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Simulated impacts of winter rye cover crop on continuous corn yield and soil parameters

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Abstract

Cover crops (CC) provide numerous ecosystem services such as improving soil health, reducing nutrient loss, increasing productivity, and mitigating greenhouse gas emission. However, adoption of CC has been hindered by perceived negative impacts on main crop productivity and additional production costs. This is partly attributed to the gap in current state of knowledge in CC and its interaction with main crop production under different biophysical conditions. In this study, Decision Support System for Agrotechnology Transfer model was used to evaluate the long-term impact of cereal rye (*Secale cereale* L.) on corn (*Zea mays* L.) yield, soil organic carbon (SOC), nitrate leaching, soil water, and drainage for a range of climate, soil, and irrigation management in Eastern and Central Nebraska. A 30-year (1991–2020) simulation showed no difference in corn yield and SOC between CC and no-cover crop treatments at both sites under irrigated and rainfed conditions. However, CC resulted in reduction of N loss by up to 48% at the Eastern Nebraska Research and Extension Center and 24% at South Central Agricultural Laboratory under irrigation. Cereal rye has no significant effect on total soil water but, a significant reduction in cumulative subsurface drainage of 44% was determined at both sites. This study has shown the possible effect of cover crop on corn crop yield and soil properties over different regions in Nebraska. Future research extending the scope and geographic area is needed to test and quantify possible impacts of multiple CC species under diverse management and biophysical conditions.

Abbreviations: APSIM, Agricultural Production Systems sIMulator; CC, cover crop; DSSAT, Decision Support System for Agrotechnology Transfer; ME, mean error; NCC, no-cover crop; r^2, coefficient of determination; RMSE, root mean square error; RRMSE, relative root mean square error; SOC, soil organic carbon.

1 | INTRODUCTION

Corn (*Zea mays L.*) is the most widely cultivated crops in the United States and represents the majority of cropped acres across the Upper Midwest Corn Belt (Hijmans et al., 2016). It is an annual cash crop that provides canopy cover for 4 to 5 months during the growing season (Kaspar & Singer, 2011). Growers across the Corn Belt may implement conservation practices to maintain or enhance soil health and ecosystem services, such as partial or no till, and cover crops. When cover crops are grown in the fallow intervals between cash crops, they often provide a range of ecosystem benefits that include improving soil structure and erosion control (Blanco-Canqui & Lal, 2004; Fageria et al., 2005; Kaspar & Singer, 2011; Reeves, 1994); enhanced soil fertility through roots uptake of residual NO_3-N during fall–spring fallow period (Constantin et al., 2015; Kaspar et al., 2012, 2007a; Li et al., 2015; Salmerón et al., 2010; Thapa et al., 2018; Valkama et al., 2015); improved water infiltration (Basche et al., 2016b); decline in greenhouse gas emissions (Tonitto et al., 2006); increase in soil organic carbon (SOC; McDaniel et al., 2014; Poeplau & Don, 2015); increase in weed control (Cherr et al., 2006; Schipanski et al., 2014); increasing or maintaining yield (Miguez & Bollero, 2005); and enhancing habitat for wildlife and biological diversity (Elhakeem et al., 2019).

Although there is a general consensus that cover cropping provides and enhances numerous ecosystem services, the magnitude of benefits is site specific (Blanco-Canqui et al., 2015). Climate, management, and genetics affect the degree and duration of benefits from cover crops. Some studies have reported that cover crops can lead to soil water depletion, increase competition for soil nutrients, and subsequently reduce cash crop yield in areas with low annual rainfall (Blanco-Canqui et al., 2015; Reeves, 1994). Thus, adoption of cover crop should be site specific by taking into account the plant genetic and biophysical traits, site abiotic and biotic environment, climate variability, and management practices.

One way to improve on the decision-making process associated with selection of cover crops would be to conduct field experiments across temporal and spatial scales. Although invaluable, this approach has limitations: duration of most field experiments (less than 5 years) is not long enough to observe some benefits of cover cropping; labor and resource requirements to conduct experiments across diverse agro-ecologies and management scenarios; and the difficulty to predict impacts of cover crops in future changing environments. These limitations can be partially addressed by combining on-field experiments with crop simulation modeling (Basche et al., 2016a). When appropriately calibrated and validated, decision support tools such as Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003) and Agricultural Production Systems sIMulator (APSIM) (Holzworth et al., 2014) can be applied to evaluate and provide insights on the impact of different cover crop management strategies on agroecosystem functioning under current and changing future climate beyond the domain of a single field in a single year (Brown et al., 2014; Muñoz-Carpena et al., 2008; Tribouillois et al., 2016).

Core Ideas

- Decision Support System for Agrotechnology Transfer crop simulation model provided an opportunity to investigate the long-term impact of cover crops.
- Long-term simulations showed that cereal rye cover crop resulted in reduction of NO_3-N loss and subsurface drain.
- Use of cover crop did not result in changes in corn yield and no-cover crop under both irrigated and rainfed conditions.
- Delaying cover crop termination date by 10 days resulted in doubling of cover crop biomass.

Recent studies (Basche et al., 2016a; Feyereisen et al., 2013; Malone et al., 2014; Martinez-Feria et al., 2016) have demonstrated the practical application of crop simulation models as a valuable tool in improving decision making related to different aspects of cover cropping. For example, Feyereisen et al. (2013) used RyeGro cover crop simulation model to evaluate the biofuel potential of winter rye in the Midwest while Martinez-Feria et al. (2016) conducted a system level analysis together with experimental data to assess cover crop impact on corn yields, drainage water, and NO_3-N losses. Basche et al. (2016a) simulated how winter rye cover crops impact crop production and environmental outcomes under current and future climate conditions over the Midwest United States.

Crop models are available for most economically important crops, and as the above studies demonstrated they have been successfully used in research and operational setting on many occasions. The objective of this study is therefore to simulate the long-term impact of cereal rye (*Secale cereale* L.) on corn yield, SOC, nitrate leaching, soil water, and drainage using the DSSAT decision support system. The information generated in this study will be an integral part of cover crop decision support system that is being developed to help producers make sound management decisions.

TABLE 1 Location of study sites and weather stations used for calibration and validation.

Site	Weather station	Latitude	Longitude	Elevation (m)	Water management	Soil series
ENREC	Mead, NE	41.17	−96.47	370	Irrigated	Tomek
ENREC	Mead, NE	41.17	−96.47	370	Rainfed	Tomek
SCAL	Harvard, NE	40.57	−98.15	556	Irrigated	Hasting
FRMNT	Fremont, NE	41.40	−96.49	363	Rainfed	Yutan
KRVEFT	Roseville, KS	39.12	−95.92	280	Irrigated	Eudora
ABRF	Manhattan, KS	39.12	−95.92	280	Irrigated	Eudora
NREC	Colby, KS	39.39	−101.07	972	Irrigated	Goshen
AEARF	Boone, IA	42.05	−93.85	346	Rainfed	Clarione
WARS	Springfield, OH	39.98	−83.66	342	Irrigated	Kokomo and Crosby
ETREC	Knoxville, TN	35.90	−83.92	300	Rainfed	Shady
MTREC	Thompson, TN	36.10	−86.92	232	Rainfed	Dickson

Abbreviations: ABRF, Ashland Bottoms Research Farm; AEARF, Iowa State University's Agricultural Engineering and Agronomy Research Farms; ENREC, Eastern Nebraska Research and Extension Center; ETREC, East Tennessee AgResearch and Education Centers in Knoxville; FRMNT, Nebraska on-farm research network site near Fremont, NE; KRVEFT, Kansas River Valley Experiment Fields at Topeka; MTREC, Middle Tennessee AgResearch and Education Centers; NREC, Kansas University's Northwest Regional-Extension Center; SCAL, South Central Agricultural Laboratory; WARS, Ohio's Western Agricultural Research Station.

2 | MATERIALS AND METHODS

2.1 | Experimental sites and measurements

A range of published datasets from field experiments and online archives were used for the crop model setup, calibration, validation, and long-term simulations. These datasets include soil surface and profile data, daily weather records, and crop management practices. Although our simulation study was primarily focused on the Eastern Nebraska Research and Extension Center (ENREC) near Mead and the South Central Agricultural Laboratory (SCAL) near Clay Center sites in Nebraska, additional data for model calibration/validation were collected from several sites in Kansas, Iowa, Ohio, and Tennessee for crop model calibration and validation (Table 1). A total of 24 site–year–treatment data from ENREC, Nebraska on-farm research network site near Fremont, Nebraska (FRMNT), Kansas River Valley Experiment Fields at Topeka (KRVEFT), Ashland Bottoms Research Farm (ABRF) near Manhattan, Kansas (ABRF), Kansas State University's Northwest Research-Extension Center (NREC) near Colby, and Ohio's Western Agricultural Research Station (WARS) at South Charleston were used for calibration/validation of CERES-Maize for P1197 corn hybrid. Calibration/validation of CERES-Wheat model for cereal rye (Elbon variety) was performed using 22 site–year–treatment data from ENREC, SCAL, FRMNT, Iowa State University's Agricultural Engineering and Agronomy Research Farms (AEARF), East Tennessee AgResearch and Education Centers in Knoxville (ETREC), and Middle Tennessee AgResearch and Education Centers (MTREC) in Spring Hill. Details of calibration and validation datasets collected from each of the above sites and their respective sources are provided in Table S1.

2.1.1 | Soil

The DSSAT decision support system requires information on physical and chemical properties of different soil layers. These required soil datasets were collected from National Cooperative Soil Survey (NCSS) Soil Characterization database (https://ncsslabdatamart.sc.egov.usda.gov/) for all sites. The soil series used at each site is presented in Table 1. DSSAT also requires initial values of soil water, nitrate, and ammonium as well as an estimate of the above- and below-ground residues from the previous crop. Initial soil water, nitrate, and ammonium were unavailable for all sites, and we estimated these parameters by conducting preliminary 5-year simulations and extracting simulated values at the start of planting. Crop residue was estimated from corn stover measurements at SCAL and undertaken by Koehler-Cole et al. (2020) during 2017 and 2018 season by assuming 60% of stover left on field as residue following harvest on all sites.

2.1.2 | Weather and irrigation management

Weather data to run DSSAT were acquired from weather stations on sites. These encompass daily records of total solar radiation incident on the top of the crop canopy (SRAD), maximum (TMAX) and minimum (TMIN) air temperature, precipitation (PRCP), wind speed (WSPD), and relative humidity (RHUM). For weather stations in Nebraska (which are under Nebraska Mesonet, https://mesonet.unl.edu/), these datasets were obtained from the Nebraska State Climate Office at the University of Nebraska–Lincoln, and for the other sites, crop model formatted data was obtained from Iowa Environmental Mesonet (IEM) website (https://mesonet.agron.iastate.edu/). Missing records in weather data were filled using Weatherman (Pickering et al., 1994) weather generator in DSSAT. Additional information on station name and location for each study site can be found in Table 1. The ENREC-irrigated, SCAL and KRVEFT sites were irrigated between June and August using a lateral move system, while ENREC-rainfed and AEARF sites were rainfed. At the SCAL site, only total irrigation amount and frequency of application were provided. We estimated the exact dates of application by running a preliminary simulation and identifying dates when the soil moisture deficit is relatively larger. For KRVEST, 241.3 mm irrigation was applied 12 times between June and August. No irrigation was applied for cover crop production after corn harvest.

2.1.3 | Management data

To run, the DSSAT requires several crop management parameters. Data collected from the above sources include hybrid name, tillage type, depth and date of operation, planting date, planting depth, row spacing, seeding rate, fertilization type, amount and date of application, and irrigation frequency and amount, harvest date (termination date), phenology (dates of emergence, anthesis and maturity, leaf number), yield and yield components (seed number and unit seed weight), biomass, and biomass N content.

Some management data are missing or lack key details and were filled with common management practices in the area. For example, the amount of residue left after corn harvest is missing for all experiments and we assumed 60% residue left on field and determined the exact amount through preliminary simulations or prior studies. A review of stover harvest literature suggests that 40% removal by mass (i.e., 60% remaining in the field) was an upper limit for maintaining SOC and preventing erosion (Ruis et al., 2017; Wilhelm et al., 2010). All experiments in the above studies were under no-till and crops were kept free of weeds and diseases during the experiments. Row spacing for corn was 76 cm at all locations. For the cereal rye cover crop, Elbon variety was used in all years at a seeding rate of 3×10^5 seeds ha^{-1} and row spacing of 18 cm. Cereal rye was drilled after corn harvest at a depth of 3 cm. The cereal rye planting and termination dates varied in accordance with expected corn harvest dates but falls between October 25 and November 11 for planting and between April 20 and May 10 for termination. Cereal rye was selected as the cover crop because it is one of the most widely grown cover crop and its ability to survive cold winters (Dietzel et al., 2016).

2.2 | Overview of DSSAT

We used two crop models in DSSAT 4.7: CERES-Maize and CERES-Wheat to simulate corn and cereal rye growth and development, respectively. These models are dynamic simulation models that operate on a daily time step to predict crop growth in response to weather, soil, and management strategies. Crop growth in the CSM-CERES-Maize model is controlled by phenologically defined growth stages, which are in turn driven by energy input in the form of growing degree-days (Jones et al., 2003). Growth stages are defined in DSSAT in terms of cultivar coefficients, which are specific to both the crop cultivar and local climate and must therefore be individually calibrated. The CSM-CERES-Maize model uses six cultivar coefficients (Jones et al., 2003), three representing early growth (P1, P2, and P5), two representing grain filling (i.e., G2 and G3), and one representing the phyllochron interval between successive leaf tip appearances (PHINT) (Table S2). Like many other cropping systems platforms, DSSAT version 4.7 does not have a specific rye model. Thus, we modified DSSAT CERES-Wheat module to represent growth and development of cereal rye following a similar procedure as Basche et al. (2014), Chatterjee et al. (2020), and Martinez-Feria et al. (2016). Wheat has been regarded as the most similar available crop. The plant and environment components in the wheat module that were modified are optimum and ceiling temperature and vernalization. The CERES-Wheat model uses seven cultivar specific genetic coefficients (Table S3). P1D, P1V, and P5 determine the timing of phonological events, such as anthesis date and maturity date. G1, G2, and G3 control the yield-related outputs, such as grain yield and biomass. PHINT influences both the phonological development and yield.

2.3 | Calibration and validation of the cultivar coefficients

If the local or new cultivars have not been previously applied with the crop model, the genetic coefficients should be estimated and then evaluated with reference to the independent observational data before the application of the crop model. Thus, both CERES-Maize and CERES-Wheat models were calibrated and validated before using them for long-term simulations using experimental data collected at different sites. Although cultivar coefficients must be calibrated to meet the observed yield or biomass under a no stress growing condition Boote (1999) (i.e., without water, heat, or nutrient deficiencies), it was not possible to find experiments where cereal rye (unlike corn) is grown under such conditions given the purpose and time of rye planting. Thus, we used experiments with least possible stress during the growing season. Calibration followed an iterative approach

(Archontoulis et al., 2014) in which several aspects of the soil–plant–atmosphere system were evaluated concurrently against measured data, expert judgments, and published literature for this region. Measured data from continuous corn and continuous corn with rye experiments (with Pioneer P1197 hybrid and Elbon winter rye variety) were used to calibrate and test model performance. Calibration was completed when a good balance was achieved between measured and simulated values judged by statistical indices (Dietzel et al., 2016).

One corn hybrid (i.e., P1197) was calibrated over 24 set of simulations during the 2016–2020 growing seasons. Measured data used for calibration were grain yield, unit kernel weight, kernel number/ear, leaf number, emergence, anthesis, and maturity dates. The above-ground biomass and biomass N content of cereal rye collected from SCAL, ENREC, FRMNT, AEARF, ETREC, and MTREC (22 site–year–treatment combinations) were parameters used for calibration of CSM-CERES-Wheat. The cultivar specific parameters for both corn and rye were modified to minimize the differences between model simulations and observations. The GENCALC program in DSSAT (Version 4.7) was used to calibrate the genetic coefficients for both corn and cereal rye varieties.

The default wheat cultivar specific coefficients of DSSAT were used as the starting point for model calibration for Elbon Rye. The first step simulated is crop development and, consequently, the process of parameterization started with the coefficients related to this phenological stage (i.e., P1V, P1D, and P5 for CSM-CERES-Wheat and P1, P2, and P5 for CSM-CERES-Maize). The coefficients that affect grain yield (G2, G3, and PHINT for CSM- CERES-Maize) were subsequently parameterized. The coefficients that affect grain yield for CSM-CERES-Wheat (i.e., G1, G2, and G3) were not calibrated as cereal rye is not left on the field to complete the whole growth stages. Conventionally day-neutral varieties should have a zero P2 value (i.e., no delays when photoperiods exceed 12.5 h). In our calibration procedure, a small positive number (0.01) was used for P2 for P1197 corn variety so that computer arithmetic problems like division by zero are prevented.

The accuracy of the procedure used to estimate the cultivar coefficients was determined by comparing the simulated mean values of physiological traits with the corresponding observed mean values (e.g., biomass, yield, N content). Evaluation metrics used for model evaluation include mean error (ME), root mean square error (RMSE), relative root mean square error (RRMSE), and coefficient of determination (r^2). A high value of r^2 and a low value of RMSE indicate goodness of fit between the simulated and observed values. These metrics were computed using the following equations:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{1}^{n}\left(S_i - O_i\right)^2}$$

$$\text{RRMSE} = \frac{1}{\bar{O}}\sqrt{\frac{1}{n}\sum_{1}^{n}\left(S_i - O_i\right)^2}$$

$$r^2 = \left[\frac{\sum_{i=1}^{n}\left(S_i - \bar{S}\right)\left(O_i - \bar{O}\right)}{\sqrt{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2 \sum_{i=1}^{n}\left(S_i - \bar{S}\right)^2}}\right]^2$$

where n is number of observation–simulation pairs, O_i is the observed value for the ith measurement S_i is simulated value for the ith measurement and $\bar{O}$ the mean of observed values. The value of RRMSE when model estimates perfectly match observed data is 0.

2.4 | Long-term simulations

The calibrated and validated corn and rye cultivars were used to conduct long-term simulations at ENREC and SCAL sites for a common period of 1985–2020. Experience using APSIM in this region for simulating corn production systems has indicated that soil organic matter pool requires approximately 4–5 years to stabilize Dietzel et al. (2016). To remove these confounding effects of microbial organic matter buildup or decline, and other uncertainties regarding initial soil conditions at sowing (i.e., unavailable information regarding amount of residue on soil surface, size of fresh organic matter pool, and soil mineral nitrogen and water), we left out the first six years of simulation (i.e., 1986–1990) and considered the remaining 30 years (1991–2020) for analysis. We used standard production management practices for the sites for long-term simulations that were kept constant over the 35 years period. Corn planting was set on May 1 of each year. Fertilizer (i.e., anhydrous ammonia) was applied post-emergence at a rate of 180 kg N ha^{-1} and injected to a depth of 10 cm. Corn harvest was set on October 21. For the cover crop, we utilized model setup to represent direct drilled planting after corn on October 22. The cover crop was terminated 2 weeks before the corn planting (i.e., April 15). For cover crop termination date treatments, additional terminations dates of April 20 and April 25 were considered. Outputs from these long-term simulations were analyzed for long-term impact of post-harvest drilled cereal rye on corn yield, SOC, NO_3-N leaching, soil moisture and soil evaporation compared to continuous corn without cereal rye.

3 | RESULTS AND DISCUSSION

3.1 | Calibration and validation of cultivar coefficients

The comparisons between the observed and simulated values of physiological traits during calibration and validation peri-

TABLE 2 Calibration and validation (values in bracket) statistics for corn (P1197 hybrid) and cereal rye (Elbon variety) using selected physiological crop traits.

Physiological trait	Sim.	Obs.	MAE	RMSE	RRMSE	r^2
Corn						
Grain yield (kg ha^{-1})	12,193 (12,394)	12,386 (11,820)	−192 (574)	680 (1496)	0.059 (0.11)	0.70 (0.65)
Unit Kernel weight (g)	0.303 (0.31)	0.281 (0.29)	0.022 (0.021)	0.026 (0.021)	0.093 (0.074)	—
Kernel number ear^{-1}	452 (557)	480 (572)	−29(15)	29 (15)	0.06 (0.026)	—
Emergence date (days)	9.3(6.8)	8.3(6)	1(0.75)	1.25(1.3)	0.2 (0.2)	—
Cereal rye						
Biomass (kg ha^{-1})	1941 (1006)	1802 (932)	139 (74)	428 (231)	0.23 (0.24)	0.97 (0.98)
Biomass N content (kg ha^{-1})	30(16)	36(21)	−6 (-5.5)	9 (6.1)	0.25 (0.27)	0.89 (0.9)

Note: Simulated (Sim.) and observed (Obs.) values of parameters averaged over sites and years, mean absolute error (MAE), root mean square error (RMSE), relative root mean square error (RRMSE), and coefficient of determination (r^2).

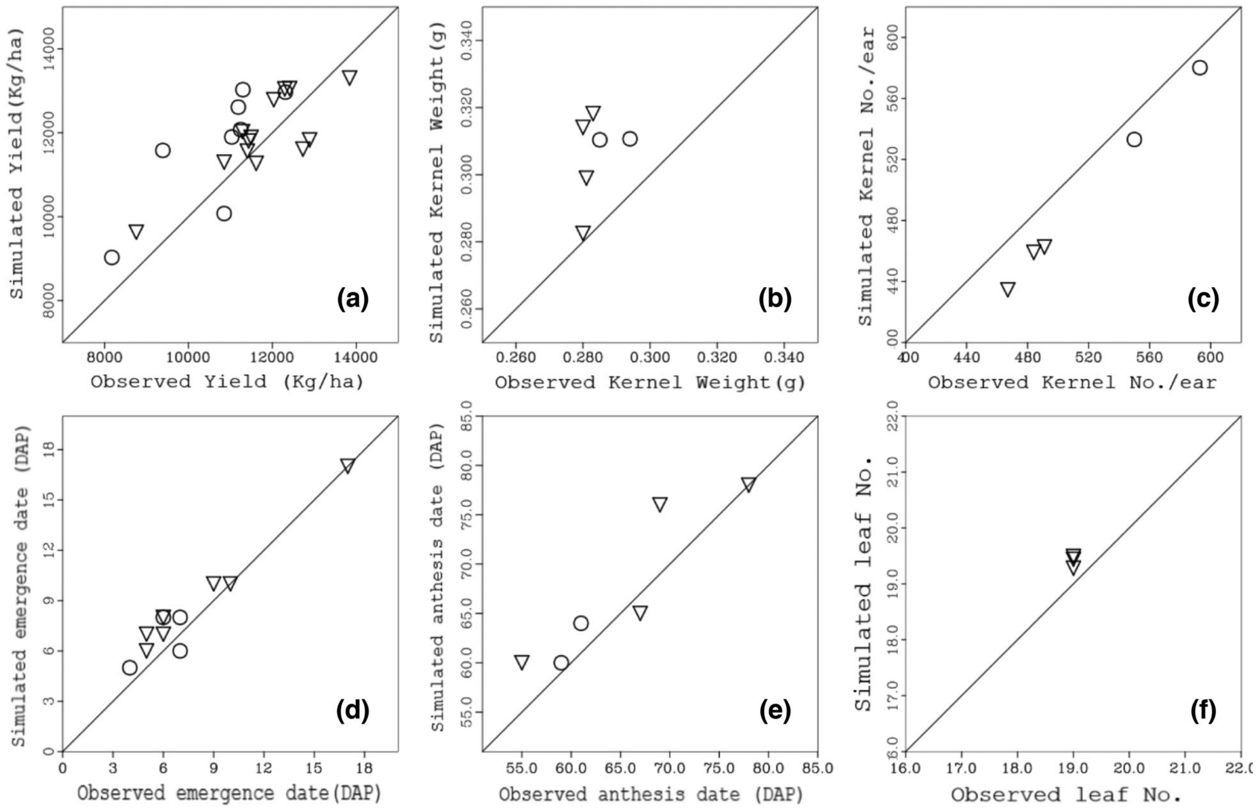

FIGURE 1 Comparison of growth traits for corn hybrid P1197 during calibration and validation. (a) Observation yield (kg ha^{-1}); (b) observed kernel weight (g); (c) observed kernel number per ear; (d) observed emergence date (days after planting [DAP]); (e) observed anthesis date (DAP); (f) observed leaf number. Triangles and circles represent comparisons during calibration and validation, respectively.

ods are shown in Table 2 and Figures 1 and 2. Comparison between observed and simulated corn yield during calibration has RMSE of 680 kg ha^{-1} and mean error of −192 kg ha^{-1}averaged over nine experiments. An RMSE and mean error of 1.25 and 1.3 days were found for date of emergence for calibration. Comparison of observed and simulated yield resulted in a higher but reasonable RMSE and mean error (i.e., 1500 and 574 kg ha^{-1}) during validation. The % RMSE for unit kernel weight at maturity (g [dm]/unit) was 9.61 and 9.85 for calibration and validation with average observed and simulated weight of 0.29 and 0.31 g, respectively.

For cereal rye during calibration, simulated average aboveground biomass was 139 kg ha^{-1} (7.7%) higher than observed value. The RMSE and RRMSE were 428 kg ha^{-1} and 0.23,

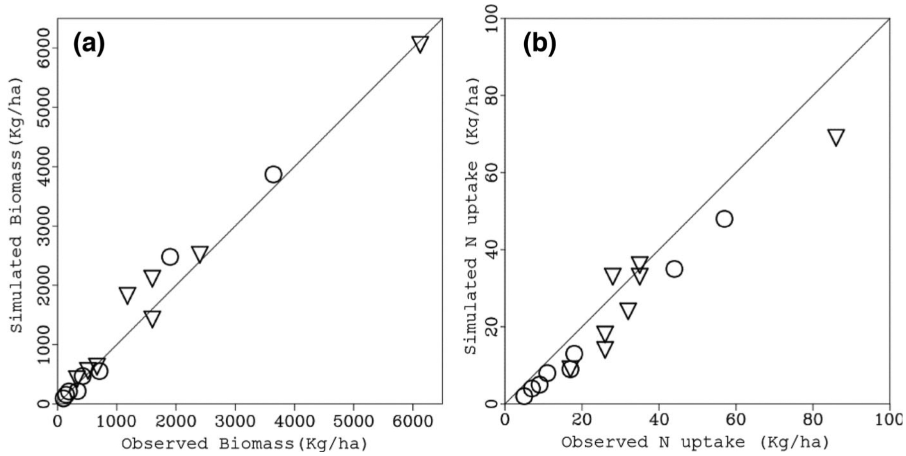

FIGURE 2 Comparison of biomass and nitrogen (N) uptake for cereal rye (Elbon variety) during calibration and validation. (a) Observation biomass (kg ha^{-1}); (b) observation N uptake (kg ha^{-1}). Triangles and circles represent comparisons during calibration and validation, respectively.

respectively (Table 2). Rye biomass was simulated within 177 kg ha^{-1} of observed biomass except for two experiments over AEARF, Iowa during 2017/2018 and 2018/2019 that overestimated biomass by a little over 500 kg ha^{-1} on average. Above-ground biomass showed a significant variation across sites/experiments as a result of significant differences in soil, climate, and management and simulation was able to capture this variation as evident from a high r^2 of above 0.9.

Simulated N uptake in the rye above-ground biomass showed a reasonable agreement with observed values. The plant N uptake predictions followed the pattern of the biomass prediction since N uptake is a function of biomass accumulation. N uptake at termination averaged over eight site-years was simulated with a 6 kg ha^{-1} mean error (<17%) and with the exception of experiment over ETREC, TN (error of 45%), all experiments simulated N uptake under 21%. Similarly, RRMSE was under a reasonable limit of 0.25. Comparison of observed and simulated biomass and N uptake during validation also yielded a similar performance metrics as in calibration with mean error, RMSE, RRMSE, and r^2 of 74 kg ha^{-1} (<8% of observed biomass), 231 kg ha^{-1}, 0.24, and 0.98 for biomass and −5.5 (<25% of observed N uptake), 6 kg ha^{-1}, 0.28, and 0.9 for N uptake, respectively.

Overall, the calibration and validation of the cultivar coefficients based on data from the field experiments resulted in satisfactory simulations of the selected physiological traits for further use in this study. Final cultivar specific coefficients selected for P1197 corn hybrid and Elbon variety cereal rye are shown in Table 3.

In addition to the above physiological traits, the model's ability to reproduce total SOC and nitrogen in soil profile was validated against long-term continuous corn-fallow experimental data from USDA carbon sequestration project at ENREC site (Schmer et al., 2014). Out of the several treatments in the project, we used two, that is, no-till zero-residue removal (NT0) and no-till 35% residue removal (NT35) continuous corn treatments. Data was collected in 2001 and 2010. Simulation was run sequentially from 2001 to 2010 where observed data for 2001 was used to initialize the model and 2010 was used for validation.

The model has reasonably captured the long-term changes in SOC and nitrogen changes (Figure 3). For both NT0 and NT35, total SOC in soil profile was underestimated by 5.4% and 3.6% while total soil N overestimated by 4.6% and 6%, respectively.

3.2 | Cover crop biomass

During the 30-year simulation period, cover crop biomass showed a high interannual variability for both sites with an average cover crop biomass of 144, 729, and 805 kg ha^{-1} and a range of 0–743 and 0–4254 kg ha^{-1} for SCAL, ENREC irrigated, and ENREC rainfed, respectively (Table 4). The highest cover crop biomass for ENREC irrigated and ENREC rainfed were 2517 and 2540 kg ha^{-1} while a significantly lower biomass (i.e., 566 kg ha^{-1}) was attained for SCAL (Figure 4). In addition, cover crops (CC) failed to establish in 7 out 30 years (e.g., 2005–2007) and biomass for half of the simulation period was less than 100 kg ha^{-1} at SCAL due to insufficient moisture resulting from either limited precipitation during the rye growing season or during critical stages of rye growth. However, at ENREC, cover crop failed to establish only in 2017 and biomass less than 100 kg ha^{-1} occurred in 3 years out of 30. Differences in cover crop biomass are in line with the amount of precipitation received at the two sites during the rye growing season (i.e., 131 and 39 mm averaged over 30 years for ENREC and SCAL, respectively).

Simulation results showed that biomass accumulation is highly dependent on precipitation and temperature during the cover crop growing period. We compared cover crop biomass between years with above average precipitation and

TABLE 3 Default and calibrated/validated cultivar-specific coefficients for corn (P1197 hybrid) and cereal rye (Elbon variety).

Elbon			P1197			
Coefficient unit	Default value	Calibrated value	Coefficient	Unit	Default value	Calibrated value
P1V days	5	50	P1	˚C day	320	255
P1D %	75	20	P2	Days	0.52	0.042
P5 ˚C day	450	450	P5	˚C day	940	775
G1 number g^{-1}	30	20	G2	Number	620	807
G2 number	35	60	G3	mg day^{-1}	6.0	8.51
G3 mg day^{-1}	1.0	1.5	PHINT	˚C day	38.9	49.79
PHINT ˚C day	60	40	—	—		—

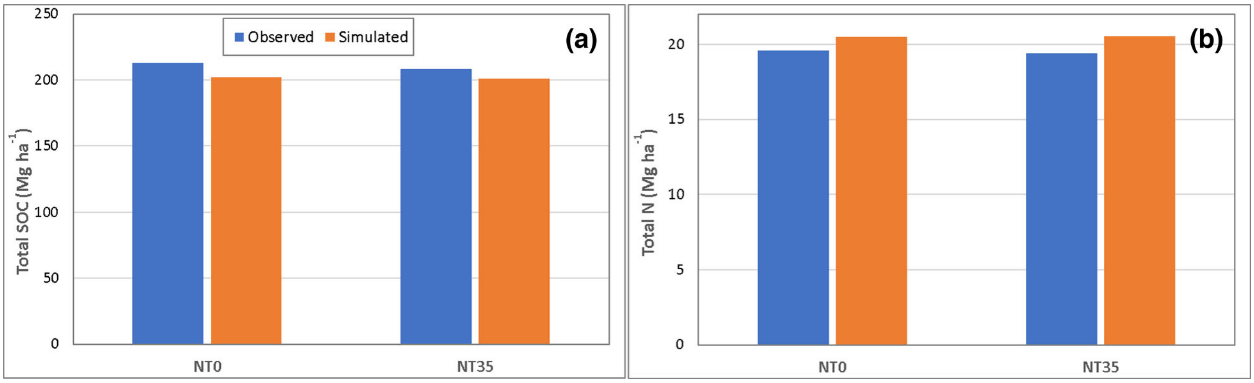

FIGURE 3 Comparison of observed and simulated total (a) SOC and (b) soil N in soil profile at Eastern Nebraska Research and Extension Center site under no-till-0% residue (NT0) and no-till-35% residue (NT35) removal treatments.

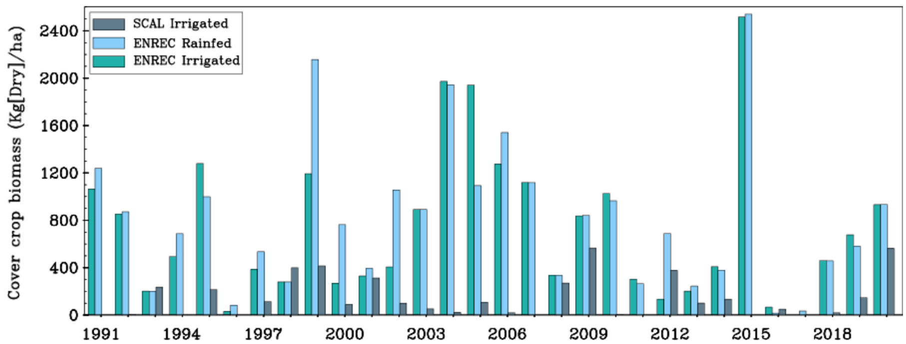

FIGURE 4 Simulated cover crop biomass (kg ha^{-1}) at Eastern Nebraska Research and Extension Center (irrigated and rainfed) and South Central Agricultural Laboratory for 1991–2020 period.

temperature, above average precipitation and below average temperature, below average precipitation and above average temperature, and below average precipitation and temperature. A combination of above average temperature and precipitation generated maximum biomass for both sites (i.e., 1308 and 279 kg ha^{-1} for ENREC and SCAL, respectively) while below normal precipitation and above normal temperature resulted in the least amount of cover crop biomass accumulation (i.e., 281 and 31 kg ha^{-1} for ENREC and SCAL, respectively) (Figure S1). Our results were in congruence with studies reported in Illinois in a corn–soybean system where rye cover crop biomass varied between years by 1820 kg ha^{-1} due to low temperature (Miguez & Bollero, 2005) and in Southwest Iowa (Gailans & Kauffman, 2018). Below average temperature early in the month of April is a cause of rye biomass variation between years in Wisconsin (Andraski & Bundy, 2005).

3.3 | Cover crop impact on corn yield

Simulations show only minor and non-significant corn yield differences between the CC and no-cover crop (NCC) treatments at both locations during the 30-year simulation. Long-term average yield differences between CC and NCC

TABLE 4 Summary of selected parameters averaged over 30-year simulation period (1991–2020) for Eastern Nebraska Research and Extension Center (ENREC) (irrigated and rainfed) and South Central Agricultural Laboratory (SCAL) sites.

Parameter	Treatment	Irrigated SCAL	ENREC	Rainfed ENREC
Corn yield (Mg ha^{-1})	NCC	9.32	11.57	5.63
	CC	9.34	11.02	5.52
Cover crop biomass (kg ha^{-1})	CC	144	729	805
Cover crop biomass (kg ha^{-1}) at different termination dates	April 15	175	675	—
	April 20	247	926	—
	Apr 25	355	1240	–
Organic soil C at maturity (Mg ha^{-1}) (November–April)	NCC	154.5	179.2	174.7
	CC	155.8	180.2	176.6
Organic soil C at maturity (Mg ha^{-1}) (May–October)	NCC	153.8	178.4	173.8
	CC	155.1	179.5	175.9
Total N leached (kg N ha^{-1}) (November–April)	NCC	0.0	0.0	1.1
	CC	0.1	0.0	1.7
Total N leached (kg N ha^{-1}) (May–October)	NCC	8.5	1.47	28.0
	CC	7.3	0.67	21.2
Total drainage (mm) (November–April)	NCC	0.0	0.0	1.4
	CC	0.2	0.0	1.6
Total drainage (mm) (May–October)	NCC	18.0	16.9	25.0
	CC	14.8	6.9	16.4
Total water in soil profile (mm) at corn planting	NCC	298	460	448
	CC	293	411	421
Total soil evaporation (mm) (November–April)	NCC	13.8	5.0	33.0
	CC	11.3	2.4	29.0
Total soil evaporation (mm) (May–October)	NCC	58.8	10.3	86.0
	CC	53.1	7.2	66.0

Abbreviations: CC, cover crop; NCC, no-cover crop.

treatments were 0.2%, −4.7%, and −1.9% for ENREC-irrigated, ENREC-rainfed, and SCAL-irrigated simulations, respectively, and fall way below the year-to-year yield variability (Table 4). Several studies (both field and simulation) over the region have reported a similar insignificant yield differences between CC and NCC treatments.

As in long-term average yield, minimal differences can also be seen with 30-year time series except for few years where there are anomalous low/high soil moisture and/or rainfall conditions especially at ENREC rainfed and SCAL (Figure 5). For example, during drier years at ENREC rainfed, the CC was able to maintain similar yields as NCC treatment and on wetter years, CC treatment had better yields (as high as 76% in 2007). At SCAL, CC was able to mitigate a yield reduction of up to 35% during 2010 and 2015 likely resulting from excessive moisture conditions resulting from very heavy rainfall events recorded during corn planting and early stages of crop development. Disregarding 1993, which was one of the relatively wetter years with the highest number of rainy days (80 days, 20 more days than the year with the second highest number of rainy days during May–October season) that resulted in exceptionally high yield, both CC and NCC treatments show a slightly increasing trend.

3.4 | Soil organic carbon

SOC in soil profile (depth of 140 cm/152 cm at ENREC/SCAL) showed an increasing trend at both ENREC and SCAL for both CC and NCC treatments ($p < 0.05$). SOC increased at a rate of around 1 Mg ha^{-1} year^{-1} for CC treatments at both ENREC (irrigated and rainfed) and SCAL.

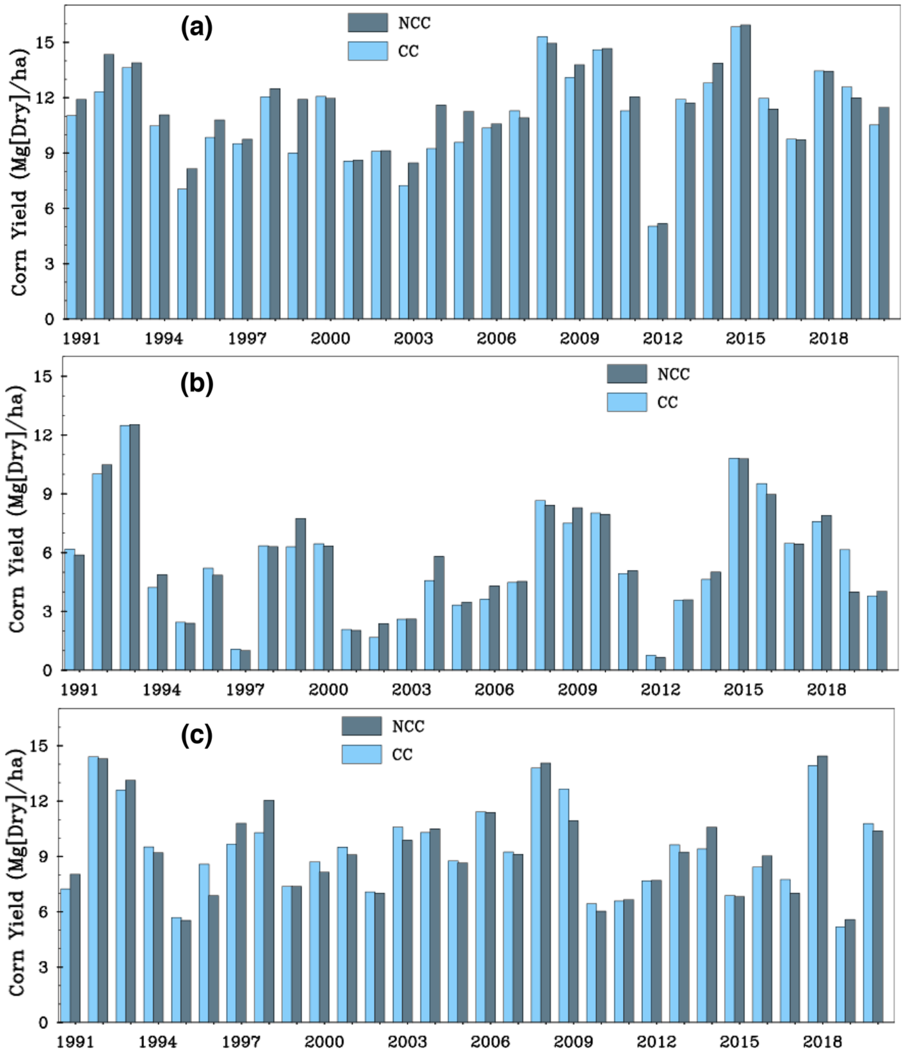

FIGURE 5 Simulated corn yield (Mg ha^{-1}) from 1991 to 2020 (a) irrigated Eastern Nebraska Research and Extension Center (ENREC) site, (b) rainfed ENREC site, and (c) irrigated South Central Agricultural Laboratory site.

For NCC, SOC increased at slightly lower rate of 0.89, 0.7, and 0.8 Mg ha^{-1} year^{-1} at ENREC irrigated, ENREC rainfed, and SCAL, respectively (Figure 6). The increase in SOC for CC and NCC is expected as long-term no-tillage together with 60% (for irrigated/rainfed) corn residue left on field each year would enhance soil carbon sequestration. The slightly higher rate of increase in SOC at ENREC irrigated for NCC compared to ENREC rainfed and SCAL (that have 37% and 42% less corn biomass than ENREC irrigated) is no more there for CC despite the higher corn biomass that still exists for ENREC irrigated (33% and 34% more compared to ENREC rainfed and SCAL) and the higher cover crop biomass. Although this will be as a result of interaction of different factors, one possible reason might be CC was able to offset the difference even if it was considerably smaller for SCAL. However, comparison among treatments shows different results over the two locations. At ENREC, average SOC over the 1991–2020 period was about 1.5% (2645 kg ha^{-1}) (Table 4) higher for CC and this difference increased to 3% when averaging SOC over the last decade of the simulation (i.e., 2011–2020). While examining the time series of SOC, differences between CC and NCC treatments are similar during the first 10 years of simulation (<0.65%) and start to increase afterward (0.65%–2.75%). Although the differences are smaller in magnitude, the same holds true when comparing SOC across termination date, which show similar SOC during the first decade.

At SCAL, CC produced an average of 1000 kg ha^{-1} less shoot biomass than ENREC, which did not contribute enough organic matter to the soil to produce a higher SOC compared to NCC. Although increasing, CC was not able to improve SOC compared to NCC unlike ENREC where there was a significant increase (more than 150 kg ha^{-1}year^{-1}). One reason for the small improvement (or slight decline) in SOC might be because cover crop residues on the surface were not incorporated into the soil layer by tillage in our simulation.

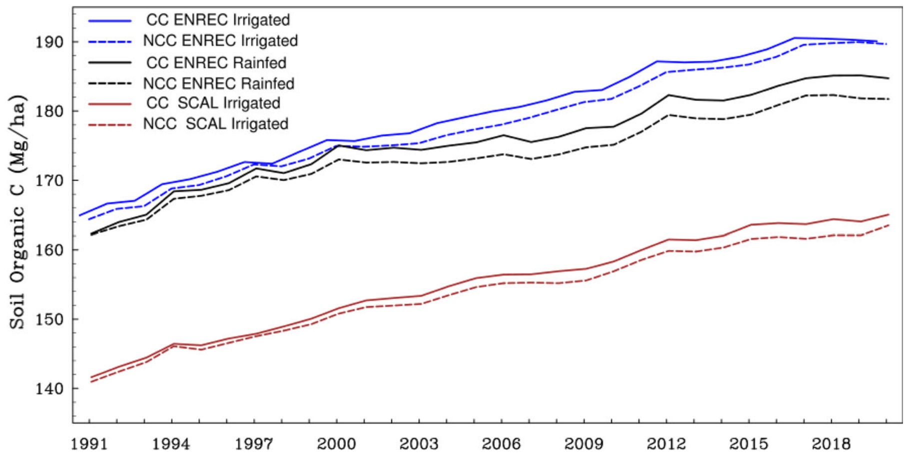

FIGURE 6 Total soil organic carbon in soil profile at Eastern Nebraska Research and Extension Center (depth of 140 cm) and South Central Agricultural Laboratory (depth of 152 cm) sites from 1991 to 2020.

We expected that changes in SOM in this soil layer would take place more slowly and would be more dependent on root residues than the surface soil layer (Moore et al., 2014).

3.5 | Impact on hydrologic cycle

In our analysis of water dynamics, simulations show higher average soil water levels for NCC treatment at corn planting at both ENREC (both rainfed and irrigated) and SCAL sites (Table 4). The 30-year mean soil water for NCC treatment is 1.7%, 10.7%, and 6% higher than CC treatments at SCAL, ENREC, and ENREC-rainfed treatments, respectively. Differences among irrigated and rainfed treatments at ENREC are small (i.e., <12mm) for both CC and NCC treatments. Comparing soil water across two sites, a relatively larger difference can be seen owing to differences in climate, soil type, and depth used for simulation. When examining time series of soil water from 1991 to 2020, soil water is consistently higher for NCC treatments at ENREC for both rainfed and irrigated conditions. However, at SCAL, the NCC treatment does not always result in higher soil water compared to CC treatments. Out of the 30-year simulation, 18 years show higher soil water content for NCC, 7 years show higher soil water for CC treatment, and similar soil water for the remaining 5 years (Figure 7).

The contribution of cover crop is noticeable during years where seasonal total precipitation (November–April) was below normal. For example, out of the 18 and 15 years with below long-term mean November–April rainfall at SCAL and ENREC, cover crop has resulted in a higher or similar soil water for 9 and 8 years, respectively. Kaspar et al. (2007b) found a 9% reduction in drainage with winter rye cover crop treatment compared to the control in a corn–soybean cropping system. Strock et al. (2004) reported 11% reduction in drainage for a corn–soybean cropping system with a rye cover crop compared with a corn–soybean cropping system without cover crop. Logsdon et al. (2002), also observed less drainage with a rye cover crop.

Simulation results indicated that the presence of cereal rye also affected other hydrologic cycle parameters (i.e., soil evaporation and subsurface drainage) (Figure 8). Soil evaporation was reduced by 18%, 52%, and 12% during rye growing season and by 10%, 30%, and 23% during the corn growing season at SCAL, ENREC (irrigated), and ENREC (rainfed), respectively. The reduction in soil evaporation in rye growing season is due to the live rye shoot stand while reduction in evaporation in corn growing season can be attributed to rye residue coverage after growth termination (Qi et al., 2011).

3.6 | NO_3-N loss through subsurface drainage

Averaged over the 30-year simulation period, CC reduced NO_3-N loss through subsurface flow by 48% and 29% at ENREC (for April 20 termination) for November–April and May–October season compared to NCC treatment (Table 4). Time series of N loss during November–April season over ENREC for the 30-year simulation mimics temporal patterns in total seasonal drainage (Figure 9). This relation is further demonstrated at SCAL where lack of drainage during November–April season resulted in zero N loss throughout the season. However, during May–October season, N loss was reduced by 17% on average compared to NCC treatment. Prior studies (Feyereisen et al., 2006; Kaspar et al., 2007b; Malone et al., 2014; Thapa et al., 2018) found similar results with respect to reduction in NO_3-N losses. Malone et al. (2014) simulated average annual NO_3-N loss reduction from adopting winter rye cover crop across 40 midwestern sites and found reductions ranging from 23.9% to 42.5% compared to NCC treatments. In Minnesota, Feyereisen et al. (2006) observed a 37% decrease in annual drainage water NO3-N concentrations while Kaspar et al. (2007b) found a

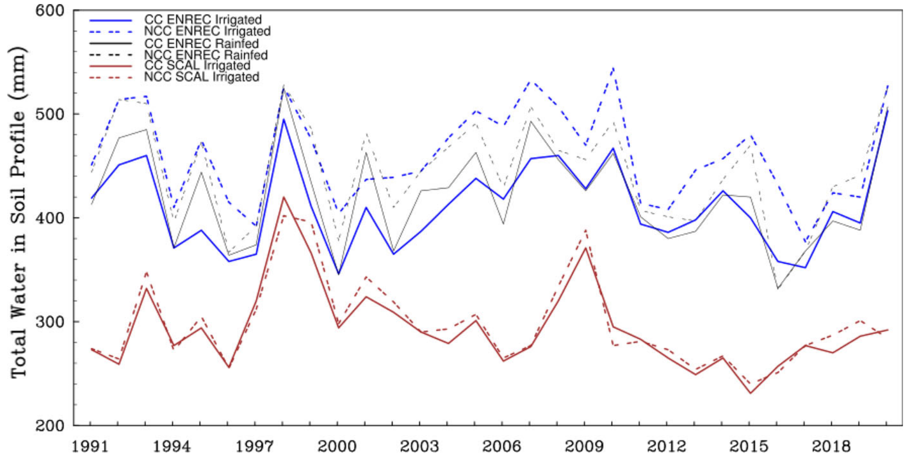

FIGURE 7 Total Water (mm) in soil profile at Eastern Nebraska Research and Extension Center (ENREC) irrigated (blue), ENREC rainfed (black), and South Central Agricultural Laboratory (SCAL) irrigated (brown) for cover crop (CC; solid) and no-cover crop (NCC; broken) treatments from 1991 to 2020. Soil profile depth at ENREC and SCAL were 140 and 152 cm, respectively.

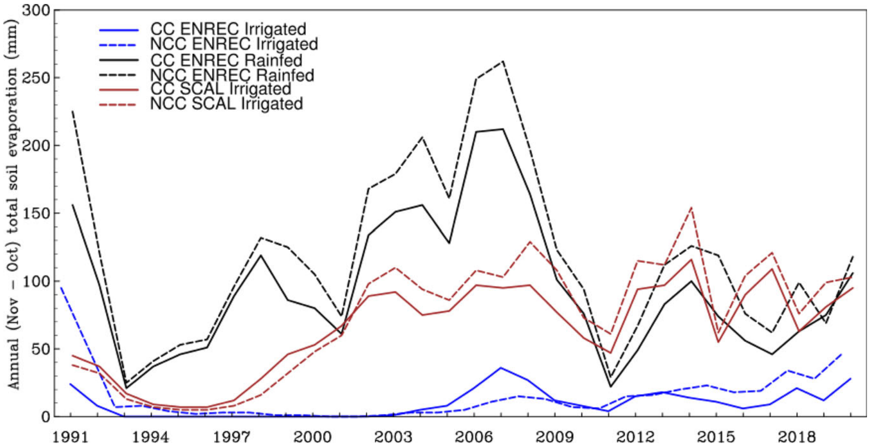

FIGURE 8 Annual (November–October) total soil evaporation (mm) at Eastern Nebraska Research and Extension Center (ENREC) irrigated (blue), ENREC rainfed (black), and South Central Agricultural Laboratory irrigated (brown) for cover crop (CC; solid) and no-cover crop (NCC; broken) treatments from 1991 to 2020.

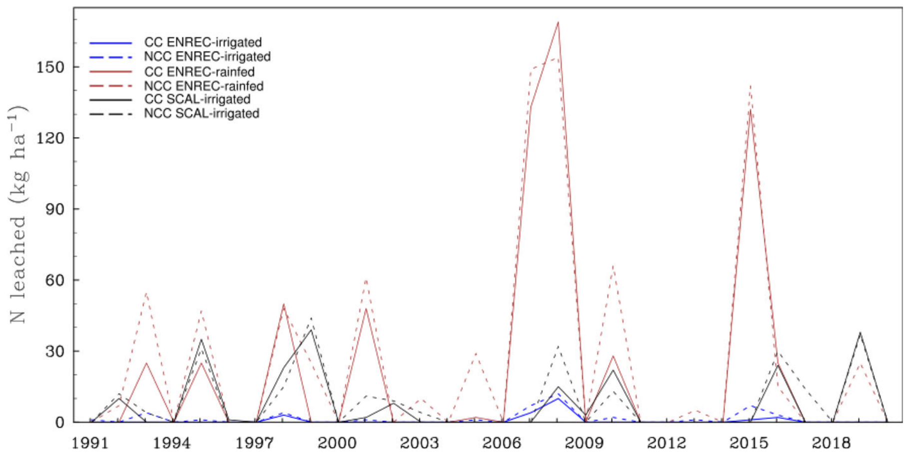

FIGURE 9 Seasonal total NO_3-N loss (kg ha^{-1}) through subsurface drainage during November–April season at Eastern Nebraska Research and Extension Center (ENREC) irrigated (blue), ENREC rainfed (red), and South Central Agricultural Laboratory (black) for cover crop (CC; solid) and no-cover crop (NCC; broken) treatments.

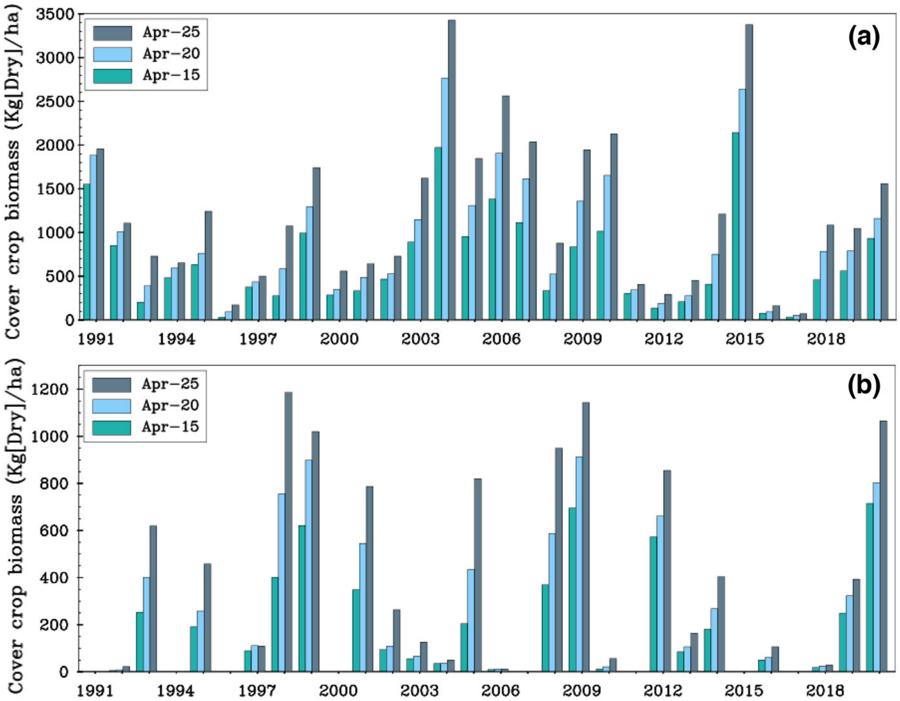

FIGURE 10 Comparison of simulated cover crop biomass (kg ha^{-1}) at different termination dates for (a) Eastern Nebraska Research and Extension Center-irrigated and (b) South Central Agricultural Laboratory-irrigated sites for 1991–2020 period.

59% reduction in NO_3-N concentration in subsurface drainage from adopting rye cover crop at the same site.

3.7 | Impact of cover crop termination dates

Determining the optimum cover crop termination date could enhance overall environmental benefits (Rosa et al., 2021). To determine the impact of termination dates on subsequent corn crop, we compared cover crop biomass accumulation, soil water content and corn grain yield (and yield components) for three termination dates (i.e., April 15, 20, and 25; 15, 10, and 5 days from corn planting, respectively). Comparison of cover crop biomass for the three termination dates showed differences in biomass at both sites (Figure 10). Rye cover crop terminated on April 15 accumulated an average biomass of 175 and 675 kg ha^{-1} at SCAL and ENREC under irrigation, respectively. With the same planting date (i.e., October 15), cover crop terminated on April 20 and April 25 accumulated an average biomass of 247 and 355 kg ha^{-1} at SCAL and 926 and 1240 kg ha^{-1} at ENREC (Table 4). Therefore, delayed termination of cover crop in spring by 5 days could generate up to 40% more biomass and delayed termination by ten days accrues close to twofold more biomass ($p < 0.05$). The majority of corn is planted between April 25 and May 20 in Nebraska (Nebraska Corn Board, 2022) terminating cover crop till April 25 will still leave enough time to plant corn without facing significant yield penalties.

Cereal rye biomass differences between termination dates appear to depend on growing season precipitation with mean Pearson correlation coefficients greater than 0.6 ($p < 0.05$). During years with above average precipitation (e.g., 2004, 2006, and 2015), a difference of more than 1000 kg ha^{-1} can be seen between the April 25 and April 15 termination dates. Gailans and Kauffman (2018) compared two cereal rye cover crop termination dates in Iowa (i.e., 15 and 0 days before corn planting) and found results in line with this study where delaying cover crop termination until the day of corn planting resulted in three times greater above-ground cover crop biomass.

For corn yield, no significant differences were found among cover crop termination dates (Figure 11). At ENREC irrigated, difference of only 0.7% and −2.8% were found between April 15 versus April 20 and April 15 versus April 25, respectively. Similarly, a very small difference of −0.3% and 0.5% were found for SCAL. Even though the yield differences among the three termination dates are very small, impact of CC termination showed positive relation with growing season precipitation. Above-average precipitation amounts tend to lead to neutral to positive effects of yield with termination dates getting closer to corn planting. For example, during 1992, 1995, 1998, 1999, 2001, 2005, and 2010 where precipitation is above average, the latter termination dates (i.e., April 25) resulted in a slightly better yield than earlier termination dates (i.e., April 15 and 20). Comparison of yield between termination dates by disaggregating years

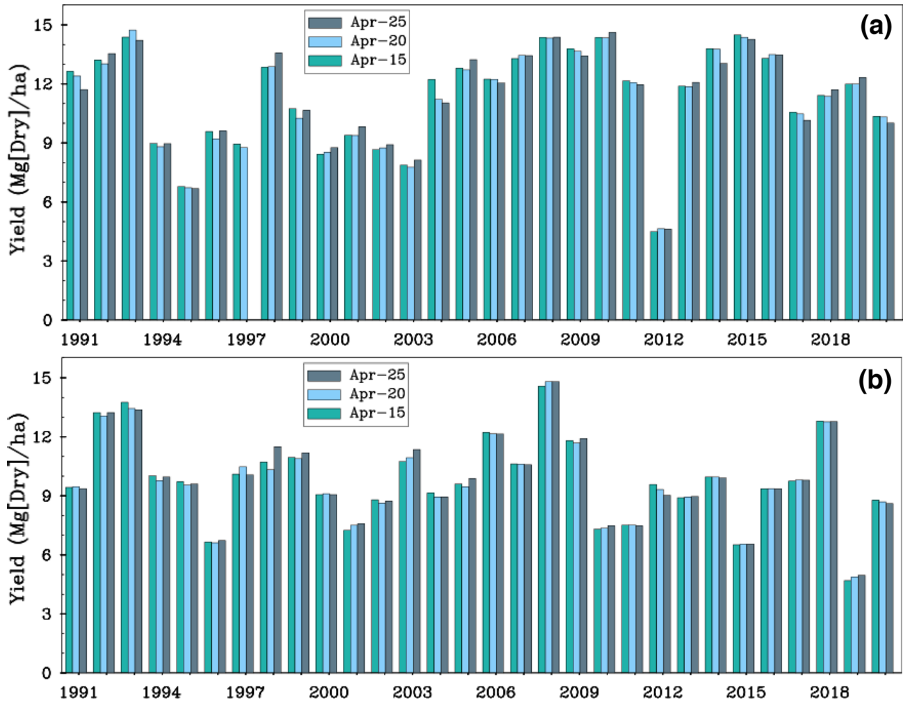

FIGURE 11 Comparison of simulated corn yield (Mg ha^{-1}) at different termination dates for (a) Eastern Nebraska Research and Extension Center-irrigated and (b) South Central Agricultural Laboratory-irrigated sites for 1991–2020 period.

with above and below average precipitation showed that differences between April 25 and April 15 over ENREC changed from −2.8% to −0.35% and to −7.6% for above average and below average precipitations, respectively. For SCAL, differences are insignificant and can be attributed to several factors that include timing, number of rain events, and seasonal total precipitation.

Soil water content at corn planting showed a consistent but small reduction with delay in termination date. A 30-year average reduction of soil water content of 2% and 3% is seen at ENREC and 0.7% and 1.6% at SCAL for 5- and 10-days delay in termination, respectively. For both sites, there are few years where soil water content is similar or slightly higher for delayed termination treatments (Figure S2). These are mostly years where cover crop failed or performed very poorly because of limited precipitation during rye growth period.

Despite the significant increase in cover crop biomass due to delayed termination, the resulting increase SOC is minimal (Figure S3). At ENREC irrigated, SOC at the end of the 30-year simulation period for April 20 and 25 termination dates is only 0.1% (250 kg ha^{-1}) and 0.3% (525 kg ha^{-1}) higher compared to April 15. Similarly, at SCAL the delayed termination dates only resulted in 0.26% (430 kg ha^{-1}) and 0.24% (386 kg ha^{-1}) increase in SOC.

Comparing across termination dates, N loss decreased with delayed termination during November–April season and increases slightly during May–October season (Figure S4). Although N loss is expected to decrease with time due to increased cover crop N uptake by the, N loss showed an increasing pattern similar to seasonal drainage that increases at the end of November–April season due to rainfall events in spring.

4 | CONCLUSION

In this study, DSSAT is used to evaluate the long-term impact of cereal rye on corn yield, SOC, N leaching, soil water, and drainage at two locations in Nebraska (ENREC and SCAL) with contrasting climate, soil, and crop management conditions. We calibrated and validated CERES-Maize and CERES-Wheat modules in DSSAT for one pioneer corn hybrid (P1197) with cumulative relative maturity of 111 days and one cereal rye cultivar (Elbon), respectively, using experimental data collected over several locations. Grain yield, unit kernel weight, kernel number/ear, and emergence date were used to calibrate/validate CERES-Maize and cover crop biomass and nitrogen uptake was used to calibrate/validate CERES-Wheat models. Overall, the calibration/validation statistics (i.e., in terms of MAE, RMSE, RRMSE, and r^2) show reasonable performance to use DSSAT for subsequent long-term simulations to assess benefits of cereal cover crop.

Comparison of 30-year (1991–2020) DSSAT simulation of continuous corn with CC and NCC showed similar corn yield (<3%) and SOC (<1%) differences between the two treatments averaged over the two locations and irrigated management condition. However, adoption of rye cover crop resulted in a significant reduction in NO_3-N leaching (14%, 54%, and 24%) associated with a reduction in subsurface drainage (i.e.,18%, 59%, and 34%) at SCAL, ENREC-irrigated, and ENREC-rainfed sites, respectively. In addition, cover crop also resulted in substantial reduction in soil evaporation at both sites (i.e., 14%, 41%, and 18% averaged over cover crop and corn growing season) with reduction being higher when considering cover crop growing season. Cover crop biomass was found to vary significantly across locations with the relatively wetter ENREC site showing biomass more than four times (729 kg ha^{-1} for irrigated and 805 kg ha^{-1} for rainfed) larger than SCAL (144 kg ha^{-1}) averaged over the 30-year simulation period. Cover crop biomass was also found to increase significantly with delay of termination dates by only 5- and 10-day without compromising corn yields. Delaying spring termination by approximately 5 days (from April 15 to April 20) produced 39% more biomass and delay by another 5 days (to April 25) produced 93% more biomass compared to April 15 termination date.

The results of this simulation-based study have demonstrated that DSSAT can be a valuable tool to investigate the outcome of adopting cover crops in continuous corn system across sites and crop management conditions. Thus, future studies should be extended over more sites with diverse environmental conditions and management practices to optimize cover crop benefits without compromising crop production goals.

AUTHOR CONTRIBUTIONS

Girma Birru: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing—original draft; writing—review & editing. **Andualem Shiferaw**: Conceptualization; data curation; formal analysis; investigation; methodology; software; validation; visualization; writing—original draft; writing—review & editing. **Tsegaye Tadesse**: Conceptualization; data curation; funding acquisition; investigation; project administration; supervision; writing—review & editing. **Virginia L. Jin**: Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; writing—original draft; writing—review & editing. **Brian Wardlow**: Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; writing—review & editing. **Katja Koehler-Cole**: Conceptualization; data curation; methodology; writing—original draft. **Tala Awada**: Conceptualization; methodology; project administration; supervision; writing—original draft; writing—review & editing. **Sarah Beebout**: Conceptualization; funding acquisition; methodology; project administration; resources; supervision. **Teferi Tsegaye**: Conceptualization; methodology; project administration; resources; supervision. **Tulsi Kahrel**: Conceptualization; methodology; writing—original draft.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

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