillage at six maize-soybean rotation sites in IL from 2013 to 2018. The middle, upper, and lower parts of the boxplots indicate 25 %, 50 % and 75 % quantile of the measured values.

3.2. Impacts of cover crop on cash crop yield based on field experiments and model simulation

3.2.1. Impacts of different types of cover crops on crop yield

We evaluated cash crop yield and cover crop biomass with the *ecosys* model at six sites across Illinois from 2013 to 2018 (Figs. 3 and 4). Impacts of cover crops on maize yield were species-specific. We found that annual ryegrass reduced maize yield but hairy vetch did not (Fig. 5a). For annual ryegrass before maize, the *ecosys* simulation shows that the multi-year and multi-site average maize yield is reduced by 3.9 ± 3% compared to no cover crops, largely consistent with the 3.5 % reduction measured in the field experiments. We conducted a *t*-test on measured maize yield to examine whether the impacts of annual ryegrass on corn yield is significant. The null hypothesis is that maize yield is equal whether with or without cover crops planted before maize. The *p* value of the *t*-test results is 0.048, which indicates that we can reject the null hypothesis (at the 95 % confidence level). In other words, though the reduction in corn yield after annual ryegrass is smaller than the standard deviation in measurements, we tend to believe that there is a statistical difference in corn yield when annual ryegrass is planted before maize. For hairy vetch before maize, we found it has no significant impacts on maize yield compared to no cover crop situation from *ecosys* simulations, consistent with field measurements. These results support that non-legume cover crops can cause maize yield reductions in Illinois, while legume cover crops have no impact on maize production. For soybean, we found that planting different types of cover crops has no significant impact on crop productivity compared with no cover crop (Fig. 5b). A *t*-test reveals that there are no statistical differences in soybean yield (at the 95 % confidence level) either with or without cover crop planted before soybean.

3.2.2. Impacts of different termination dates of cover crop on cash crop yield and cover crop biomass

Besides cover crop species, another important factor that may affect cash crop yield is the termination date of cover crops. Since planting legume cover crops has no significant impacts on maize and soybean yield (Fig. 5), here we only discuss the impacts of termination time of non-legume cover crops (cereal rye) on maize yield.

The *ecosys* simulation shows that early termination of cover crops can mitigate the negative effects of cover crops on maize yield. However, there is a trade-off between cover crop biomass and maize yield. When the termination date is postponed from late March to mid-April, cover crop biomass may be doubled. However, maize yield is reduced more when cover crop biomass is higher. Fig. 6 shows *ecosys*-simulated and field measured maize yield and cover crop biomass with different cover crop termination times at UR02. When cereal rye is terminated only one day before maize planting, maize yield decreases by 10 % and 6.4 % in model simulation and field experiment, respectively (Fig. 6a). However, when cereal rye is terminated one month before maize planting, the yield loss is reduced to 5.1 % and 3 % in model simulation and field experiment, respectively (Fig. 6a). For cover crop biomass, when cereal rye is terminated only one day before maize, cereal rye aboveground C biomass reaches 1.21 ± 0.17 and 1.05 Mg C/ha in field experiment and model simulation. If cereal rye is terminated one month before maize planting, cereal rye above ground C biomass is only 0.33 ± 0.11 and 0.56 MgC/ha in field experiment and model simulation (Fig. 6b), which is due to the short growing window in the winter for cereal rye in Illinois.

3.3. Mechanistic pathways of cover crops' impacts on cash crop

Our results demonstrate that cover crops could affect cash crop growth through the following pathways (Fig. 7): (1) soil water content, (2) soil N concentration, (3) soil O_2 concentration, and (4) soil temperature. We synthesized these mechanistic pathways through the comparison of the simulated intermediate variables (i.e., soil water, N and O_2) in the maize-soybean rotation systems (Fig. 8).

First, water stress, either too dry or too wet, plays a role. We found that the maize yield change induced by growing cover crops is correlated with precipitation during the maize growing season (Fig. 8a-b). Specifically, there is an increasing trend of yield response to cover crops and growing season precipitation when precipitation is lower than 400 mm, as cover crops could cause cash crop yield loss by reducing soil water content under dry conditions (Meyer et al., 2020; Paul and Juma, 1981), while there is a decreasing trend of yield response to cover crops and growing season precipitation when precipitation is higher than 400 mm, as cover crops could aggravate the wet soil condition by increasing soil water infiltration under humid conditions (Krueger et al., 2011; Basche et al., 2016b).

Second, for the impacts of cover crops on the N cycle, legume and non-legume cover crops have different impacts on cash crop yield. As for non-legume cover crops, *ecosys* simulations show that soil N concentration reduces after the termination of cover crops (Fig. 8c-d), due to the immobilization from cover crop residue (Li et al., 2020; Sievers and Cook, 2018; Williams et al., 2018). Consequently, non-legume cover crops may limit maize N uptake during early maize growing stages, leading to maize yield reduction; while soybean yields are not significantly reduced, because soybean can fix N to overcome limited soil N availability (Clark et al., 2007; Thomas et al., 2017; Uchino et al., 2009). As for legume cover crops, they can release a large amount of inorganic N through mineralization (Kramberger et al., 2009). As a result, legume cover crops

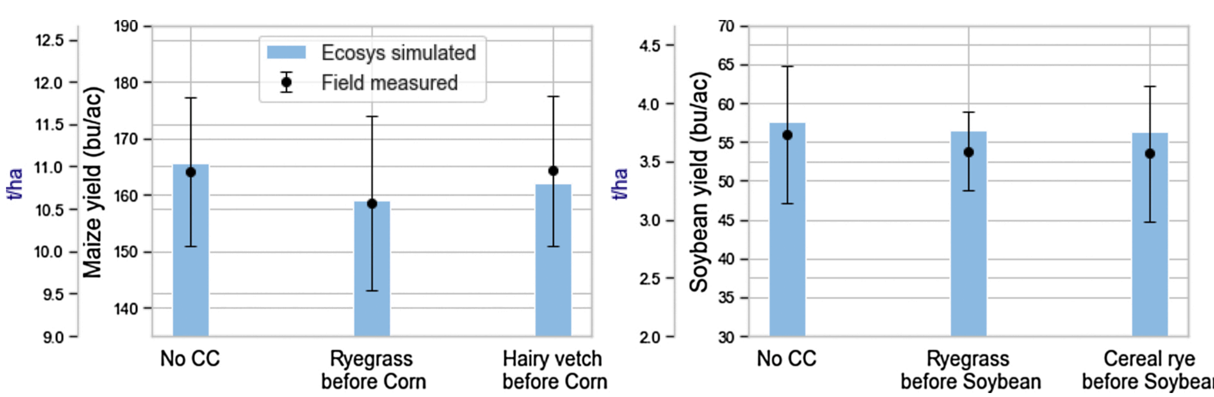

Fig. 5. *Ecosys*-simulated average maize yield and soybean yield at six sites from 2013-2018 in Illinois with different types of cover crops. Blue bars represent mean yield of ecosys simulations for each application; center points of the error bars are mean yield of field measurements for each application; Error bars represent site-averaged standard deviation of the measurements $\overline{(\mathrm{sd})}$ for each application. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

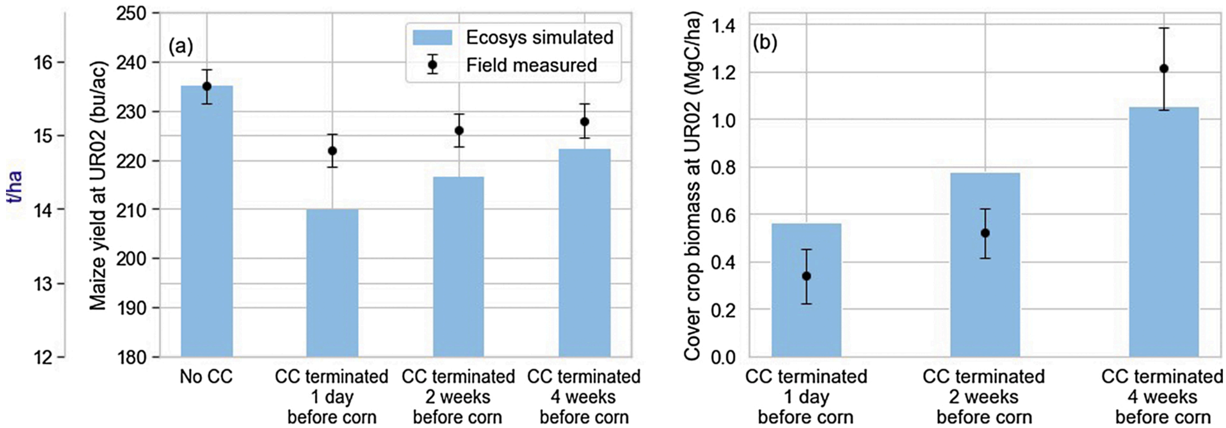

Fig. 6. *Ecosys*-simulated (a) maize yield and (b) cover crops above ground C biomass at UR02 with different cover crop termination time (cereal rye are terminated 1 day, 2 weeks and 4 weeks before maize planting vs. no cover crops). Blue bars represent mean yield in *ecosys* simulations for each subplot; center points of the error bars represent mean yield of field measurements for each subplot; error bars represent standard deviation of the measurements for each subplot. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

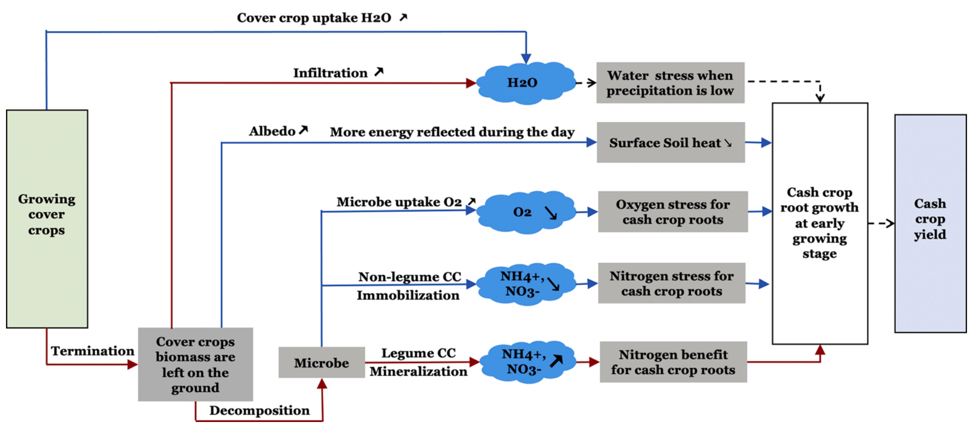

Fig. 7. Diagram of the mechanistic pathways of cover crops to affect cash crop growth and yield (Positive effects[red], negative effects[blue], and uncertain effects [dashed]). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

have different effects on cash crop yields when different N fertilizer rates are applied, which will be further discussed in Section 3.4.

Third, less O_2 at the early growing stage of maize can harm maize growth, and this O_2-deficient stress can be due to the more O_2 consumptions by cover crops (Fig. 8e-f). Specifically, this O_2 stress results from the increased O_2 consumption by microbes during the decomposition of cover crop residue (Fischer et al., 1989; Kavdır and Smucker, 2005). Especially, for fields in Illinois with wetter springs, the seasonal saturation could exacerbate O_2 demands.

Furthermore, with the direct impacts of cover crops on water, N and O_2 uptake for the cash crops, some indirect effects should also be considered. Former studies have shown that cover crops could increase ground albedo and reduce evaporation, thereby slowing soil warming in spring (Blanco-Canqui and Ruis, 2020; Carrer et al., 2018; Kaye and Quemada, 2017). The *ecosys* results confirm that the cooler soil surface of cover crop systems during spring could slow down the cash crop growth (Fig. S1).

3.4. Maize yield response to legume cover crop under different fertilizer rates

The impacts of legume cover crop on maize yield are different under different N fertilizer inputs. We modeled maize yield response to legume cover crop (hairy vetch) under different fertilizer rates (Fig. 9, Table S2). Our results show that when no/low N fertilizer is applied in spring before maize, legume cover crops have a positive effect on maize yield. As N fertilization rates increase, maize yield no longer increases with the existence of cover crops. Different responses of maize yield with respect to legume cover crops could be explained by Liebig's law of the minimum (Chapin et al., 2011). When no/low N fertilizer is applied, N benefit from legume cover crops could compensate for the N deficiency, since N is the most limiting resource for maize growth. As N fertilization rates increase, water and O_2 stress caused by cover crops become limiting, because the supply of N is already above the point of limitation under these high fertilization rates.

4. Discussion

4.1. Impacts of cover crops on cash crop yield

The impacts of cover crops on cash crop yield are species dependent. For maize, we found that when annual ryegrass is planted before maize, *ecosys* simulation shows that averaged maize yield is reduced 3.9 ± 3% compared to no cover crops simulations (3.5 % in field experiments). These results are consistent with a former meta-study, which reports that planting non-legume cover crops results in about 4% of cash crop yield loss averaged from 154 paired experiments (Abdalla et al., 2019). Meanwhile, we found that hairy vetch has relatively neutral effects on maize yield from both field data and model simulations under high fertilization rates (e.g. 190 kgN/ha for maize); while hairy vetch could

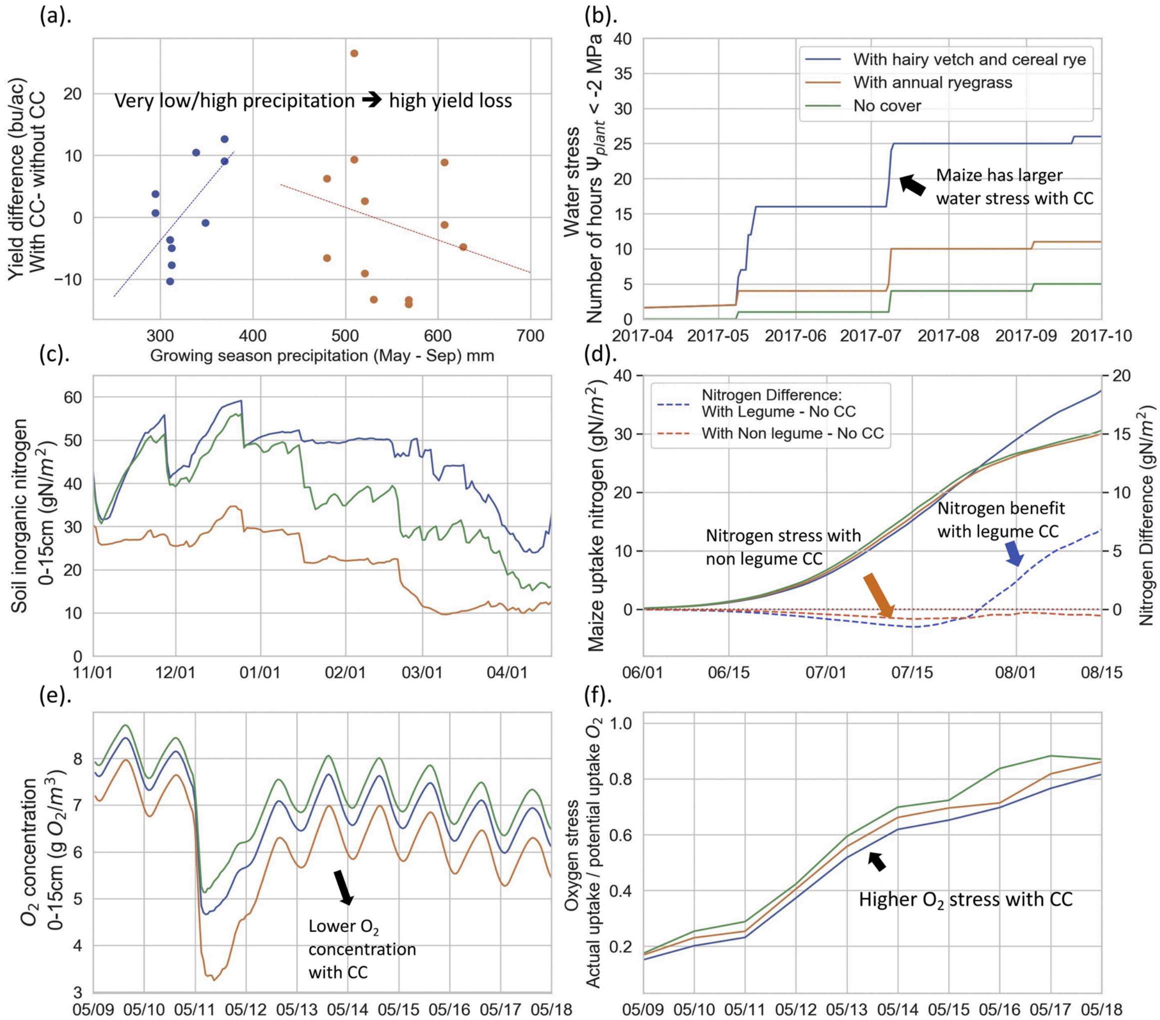

Fig. 8. *Ecosys*-simulated water, N and O_2 under the conditions with and without cover crops. (a) Relationship between yield difference (maize yield with cover crops - maize yield with winter fallow) and annual maize growing season precipitation; (b) *ecosys*-simulated water stress (number of hours when maize canopy water potential is lower than −2 MPa) under different cover crop conditions at MN site; (c) *ecosys*-simulated soil inorganic N at 0-15 cm soil under different cover crops conditions at MN site; (d) *ecosys*-simulated maize N uptake under different cover crops conditions at MN site; (e) *ecosys*-simulated O_2 concentration under different cover crop conditions at MN site; (f) *ecosys*-simulated O_2 stress (plant actual O_2 uptake/potential plant O_2 uptake under non-limiting O_2 condition) under different cover crop conditions at MN site.

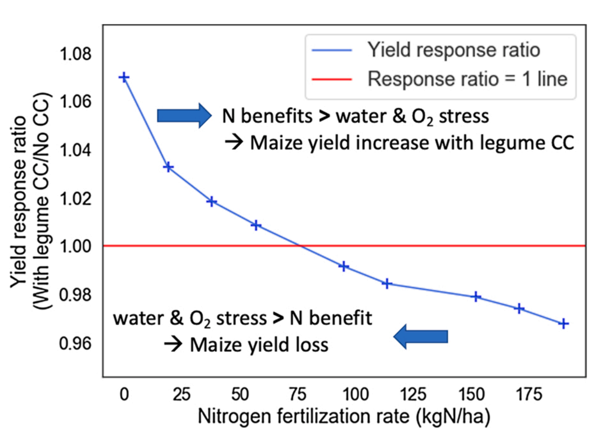

Fig. 9. Relationship between yield response ratio (maize yield following legume cover crops/maize yield following winter fallow) and N fertilization rate (for maize) by *ecosys* simulation.

benefit maize yield when no/low N fertilizer is applied (Fig. 9, Table S2). The effects of hairy vetch on maize yield under different fertilization rates are consistent with the pattern found in meta-studies of field experiments (Miguez and Bollero, 2005; Tonitto et al., 2006). Since adding no/low fertilizer seldom occurs in commercial maize fields, normally planting legume cover crops has a neutral effect on maize yield. For soybean, our results also show that planting cover crops has no significant impact on soybean yield (Fig. 5), consistent with results from several field experiments around the world (Acuña and Villamil, 2014; De Bruin et al., 2005; Dozier et al., 2017; Peterson et al., 2019; Restovich et al., 2012; Ruffo et al., 2004).

4.2. *Management implications to mitigate negative impacts of cover crops on cash crop productivity*

Our results show that non-legume cover crops reduce maize yield through competition for water, N, and O_2 and indirect effects on cooling the surface soil (Figs. 7 and 8). Model simulation results suggest that this negative effect on cash crop yield could be mitigated

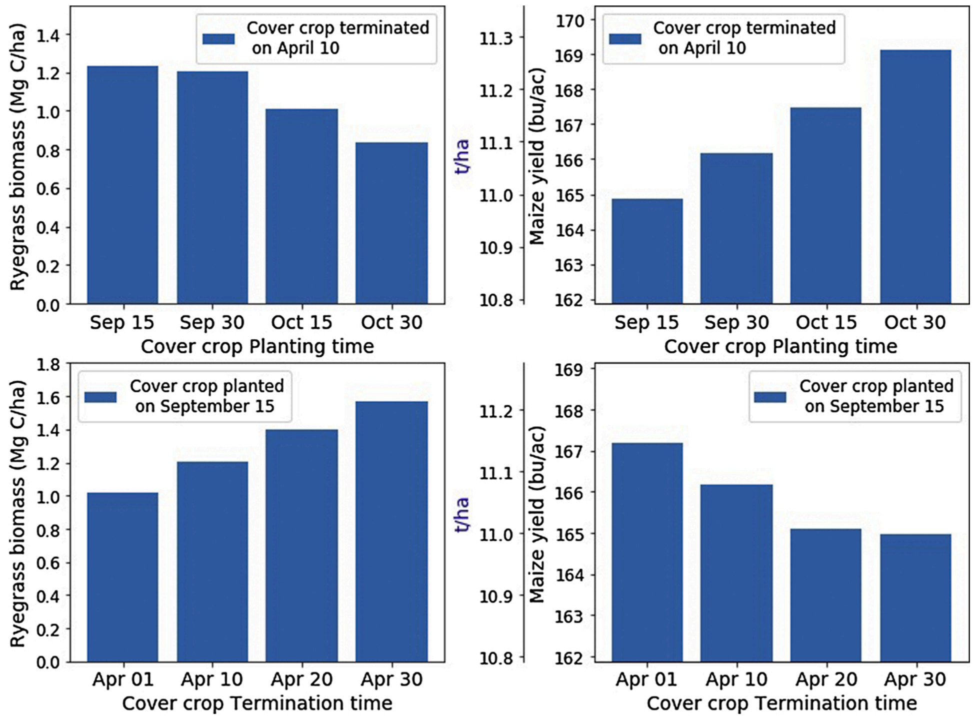

Fig. 10. *Ecosys*-simulated annual ryegrass biomass and maize yield under different cover crop planting and termination time.

through management. There are two possible ways to minimize yield loss: (i) adding more N fertilizer to maize in the spring (Fig. S2), and (ii) controlling cover crop growing season. Normally, cover crops should avoid being planted in fields where N is insufficient. Otherwise, additional fertilizer should be applied. As discussed in Section 3.3, non-legume cover crops lead to maize yield loss mainly due to enhanced soil N immobilization (Li et al., 2020; Sievers and Cook, 2018; Williams et al., 2018). Therefore, the negative impact of cover crops on cash crop yield could be mitigated if addition N is applied after cover crops termination. However, adding more fertilizer to maize in the spring increases N fertilizer usage, which may increase the costs and cause other problems, including offsetting the nitrate leaching benefits from cover crops and increasing gaseous emissions (Basche et al., 2014).

Controlling cover crops growing season is a more effective management practice to mitigate the negative impacts of cover crops and optimize their benefits. Both *ecosys* simulations and field experiments at UR02 show that later planting and earlier termination of non-legume cover crops could mitigate yield loss, which was also observed in other field experiments by Krueger et al. (2011) and Chatterjee et al. (2020). Studies show that when cover crops are terminated early enough (e.g. a month), immobilized N is gradually remineralized (Sievers and Cook, 2018), which reduces the negative effects of cover crops. In addition, the soil could also have more time to develop a richer O_2 environment. As a result, maize yield is higher when cover crops termination time is earlier (Fig. 10). However, under these circumstances, cover crop biomass is relatively low due to the short growing seasons. On the contrary, if cover crops are planted in early September and are terminated only one day before maize planting, maize yield is lower but cover crops reach higher biomass. Concerning the trade-off between cover crops biomass and maize yield, the agronomically optimum cover crop planting and termination time shall be determined with consideration of both economic costs and environmental benefits, which requires further study with the determined optimizers or the combination of economic models.

In addition to competition for N, cover crops may have negative effects on cash crop yield (Fig. 8a-b) by aggravating a wet soil condition during flood (Krueger et al., 2011; Basche et al., 2016b) or excessive water usage from water uptake under drought (Meyer et al., 2020; Paul and Juma, 1981; Unger and Vigil, 1998). Thus, cover crops shall also avoid being planted in regions either too dry or too wet. However, the regional pattern of soil water response with respect to cover crops remains unclear under different weather and different soil conditions, which requires further studies to provide a more comprehensive understanding and guide water management in cover crop systems for farmers.

4.3. Benefits of using a well-validated agroecosystem model to study cover crop impacts

In this study, we validated the *ecosys* model with rich ground measured maize and soybean yield and cover crop biomass data at seven sites across Illinois in the heart of the U.S. Corn Belt. Rigorous validation of models is the prerequisite for all model-related applications. Model-based approaches need to be validated by robust and multi-facet measurements to demonstrate their capability before applying them to guide management decisions (Paustian et al., 2019). Current field experiments usually only measure yield and biomass in cover crops trials, and we believe that to improve the modeling of cover crop impacts requires field experiments to collect more intermediate and process-level measurements in soil and plant. For example, the impacts of cover crops on O_2 fluxes have been largely neglected in former studies. Here we highlight opportunities for future field work to measure soil O_2 fluxes at fields with and without cover cropping to test our hypothesis of the competition between cover crops and subsequent cash crops for O_2.

Overall, the *ecosys* model captures the spatial and temporal variation of cash crop yield and cover crop biomass under different management practices. Admittingly, there still are some uncertainties in the simulation and we have made further efforts to reduce possible uncertainties. First, there are uncertainties in the model forcings including weather and soil data. For example, air temperature from NLDAS-2 may have ±2 °C uncertainty compared to actual temperature at fields (Jung et al., 2021). Soil parameters we used are from gSSURGO at scales ranging from 1:12,000 to 1:63,360, which may have in-field variations. These weather and soil forcings are the data with best accuracy we could obtain, and the sensitivity analysis with *ecosys* shows the uncertainty in the forcings have little influence in our results (not reported here). Second, the *ecosys* model only has a moderate performance in simulating soybean yield, and bias exists between field measured data and model simulations. It is possible that the field measurements may contain uncertainty and also models should be further improved.

Using the validated *ecosys* model to assess the impacts of cover crops on cash crop yield helps us synthesize the trial data and allows mechanistic understanding, especially for variables that are difficult to measure in the field experiments (Fig. 8). Compared to field experiments, which are restricted to certain areas and a limited suite of management practices, agroecosystem models provide the ability to extrapolate simulations to other regions and other management practices, as shown in this study for *ecosys*. Accurate modeling of cover crops biomass and cash crop yield enables further evaluation of cover crops suitability in the U.S. Midwest agroecosystems, and this provides potentials to use *ecosys* to develop a decision-making tool to guide farmers to adopt the most suitable practices for cover crop management.

5. Conclusion

Our analysis assessed the impacts of cover crops on maize and soybean yield in the U.S. Midwestern agroecosystems. By analyzing field experiment data and validated *ecosys* simulation results, we quantified the impact of legume and non-legume cover crops on maize and soybean yield with different cover crop termination times. We also identified mechanisms of cash crops' yield response with respect to cover crops based on the validated *ecosys* simulations. Overall, *ecosys* has a reliable performance in simulating maize and soybean yield and cover crops biomass at the site level. Based on *ecosys* model simulation results, we found that non-legume cover crops cause a 3.9 $\pm$ 3% (uncertainty level is calculated based on variation among sites) reduction in maize yield, while legume cover crops do not have significant impacts on maize yield, which is consistent with the prior field and meta-studies. The impact of cover crops on soybean yield is relatively neutral. Later termination of non-legume cover crops before maize causes larger maize yield loss due to intensive competition for resources (e.g., water, N, and O_2). Though non-legume cover crops cause a reduction in maize yield, this yield loss could be mitigated through management practices, such as putting more N fertilizer for cash crops and controlling termination time of cover crops. Our results also demonstrate that *ecosys* can accurately simulate cover crops biomass and cash crop yields, enabling its application to evaluate cover crop suitability in high-production agricultural systems of the U.S. Midwest.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fcr.2021.108264.

References

Abdalla, M., Hastings, A., Cheng, K., Yue, Q., Chadwick, D., Espenberg, M., Truu, J., Rees, R.M., Smith, P., 2019. A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. Glob. Chang. Biol. 25, 2530–2543. https://doi.org/10.1111/gcb.14644.

Acuña, J.C.M., Villamil, M.B., 2014. Short-term effects of cover crops and compaction on soil properties and soybean production in Illinois. Agron. J. 106, 860–870. https://doi.org/10.2134/agronj13.0370.

Alonso-Ayuso, M., Quemada, M., Vanclooster, M., Ruiz-Ramos, M., Rodriguez, A., Gabriel, J.L., 2018. Assessing cover crop management under actual and climate change conditions. Sci. Total Environ. 621, 1330–1341. https://doi.org/10.1016/j.scitotenv.2017.10.095.

Alvarez, R., Steinbach, H.S., De Paepe, J.L., 2017. Cover crop effects on soils and subsequent crops in the pampas: a meta-analysis. Soil Tillage Res. 170, 53–65. https://doi.org/10.1016/j.still.2017.03.005.

Basche, A.D., Miguez, F.E., Kaspar, T.C., Castellano, M.J., 2014. Do cover crops increase or decrease nitrous oxide emissions? A meta-analysis. J. Soil Water Conserv. 69, 471–482. https://doi.org/10.2489/jswc.69.6.471.

Basche, A.D., Archontoulis, S.V., Kaspar, T.C., Jaynes, D.B., Parkin, T.B., Miguez, F.E., 2016a. Simulating long-term impacts of cover crops and climate change on crop production and environmental outcomes in the Midwestern United States. Agric. Ecosyst. Environ. 218, 95–106. https://doi.org/10.1016/j.agee.2015.11.011.

Basche, A.D., Kaspar, T.C., Archontoulis, S.V., Jaynes, D.B., Sauer, T.J., Parkin, T.B., Miguez, F.E., 2016b. Soil water improvements with the long-term use of a winter rye cover crop. Agric. Water Manage. 172, 40–50. https://doi.org/10.1016/j.agwat.2016.04.006.

Behnke, G.D., Kim, N., Villamil, M.B., 2020. Agronomic assessment of cover cropping and tillage practices across environments. Agron. J. 112, 3913–3928. https://doi.org/10.1002/agj2.20337.

Blanco-Canqui, H., Ruis, S.J., 2020. Cover crop impacts on soil physical properties: a review. Soil Sci. Soc. Am. J. 84 (5), 1527–1576. https://doi.org/10.1002/saj2.20129.

Blaser, B.C., Singer, J.W., Gibson, L.R., 2007. Winter cereal, seeding rate, and intercrop seeding rate effect on red clover yield and quality. Agron. J. 99, 723–729. https://doi.org/10.2134/agronj2006.0247.

Carrer, D., Pique, G., Ferlicoq, M., Ceamanos, X., Ceschia, E., 2018. What is the potential of cropland albedo management in the fight against global warming? A case study based on the use of cover crops. Environ. Res. Lett. 13, 044030 https://doi.org/10.1088/1748-9326/aab650.

Casey, P.A., 2012. Plant Guide for Cereal Rye (Secale Cereale). USDA-Natural Resources Conservation Service. Plant Materials Center, Elsberry, MO.

Chai, T., Draxler, R.R., 2014. Root mean square error (RMSE) or mean absolute error (MAE)? – arguments against avoiding RMSE in the literature. Geosci. Model. Dev. Discuss. 7, 1247–1250. https://doi.org/10.5194/gmd-7-1247-2014.

Chapin I.I.I., F.S., Matson, P.A., Vitousek, P., 2011. Principles of Terrestrial Ecosystem Ecology. Springer Science & Business Media. Chapter 6, P173.

Chatterjee, N., Archontoulis, S.V., Bastidas, A., Proctor, C.A., Elmore, R.W., Basche, A.D., 2020. Simulating winter rye cover crop production under alternative management in a corn-soybean rotation. Agron. J. 112, 4648–4665. https://doi.org/10.1002/agj2.20377.

Clark, A.J., Meisinger, J.J., Decker, A.M., Mulford, F.R., 2007. Effects of a grass-selective herbicide in a vetch–rye cover crop system on nitrogen management. Agron. J. 99, 36–42.

David, M.B., Flint, C.G., Gentry, L.E., Dolan, M.K., Czapar, G.F., Cooke, R.A., Lavaire, T., 2015. Navigating the socio-bio-geo-chemistry and engineering of nitrogen management in two illinois tile-drained watersheds. J. Environ. Qual. 44, 368–381. https://doi.org/10.2134/jeq2014.01.0036.

De Bruin, J.L., Porter, P.M., Jordan, N.R., 2005. Use of a rye cover crop following corn in rotation with soybean in the upper Midwest. Agron. J. 97, 587–598. https://doi.org/10.2134/agronj2005.0587.

Dozier, I.A., Behnke, G.D., Davis, A.S., Nafziger, E.D., Villamil, M.B., 2017. Tillage and cover cropping effects on soil properties and crop production in Illinois. Agron. J. 109, 1261–1270. https://doi.org/10.2134/agronj2016.10.0613.

Fischer, W.R., Flessa, H., Schaller, G., 1989. pH values and redox potentials in microsites of the rhizosphere. Z. Pflanzenernaehr. Bodenkd. 152, 191–195. https://doi.org/10.1002/jpln.19891520209.

Florence, A.M., Higley, L.G., Drijber, R.A., Francis, C.A., Lindquist, J.L., 2019. Cover crop mixture diversity, biomass productivity, weed suppression, and stability. PLoS One 14, e0206195. https://doi.org/10.1371/journal.pone.0206195.

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., 2001. 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., 2004. 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., Hesketh, J.D., 1992. Canopy structure of maize (zea mays l.) at different. Biotronics 21, 11–24.

Grant, R.F., Juma, N.G., McGill, W.B., 1993a. Simulation of carbon and nitrogen transformations in soil: microbial biomass and metabolic products. Soil Biol. Biochem. 25, 1331–1338. https://doi.org/10.1016/0038-0717(93)90047-F.

Grant, R.F., Juma, N.G., McGill, W.B., 1993b. 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., Arkebauer, T.J., Dobermann, A., Hubbard, K.G., Schimelfenig, T.T., Suyker, A.E., Verma, S.B., Walters, D.T., 2007a. Net biome productivity of irrigated and rainfed maize-soybean rotations: modeling vs. Measurements. Agronomy Journal. https://doi.org/10.2134/agronj2006.0308.

Grant, R.F., Barr, A.G., Black, T.A., Gaumont-Guay, D., Iwashita, H., Kidson, J., McCAUGHEY, H., Morgenstern, K., Murayama, S., Nesic, Z., Saigusa, N., Shashkov, A., Zha, T., 2007b. Net ecosystem productivity of boreal jack pine stands regenerating from clearcutting under current and future climates. Glob. Chang. Biol. 13, 1423–1440. https://doi.org/10.1111/j.1365-2486.2007.01363.x.

Grant, R.F., Black, T.A., Humphreys, E.R., Morgenstern, K., 2007c. Changes in net ecosystem productivity with forest age following clearcutting of a coastal Douglas-fir forest: testing a mathematical model with eddy covariance measurements along a forest chronosequence. Tree Physiol. 27, 115–131. https://doi.org/10.1093/treephys/27.1.115.

Grant, R.F., Kimball, B.A., Conley, M.M., White, J.W., Wall, G.W., Ottman, M.J., 2011. Controlled warming effects on wheat growth and yield: field measurements and modeling. Agron. J. 103, 1742–1754. https://doi.org/10.2134/agronj2011.0158.

Grant, R.F., Dyck, M., Puurveen, D., 2020. 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.

Huang, Y., Ren, W., Grove, J., Poffenbarger, H., Jacobsen, K., Tao, B., Zhu, X., McNear, D., 2020. Assessing synergistic effects of no-tillage and cover crops on soil carbon dynamics in a long-term maize cropping system under climate change. Agric. For. Meteorol. 291, 108090 https://doi.org/10.1016/j.agrformet.2020.108090.

Jian, J., Du, X., Stewart, R.D., 2020a. Quantifying cover crop effects on soil health and productivity. Data Brief 29, 105376. https://doi.org/10.1016/j.dib.2020.105376.

Jian, J., Du, X., Stewart, R.D., 2020b. A database for global soil health assessment. Sci. Data 7, 16. https://doi.org/10.1038/s41597-020-0356-3.

Jung, Jihoon, Al-Hamdan, Mohammad Z., Crosson, William L., Uejio, Christopher K., Duclos, Chris, Kintziger, Kristina W., Reid, Keshia, Jordan, Melissa, Zierden, David, Spector, June T., Insaf, Tabassum Z., 2021. Evaluation of NLDAS-2 and downscaled air temperature data in Florida. Phys. Geogr. https://doi.org/10.1080/02723646.2021.1928878.

Kavdır, Y., Smucker, A.J.M., 2005. Soil aggregate sequestration of cover crop root and shoot-derived nitrogen. Plant Soil 272, 263–276. https://doi.org/10.1007/s11104-004-5294-x.

Kaye, J.P., Quemada, M., 2017. Using cover crops to mitigate and adapt to climate change. A review. Agron. Sustain. Dev. 37, 4. https://doi.org/10.1007/s13593-016-0410-x.

Kaye, J., Finney, D., White, C., Bradley, B., Schipanski, M., Alonso-Ayuso, M., Hunter, M., Burgess, M., Mejia, C., 2019. Managing nitrogen through cover crop species selection in the U.S. Mid-Atlantic. PLoS One 14, e0215448. https://doi.org/10.1371/journal.pone.0215448.

Kramberger, B., Gselman, A., Janzekovic, M., Kaligaric, M., Bracko, B., 2009. Effects of cover crops on soil mineral nitrogen and on the yield and nitrogen content of maize. Eur. J. Agron. 31, 103–109. https://doi.org/10.1016/j.eja.2009.05.006.

Krueger, E.S., Ochsner, T.E., Porter, P.M., Baker, J.M., 2011. Winter rye cover crop management influences on soil water, soil nitrate, and corn development. Agron. J. 103, 316–323. https://doi.org/10.2134/agronj2010.0327.

Ku, H.H., 1966. Notes on the use of propagation of error formulas. J. Res. Bur. Stand. (1934) 70 (4), 263–273.

Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304, 1623–1627. https://doi.org/10.1126/science.1097396.

Lal, R., 2015. Soil carbon sequestration and aggregation by cover cropping. J. Soil Water Conserv. 70, 329–339. https://doi.org/10.2489/jswc.70.6.329.

Lawson, A., Cogger, C., Bary, A., Fortuna, A.-M., 2015. Influence of seeding ratio, planting date, and termination date on rye-hairy vetch cover crop mixture performance under organic management. PLoS One 10, e0129597. https://doi.org/10.1371/journal.pone.0129597.

Li, F., Sørensen, P., Li, X., Olesen, J.E., 2020. Carbon and nitrogen mineralization differ between incorporated shoots and roots of legume versus non-legume based cover crops. Plant Soil 446, 243–257. https://doi.org/10.1007/s11104-019-04358-6.

Marcillo, G.S., Miguez, F.E., 2017. Corn yield response to winter cover crops: an updated meta-analysis. J. Soil Water Conserv. 72, 226–239. https://doi.org/10.2489/jswc.72.3.226.

Meyer, N., Bergez, J.-E., Constantin, J., Belleville, P., Justes, E., 2020. Cover crops reduce drainage but not always soil water content due to interactions between rainfall distribution and management. Agric. Water Manage. 231, 105998 https://doi.org/10.1016/j.agwat.2019.105998.

Mezbahuddin, S., Spiess, D., Hildebrand, D., Kryzanowski, L., Itenfisu, D., Goddard, T., Iqbal, J., Grant, R., 2020. Assessing effects of agronomic nitrogen management on crop nitrogen use and nitrogen losses in the western Canadian prairies. Front. Sustain. Food Syst. 4 https://doi.org/10.3389/fsufs.2020.512292.

Miguez, F.E., Bollero, G.A., 2005. Review of corn yield response under winter cover cropping systems using meta-analytic methods. Crop Sci. 45, 2318–2329. https://doi.org/10.2135/cropsci2005.0014.

Nichols, V., Martinez-Feria, R., Weisberger, D., Carlson, S., Basso, B., Basche, A., 2020. Cover crops and weed suppression in the US Midwest: a meta-analysis and modeling study. Agricultural & Environmental Letters 5, e20022.

Noland, R.L., Wells, M.S., Sheaffer, C.C., Baker, J.M., Martinson, K.L., Coulter, J.A., 2018. Establishment and function of cover crops interseeded into corn. Crop Sci. 58, 863–873. https://doi.org/10.2135/cropsci2017.06.0375.

Paul, E.A., Juma, N.G., 1981. Mineralization and immobilization of soil nitrogen by microorganisms. Ecol. Bull. 179–195.

Paustian, K., Collier, S., Baldock, J., Burgess, R., Creque, J., DeLonge, M., Dungait, J., Ellert, B., Frank, S., Goddard, T., Govaerts, B., Grundy, M., Henning, M., Izaurralde, R.C., Madaras, M., McConkey, B., Porzig, E., Rice, C., Searle, R., Seavy, N., Skalsky, R., Mulhern, W., Jahn, M., 2019. Quantifying carbon for agricultural soil management: from the current status toward a global soil information system. Carbon Manag. 10, 567–587. https://doi.org/10.1080/17583004.2019.1633231.

Peng, B., Guan, K., Tang, J., Ainsworth, E.A., Asseng, S., Bernacchi, C.J., Cooper, M., Delucia, E.H., Elliott, J.W., Ewert, F., Grant, R.F., Gustafson, D.I., Hammer, G.L., Jin, Z., Jones, J.W., Kimm, H., Lawrence, D.M., Li, Y., Lombardozzi, D.L., Marshall-Colon, A., Messina, C.D., Ort, D.R., Schnable, J.C., Vallejos, C.E., Wu, A., Yin, X., Zhou, W., 2020. Towards a multiscale crop modelling framework for climate change adaptation assessment. Nat. Plants 6, 338–348. https://doi.org/10.1038/s41477-020-0625-3.

Peterson, A.T., Berti, M.T., Samarappuli, D., 2019. Intersowing cover crops into standing soybean in the US Upper Midwest. Agronomy 9, 264. https://doi.org/10.3390/agronomy9050264.

Poeplau, C., Don, A., 2015. Carbon sequestration in agricultural soils via cultivation of cover crops–A meta-analysis. Agriculture, Ecosystems & Environment 200, 33–41.

Qi, Z., Helmers, M.J., Malone, R.W., Thorp, K.R., 2011. Simulating long-term impacts of winter rye cover crop on hydrologic cycling and nitrogen dynamics for a corn-soybean crop system. Trans. Asabe 54, 1575–1588.

Restovich, S.B., Andriulo, A.E., Portela, S.I., 2012. Introduction of cover crops in a maize–soybean rotation of the Humid Pampas: Effect on nitrogen and water dynamics. Field Crops Res. 128, 62–70. https://doi.org/10.1016/j.fcr.2011.12.012.

Ruffo, M.L., Bullock, D.G., Bollero, G.A., 2004. Soybean yield as affected by biomass and nitrogen uptake of cereal rye in winter cover crop rotations. Agron. J. 96, 1. https://doi.org/10.2134/agronj2004.0800.

Schubert, K.R., 1982. The Energetics of Biological Nitrogen Fixation.

Schütte, R., Plaas, E., Gómez, J.A., Guzmán, G., 2020. Profitability of erosion control with cover crops in European vineyards under consideration of environmental costs. Environ. Dev. 35, 100521 https://doi.org/10.1016/j.envdev.2020.100521.

Sievers, T., Cook, R.L., 2018. Aboveground and root decomposition of cereal rye and hairy vetch cover crops. Soil Sci. Soc. Am. J. 82, 147–155. https://doi.org/10.2136/sssaj2017.05.0139.

Soldevilla Martínez, M., Gabriel Pérez, J.L., Lizaso Oñate, J.I., Quemada Saenz-Badillos, M., 2014. Initializing the DSSAT-century model: inverse calibration of carbon pools from apparent soil N mineralization, in: the nitrogen challenge: building a blueprint for nitrogen use efficiency and food security. Presented at the Proceedings of the 18th Nitrogen Workshop, E.T.S.I. Agrónomos (UPM) 2.

Thapa, R., Mirsky, S.B., Tully, K.L., 2018. Cover crops reduce nitrate leaching in agroecosystems:a global meta-analysis. J. Environ. Qual. 47, 1400–1411. https://doi.org/10.2134/jeq2018.03.0107.

Thomas, B.W., Larney, F.J., Chantigny, M.H., Goyer, C., Hao, X., 2017. Fall rye reduced residual soil nitrate and dryland spring wheat grain yield. Agron. J. 109, 718–728. https://doi.org/10.2134/agronj2016.10.0616.

Tonitto, C., David, M.B., Drinkwater, L.E., 2006. Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: a meta-analysis of crop yield and N dynamics. Agric. Ecosyst. Environ. 112, 58–72. https://doi.org/10.1016/j.agee.2005.07.003.

Tonitto, C., David, M.B., Li, C., Drinkwater, L.E., 2007. Application of the DNDC model to tile-drained Illinois agroecosystems: model comparison of conventional and diversified rotations. Nutr. Cycling Agroecosyst. 78, 65–81. https://doi.org/10.1007/s10705-006-9074-2.

Uchino, H., Iwama, K., Jitsuyama, Y., Yudate, T., Nakamura, S., 2009. Yield losses of soybean and maize by competition with interseeded cover crops and weeds in organic-based cropping systems. Field Crops Res. 113, 342–351. https://doi.org/10.1016/j.fcr.2009.06.013.

Unger, P.W., Vigil, M.F., 1998. Cover crop effects on soil water relationships. J. Soil Water Conserv. 53, 200–207.

USDA NASS, 2019. Census of Agriculture 2017. USDA (United States Department of Agriculture)-NASS (National Agricultural Statistics Service).

Villamil, M.B., Nafziger, E.D., 2019. Agronomic and Environmental Assessment of Cover Crops Project Data. Mendeley Data. https://data.mendeley.com/datasets/7rn62y2cps/1.

Wheeler, T.A., Leser, J.F., Keeling, J.W., Mullinix, B., 2008. Effect of a terminated cover crop and aldicarb on cotton yield and Meloidogyne incognita population density. J. Nematol. 40, 147–151.

Williams, A., Scott Wells, M., Dickey, D.A., Hu, S., Maul, J., Raskin, D.T., Chris Reberg-Horton, S., Mirsky, S.B., 2018. Establishing the relationship of soil nitrogen immobilization to cereal rye residues in a mulched system. Plant Soil 426, 95–107. https://doi.org/10.1007/s11104-018-3566-0.

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. https://doi.org/10.1016/j.agrformet.2021.108521, 108521.