

TECHNICAL REPORT

Environmental Models, Modules, and Datasets

Cover crop performance under a changing climate in continuous corn system over Nebraska

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Abstract

Fall-planted cover crop (CC) within a continuous corn (*Zea mays* L.) system offers potential agroecosystem benefits, including mitigating the impacts of increased temperature and variability in precipitation patterns. A long-term simulation using the Decision Support System for Agrotechnology Transfer model was made to assess the effects of cereal rye (*Secale cereale* L.) on no-till continuous corn yield and soil properties under historical (1991–2020) and projected climate (2041–2070) in eastern Nebraska. Local weather data during the historical period were used, while climate change projections were based on the Canadian Earth System Model 2 dynamically downscaled using the Canadian Centre for Climate Modelling and Analysis Regional Climate Model 4 under two representative concentration pathways (RCP), namely, RCP4.5 and RCP8.5. Simulations results indicated that CC impacts on corn yield were nonsignificant under historical and climate change conditions. Climate change created favorable conditions for CC growth, resulting in an increase in biomass. CC reduced N leaching under climate change scenarios compared to an average reduction of 60% (7 kg ha⁻¹) during the historical period. CC resulted in a 6% (27 mm) reduction in total water in soil profile (140 cm) and 22% (27 mm) reduction in plant available water compared to no cover crop during historical period. CC reduced cumulative seasonal surface runoff/soil evaporation and increased the rate of soil organic carbon buildup. This research provides valuable information on how changes in climate can impact the performance of cereal rye CC in continuous corn production and should be scaled to wider locations and CC species.

Abbreviations: CC, cover crop; DSSAT, Decision Support System for Agrotechnology Transfer; ENREEC, Eastern Nebraska Research, Education and Extension Center; GCM, global circulation; GHG, greenhouse gases; HIST, historical simulations; NCC, no cover crop; PAW, plant available water; PREC, precipitation; RCP, representative concentration pathways; RH, relative humidity; SOC, soil organic carbon; SRAD, solar radiation incident on the top of the crop canopy; SW, total water in the soil profile; TMAX, maximum; TMIN, minimum.

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1 | INTRODUCTION

Cover crops (CCs) can provide numerous ecosystem benefits when grown in the fallow intervals between cash crops that include improving soil structure and erosion control (Blanco-Canqui & Lal, 2004; Fageria et al., 2005; Kaspar & Singer 2011), enhancing soil fertility through roots uptake of residual nitrate (NO₃⁻-N) during fall-spring fallow period (Li

et al., 2015; Kaspar et al., 2012; Malone et al., 2017; Salmerón et al., 2010; Thapa et al., 2018), improving soil water dynamics (Basche et al., 2016b; Daigh et al., 2014; Qi & Helmers, 2010), improving weed control (Cherr et al., 2006; Schipanski et al., 2014), increasing or maintaining cash-crop yield (Miguez & Bollero, 2005), and enhancing habitat for wildlife and biological diversity (Elhakeem et al., 2019). CCs also provide climate change mitigation benefits by reducing emission of greenhouse gases (GHG) (Tonitto et al., 2006) and increasing soil organic carbon (SOC) (McDaniel et al., 2014; Poeplau & Don, 2015; Sisti et al., 2004). The increase in SOC under cover cropping and the resultant increases in water holding capacity have been reported to build systemic buffering capacity and increase yield resistance to extreme and variable climate conditions (e.g., drought, higher temperatures, and more variable precipitation) in rainfed systems (Letter et al., 2003; Williams et al., 2018). Because extreme weather conditions and variability are expected to intensify in the future, CCs are a key strategy to adapt agricultural systems to projected climate change.

Managing agricultural systems to simultaneously optimize economic returns and multiple ecosystem services from CCs, however, is challenging due to dynamic interactions among services and the tradeoffs involved (Oliveira et al., 2019; Power, 2010; Snapp et al., 2005). The dynamic interactions that exist under current conditions are further complicated by the anticipated changes in climate, necessitating adjustments to CC management practices. For example, one of the biggest challenges currently reported by CC adopters in a temperate continental climate, such as Nebraska, is establishing a decent stand before winter (Oliveira et al., 2019). The anticipated rise in temperatures is expected to enhance the establishment and growth of CCs in these regions. However, without appropriate adjustments in CC termination dates, subsequent cash crops can be adversely impacted due to soil water and nitrogen (N) depletion (Rosa et al., 2021; Unger & Vigil, 1998).

Considering the uncertainties associated with climate change, it is crucial to study the performance of CCs under future climate conditions and identify adaptive strategies that maximize benefits and minimize tradeoffs. Cropping system models are one of the valuable tools for gaining long-term insights into the impact of climate change on CC performance and assessing the effectiveness of adaptation strategies (Kahiluoto et al., 2014; Matthews et al., 2013). In recent years, models have been used to predict the interaction between climate change and agriculture, reporting impacts on crop yields (Deryng et al., 2011; Rosenzweig et al., 2014; Tatsumi et al., 2011), soil carbon (C) stocks (Jones et al., 2005; Robertson et al., 2018; Thomson et al., 2006), and GHG emissions (De Gryze et al., 2010; Valin et al., 2013) under varying land management options and climate change scenarios. Although limited, crop modeling has also been used to assess the interaction between climate change and CCs, as evidenced by

Core Ideas

- Climate change projections accelerated the development rate of cover crop biomass.
- Cereal rye had no significant impact on corn yield under historical and future climate.
- Cover crops reduced surface runoff and soil evaporation during the growing seasons.
- Cereal rye depleted more soil moisture compared to winter fallow.
- Cover crop increased soil organic carbon under both historical and representative concentration pathways scenarios.

recent studies (e.g., Basche et al., 2016a; Birru et al., 2022; Chatterjee et al., 2020; Malone et al., 2014; Martinez-Feria et al., 2016; Shiferaw et al., 2021). Unlike the conventional on-field experiments, this study will provide an insight on how climate change will alter CC performance, and what CC and corn management practices that need to be adjusted to get the optimum benefits CCs can offer or minimize negative effects on main crops. Thus, the objective of this study was to assess the impact of climate change on cereal rye CC performance in a continuous corn cropping system under rainfed and irrigated environments in terms of ecosystem services, corn productivity, and climate change resilience using the Decision Support System for Agrotechnology Transfer (DSSAT) in eastern Nebraska.

2 | MATERIALS AND METHODS

2.1 | Crop models (and cultivars)

The CERES-Maize and CERES-Wheat crop models in DSSAT version 4.7 (Jones et al., 2003) were used to simulate corn and cereal rye growth, 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. Previously calibrated and validated cultivar-specific parameters for corn and cereal rye were used for 111-day maturity corn hybrid (i.e., P1197) and Elbon cereal rye (Birru et al., 2023; Shiferaw et al., 2021). Model calibration/validation for P1197 was undertaken using grain yield, unit kernel weight, kernel number, and emergence date, while for Elbon biomass and biomass N content data collected from 10 sites across the United States were used. For more details on calibration/validation statistics and final cultivar-specific parameters for P1197 corn hybrid and Elbon cereal variety, see Birru et al. (2023).

The simulations were conducted under a continuous corn cropping system with (CC) and without (no cover crop [NCC]) cereal rye CC at the University of Nebraska-Lincoln's Eastern Nebraska Research, Education, and Extension Center (ENREEC), Mead, NE. The simulations cover the period 1991–2020 for historical simulations (HIST) and 2041–2070 for future simulation under representative concentration pathways (RCP) 4.5 and 8.5 scenarios.

2.2 | Agronomic management

Corn was planted on April 21 for all simulation years (close to the median of corn planting window over the area) at 76-cm row spacing and at a rate of 6.5/8.4 plants m⁻² for rainfed/irrigated conditions, respectively. The corn harvest was set on October 20 of each year. Cereal rye (*Secale cereale* L.) was drilled after corn harvest (i.e., on October 21) at a depth of 3 cm and a rate of 300 seeds m⁻² and terminated 10 days before corn planting (i.e., April 11) to minimize N immobilization due to CC decomposition and allow soil moisture recharge (Oliveira et al., 2019; Redfearn et al., 2018). All CC residue was set to remain on the field after termination. To determine the optimum amount of corn residue to be retained without compromising corn yield, we conducted a preliminary set of simulations with different rates of residue removal (10%–70%) for both rainfed and irrigated corn. Based on the results of these simulations, corn residue removal rates of 20%–40% were selected for rainfed and irrigated corn, respectively.

Corn was fertilized using equally split applications of 180 N kg ha⁻¹ anhydrous ammonia at planting and 30 days after planting (i.e., an approximate time when corn is at V8 stage) at a depth of 10 cm. No fertilizer was applied to the CC. Both corn and CC were under no-till system and planting was performed using “no-till planter” and “no-till drill” for corn and CC, respectively. For irrigated treatments, a uniform total irrigation amount of 160 mm was applied using a lateral move sprinkling system. Irrigation scheduling was performed using an automated growth stage-based algorithm in DSSAT (Lopez et al., 2017), where 160 mm of total irrigation was split into three growth stages: 35 mm during heading, 45 mm during floral initiation, and 80 mm during grain filling stages. For all three stages, at least 5 days were left between irrigation events. No irrigation was applied during the CC growing season.

2.3 | Soil and historical climate data

Soil profile data were collected from the National Cooperative Soil Survey Soil Characterization database (<https://ncsslabdatamart.sc.egov.usda.gov/>). The soil series at the site was Tomek silt loam (fine, smectitic, mesic Pachic Argui-

dolls), and data were available to a depth of 140 cm. Historical daily weather data for an on-site station at ENREEC were acquired from the Nebraska State Climate Office's Nebraska Mesonet (Station ID: MEAD 4S; 41° 10' 12" N, 96° 28' 12" W; <https://meso.net.unl.edu/>). The weather data include daily records of total solar radiation incident on the top of the crop canopy (SRAD), maximum (TMAX) and minimum (TMIN) air temperature, precipitation (PREC), wind speed, and relative humidity.

2.4 | Climate change projections

Climate change projections used in this study were based on coarse resolution global circulation (GCM) output from the Canadian Earth System Model 2 (CanESM2) (Arora et al., 2011) dynamically downscaled using the Canadian Centre for Climate Modelling and Analysis Regional Climate Model 4 (CanRCM4) (Scinocca et al., 2016) under RCP4.5 and RCP8.5 (Vuuren et al., 2011). The downscaled projections were at a spatial resolution of 0.22° × 0.22° and bias-corrected using a multivariate quantile-mapping method against gridMET (Abatzoglou, 2013), gridded daily observational dataset. Climate change projections covering the period 1976–2070 were downloaded from the North American CORDEX archives (Mearns et al., 2017).

To avoid the common issue of overestimated rainy days in climate model outputs, direct model outputs were not used as input to DSSAT. The delta change approach was used, where change factors derived from future and historical projections are added to the observations from weather station to generate projections. The method comprises the following steps: (1) calculate 30-year monthly averages for historical (1976–2005) and future period (2041–2070) for each variable and RCP; (2) calculate monthly delta change for each RCP and variable as the absolute difference between future and historical values in temperature (Equation 1a) and as proportional differences in PREC, SRAD, relative humidity (RH), and WIND (Equation 1b); and (3) apply the delta changes to the current climates from weather stations (Equation (2a),b).

$$\Delta X_i = X_{fi} - X_{hi} \quad (1a)$$

$$\Delta X_i = (X_{fi} - X_{hi})/X_{hi} \quad (1b)$$

$$X_{dci} = X_{obsi} + OX_i \quad (2a)$$

$$X_{dci} = X_{obsi} + OX_i \times X_{obsi} \quad (2b)$$

where ΔX_i is the delta change, X_{hi} is the 30-year mean of the variable in the current climate, X_{fi} is the 30-year mean of the variable in the future climate, X_{obsi} is the current climate

from weather stations, and $X_{dc,i}$ is the downscaled future climate at weather station of each RCP in the month i .

An atmospheric carbon dioxide (CO_2) concentration of 380 ppm was used for HIST, while concentrations of 495 and 578 ppm were used for mid-century (2041–2070) under RCP4.5 (Clarke et al., 2007; Wise et al., 2009) and RCP8.5 (Riahi et al., 2007) scenarios, respectively. The CO_2 levels for RCP4.5 and RCP8.5 were averages of concentrations for the three decades (i.e., 2041–2050, 2051–2060, and 2061–2070) reported on RCP database version 2.0.5.

2.5 | Statistical analysis

The performance of CC was assessed using CC biomass, corn yield, total water in the soil profile (SW), plant available water (PAW), surface runoff, N leached through subsurface flow, and total SOC in soil profile. The SW and PAW are generated on daily time steps by the model, and values at the day of termination were used for comparison. Surface runoff and N leached cumulative of daily values at the end of the growing season were used. Total SOC for the entire soil profile at the end of the corn growing season for each year was used to compare trend among treatments, and SOC value for the final year of the 30-year simulation was used to compare change over a 30-year period. The statistical significance of differences in long-term mean between treatments for different parameters such as corn yield and CC biomass was estimated using a Student's t -test ($p < 0.05$). The Theil–Sen method and the Mann–Kendall test were used to estimate linear trend in SOC stock and determine trend significance, respectively (trend manken; NCL version 6.5).

3 | RESULT AND DISCUSSION

3.1 | Projected changes in climate

Under RCP4.5, PREC was projected to increase for all months except during the fall season ($\sim 20\%$ reduction in September and October). Under RCP8.5, reduction in PREC is limited to September, and unlike RCP4.5, PREC is projected to increase in November and decrease during January. In addition, the slight increase in PREC during summer months under RCP4.5 ($\sim 5\%$ on average) is projected to increase further ($\sim 14\%$) under RCP8.5 scenario. The increase in TMAX ranged from 1.16°C in May to 4.7°C in September for RCP4.5 and from 2.3°C in April to 5.2°C in September for RCP8.5. Similarly, the increase in TMIN ranged from 1.5 to 4°C and 2.3 to 4.8°C under RCP4.5 and RCP8.5, respectively. Overall, the fall season showed the largest increase in temperature, while the spring season showed the least increase. Projected changes

in monthly PREC, TMAX, and TMIN for RCP4.5 and RCP8.5 are provided in Table S1.

3.2 | Changes in cover crop biomass

The mean CC biomass during the 30-year HIST rainfed simulation was 941 kg ha^{-1} (Figure 1a) and ranged from 91 to 2961 kg ha^{-1} . Simulated biomass fell below 300 kg ha^{-1} in 5 out of 30 years owing to anomalously cold temperatures and/or low precipitation during CC growing (especially during the second half of the growing season). This is evident from correlation coefficient between CC biomass and mean January–April temperature exceeding 0.5 ($p < 0.05$). CC biomass was most sensitive to temperature in March when plants began rapid growth after winter dormancy.

The RCP4.5 and RCP8.5 scenarios created more favorable conditions for CC growth, with 287% and 230% increase in mean CC biomass, respectively (Figure 1a). The potential factors for the sharp increase in biomass include increased rates of photosynthesis/increased rate of growth induced by elevated CO_2 concentration, reduced transpiration, and an increase in precipitation ($\sim 30\%$ increase in December–April months). Except for 2011/2012 CC growing season, CC has not reached to the end of vegetative stage at time of termination under HIST conditions. The 2011/2012 CC season was characterized by warmer than average temperatures (e.g., TMAX for December, January, February, and March in 2011/2012 was 1.5 , 4.8 , 1.2 , and 10°C warmer than long-term mean, respectively) and anomalously high precipitation in February (42.5 mm compared to long-term average of 15 mm). On the contrary, under RCP4.5 scenario, CC has reached (or passed) the end of vegetative stage for 25 out of 30 simulation years and reached the end of ear growth stage for 9 out of 30 years at the time of termination. For RCP8.5, 27 out of 30 and 10 out of 30 years have reached the end of vegetative and ear growth stages, respectively.

Under irrigated conditions, the 30-year average CC biomass was 2422 and 2292 kg ha^{-1} for RCP4.5 and RCP8.5 scenarios, respectively. These amounts to a 230% and 220% increase compared to the 720 kg ha^{-1} during HIST periods. The difference between RCP4.5 and RCP8.5 was slightly lower compared to the rainfed condition because of the slightly higher residual soil moisture after corn harvest that minimizes stress induced by higher temperature. It can also be noted that rainfed treatment has a considerably higher CC biomass than irrigated treatment. This is attributed to the lower amount of residual N in the soil available for CC because of the higher N uptake by irrigated corn associated with higher water use (Figure S1).

The increase in CC biomass under RCP scenarios will enhance some of CC benefits, such as improving SOC.

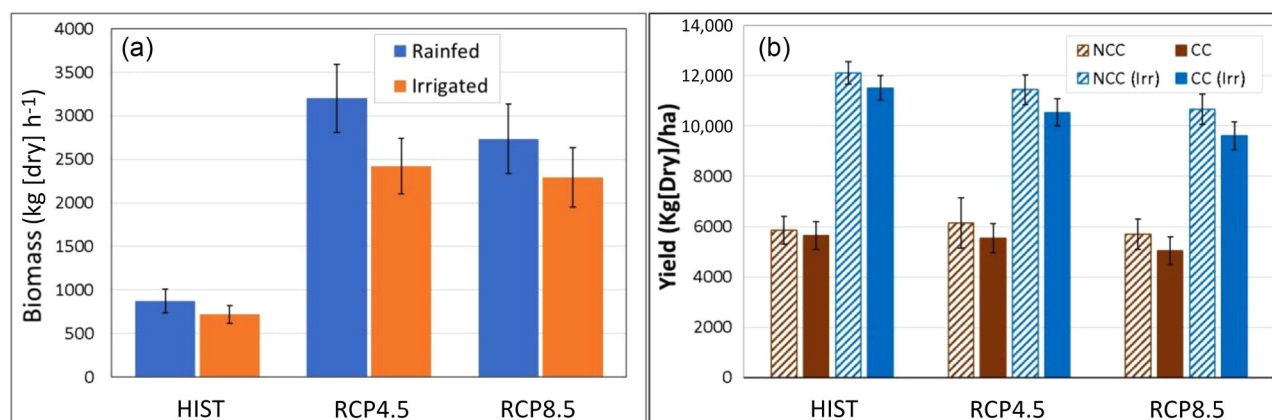


FIGURE 1 (a) Cover crop biomass (kg [dry] ha⁻¹) for rainfed (blue) and irrigated [Irr] (orange) conditions and (b) corn yield (kg [dry] ha⁻¹) for no cover crop (NCC; pattern) and cover crop (CC; solid) treatments under rainfed (brown) and irrigated (blue) conditions under historical simulations, representative concentration pathways (RCP) 4.5, and RCP8.5 scenarios at the Eastern Nebraska Research, Education, and Extension Center (ENREEC) site. Black lines show standard error bar.

However, CC reaching its later growth stages during termination results in tradeoffs that include (1) increased competition with corn due to increased water and nutrient demand at CC later growth stages; (2) reduction in biomass quality (i.e., increase in C:N ratio with growth stage) that will result in higher N immobilization; and (3) reduced CC termination efficiency as herbicide efficacy decreases with cereal rye growth stage. These suggest the need for CC termination date earlier than April 10 and increasing the 10-day gap between CC termination and corn planting to facilitate soil moisture recovery.

3.3 | Soil organic carbon

Total SOC for the NCC treatment during HIST period increased at a rate of 0.614 and 0.789 Mg ha⁻¹year⁻¹ ($p < 0.05$), and total SOC stock by the end of the 30-year simulation period was 181.65 and 188.11 Mg ha⁻¹ for rainfed and irrigated conditions, respectively (Figure 2c,d). The irrigated treatment had a 3.6% ($p < 0.05$) higher SOC stock and increased at a rate 28.5% (0.175 Mg ha⁻¹year⁻¹) faster than rainfed, owing to the 42% (3167 kg ha⁻¹) more corn above-ground biomass. Under RCP scenarios, SOC for NCC treatment also showed an increasing trend ($p < 0.05$), but at a ~14% and ~10% slower rate than HIST scenario under rainfed and irrigated conditions, respectively. Consequently, SOC stock at the end of the 30-year simulation was ~1% (1.75 Mg ha⁻¹) and ~1.6% (3.1 Mg ha⁻¹) lower than HIST period under rainfed and irrigated conditions, respectively. Under rainfed conditions, the rate of increase in SOC was similar among HIST and RCP scenarios during the first two decades of simulation, but at the third decade, SOC increased at a faster rate under HIST scenario. Under irrigated conditions, SOC rate

was higher for HIST for majority of the simulation period (2a and b).

It should also be noted that the comparable mean SOC stock and rate of increase under HIST and RCP scenarios were despite the more than 22% projected increase in corn biomass under RCP scenarios. This was mainly attributed to increased rate of SOC loss due to accelerated organic matter decomposition induced by increased temperature and soil moisture under RCP scenarios (Johnson et al., 2006; Joshi et al., 2023; Kirschbaum, 2006; Moyano et al., 2013; Wang et al., 2016). This is evident from 9.5% (5%) increase in mean cumulative seasonal CO₂ emissions from soil organic matter decomposition in RCP scenarios compared to HIST periods under NCC rainfed (irrigated) treatments (Figure S7). The amount of corn biomass increase was not large enough to offset decomposition for SOC to increase at a rate similar to or higher than HIST period.

The introduction of CC under rainfed condition resulted in a 14.5% (0.089 Mg ha⁻¹year⁻¹), 44.7% (0.237 Mg ha⁻¹year⁻¹), and 40.8% (0.214 Mg ha⁻¹year⁻¹) rise in the rate at which SOC was increasing (Figure 2d), and thus, a 1.9%, 5.5%, and 5.1% more SOC stock than NCC by the end of 30-year simulation for HIST, RCP4.5, and RCP8.5 scenarios, respectively (Figure 2c). Although CC has resulted in a 2%, 6.5%, and 7.7% ($p < 0.05$) reduction in corn above ground biomass, the additional residue from CC (Figure 1a) resulted in a proportional net increase in SOC. Although the impact of CC under irrigation was smaller compared to rainfed, it resulted in a 4.7% (0.037 Mg ha⁻¹year⁻¹), 25.7% (0.18 Mg ha⁻¹year⁻¹), and 23.9% (0.171 Mg ha⁻¹year⁻¹) improvement in the rate at which SOC increased from year to year and 1.6%, 4.2%, and 3.7% more SOC stock than NCC by the end of 30 years under HIST, RCP4.5, and RCP8.5 scenarios, respectively. The relatively slower rate of SOC

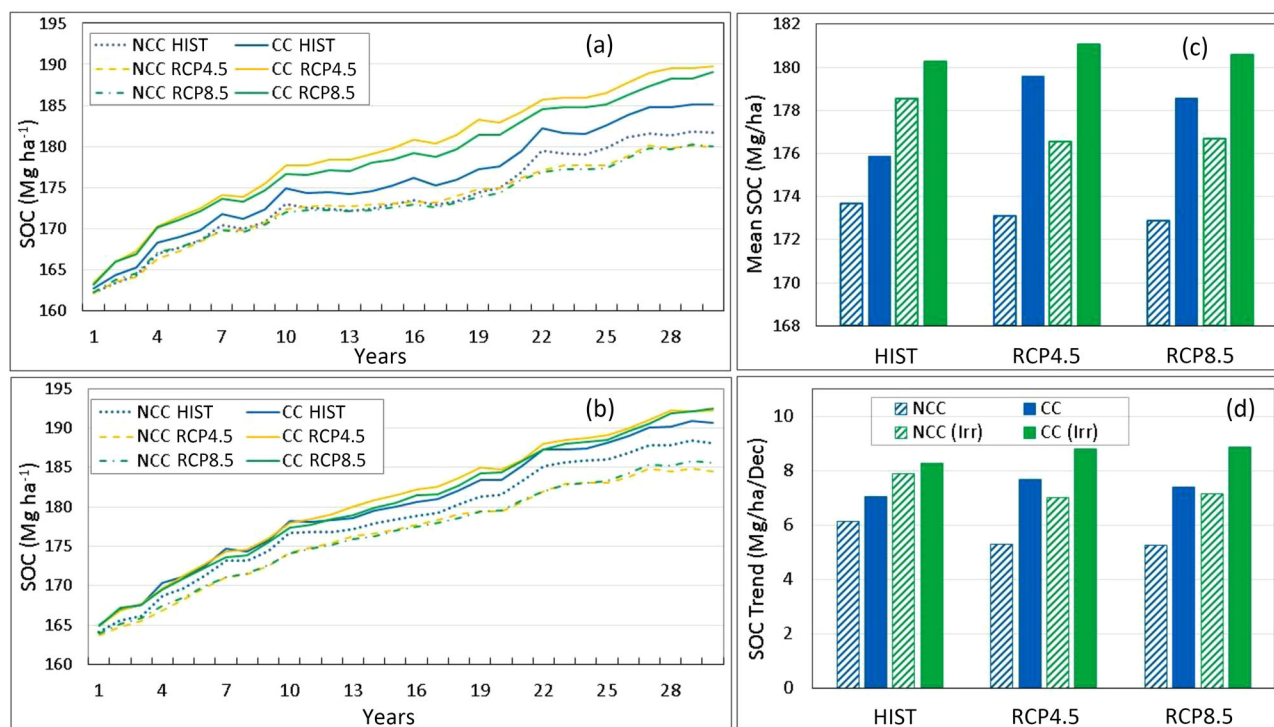


FIGURE 2 Time series of total soil organic carbon (SOC) in soil profile (depth = 150 cm) for (a) rainfed, (b) irrigated conditions, (c) total SOC at the end of the 30-year simulation period, and (d) SOC trend ($\text{Mg ha}^{-1} \text{ year}^{-1}$) ($p < 0.05$) for historical simulations (HIST), representative concentration pathways (RCP) 4.5, and RCP8.5 scenarios at the Eastern Nebraska Research, Education, and Extension Center (ENREEC) site. CC, cover crop; NCC, no cover crop.

increase for irrigated CC compared to rainfed was associated with smaller amount of CC biomass and higher rate of soil organic matter decomposition under irrigated conditions (Figure 2).

3.4 | Soil hydrology and water availability

We hypothesized that CC would deplete soil moisture during spring compared to NCC. A comparison of SW at the time of CC termination during HIST period showed a 6% (27 mm) reduction in SW in CC treatment compared to NCC. Soil water was further reduced by 12% (55 mm) and 13% (60 mm) under RCP4.5 and RCP8.5 scenarios, respectively. The reduction in SW due to CC becomes even more pronounced when comparing PAW which exhibited 22% (27 mm), 38% (56 mm), and 46% (60 mm) reduction under HIST, RCP4.5, and RCP8.5 scenarios, respectively. The volumetric water content in the top 41 cm of the soil profile (Figure 3) also showed a similar reduction in moisture resulting from CC.

As mentioned in the earlier section, a 10-day period was left between CC termination and corn planting to allow soil moisture recovery. A comparison of soil moisture at CC termination and corn planting showed that the 10-day period helped in reducing the deficit caused by CC. For example, for CC treatment under rainfed conditions, PAW at corn planting was

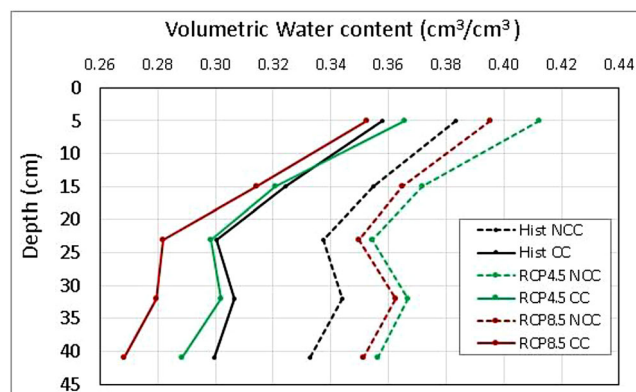


FIGURE 3 Average volumetric water content ($\text{cm}^3 \text{ cm}^{-3}$) by soil layer at cover crop termination for no cover crop (NCC; dashed) and cover crop (CC; solid) under historical simulations, representative concentration pathways (RCP) 4.5, and RCP8.5 scenarios for rainfed corn.

14%, 20%, and 26% higher than at CC termination. In addition, more soil water (in terms of PAW) was stored during this 10-day period in CC than NCC owing to improved soil properties (Table S2). For instance, PAW at corn planting for CC under rainfed condition was 19%, 33%, and 39% lower than NCC compared to 22%, 38%, and 46% during CC termination under HIST, RCP4.5, and RCP8.5 scenarios, respectively.

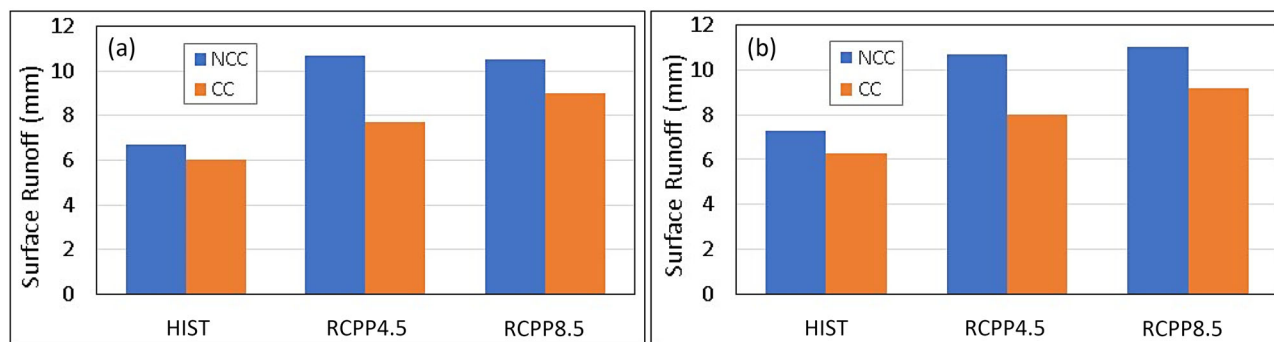


FIGURE 4 Cumulative seasonal surface runoff during the cover crop growing season averaged over 30-year simulation period for (a) rainfed and (b) irrigated conditions (averaging performed on years with non-zero runoff). CC, cover crop; NCC, no cover crop.

We also hypothesized that if the CC had caused accumulated improvements in soil properties (i.e., surface residue cover, aggregation, soil organic matter, and porosity) over time, there could be evidence of greater soil moisture during corn growing season. A comparison of PAW for rainfed condition at the end of the corn growing season showed that CC has 5% (2.1 mm), 22% (5.6 mm), and 15% (3.9 mm) more PAW than NCC. Basche, Kaspar et al. (2016) also found a similar result from a long-term experiment where CC treatment had significantly higher ($p < 0.05$) soil water storage at the 0- to 30-cm depth when compared to the NCC treatment during the cash crop growing season, and CC significantly increased the field capacity water content by 10%–11% and plant available water by 21%–22%.

During HIST period, CC resulted in 10.4% (rainfed) and 13.7% (irrigated) reduction in cumulative seasonal surface runoff during the CC growing season. For NCC treatment, runoff was projected to increase by 53% (3.7 mm) on average (Figure 4) due to the projected increase in rainfall intensity that led to quicker ponding at the soil surface (Morán-Ordóñez et al., 2020; Wang et al., 2020). As in HIST period, CC reduced surface runoff by 27% (15%) under RCP4.5 (RCP8.5) scenarios owing to the increased cover biomass. In addition to CC growing season, CC also reduced runoff by about 3.5% under RCP scenarios during corn growing season by improving the soil's physical quality.

CC impact on soil evaporation showed a similar pattern as in surface runoff. CC has reduced total seasonal soil evaporation during CC season (November–April) by 17.8%, 49.3%, and 47.0% under HIST, RCP4.5, and RCP8.5 scenarios, respectively. Percentage reduction in future scenario is significantly higher because of higher temperature, higher evaporative demand of atmosphere, and high biomass that avoids nearly half of soil evaporation. The reduction in soil evaporation also continues further into the corn growing season after CC is terminated as the residue provides additional soil coverage and reduces light exposure, thus limiting evaporation. On average, CC reduced soil evaporation during the corn growing season by 25.7%, 61.6%, and

51.0% for HIST, RCP4.5, and RCP8.5 scenarios, respectively (Figure S5).

3.5 | Corn yield

The long-term average corn yield for CC treatment during HIST period was lower than NCC by 3.5% and 4.9% for rainfed and irrigated corn, respectively ($p < 0.05$) (Figure 1b). These yield differences resulted from low grain yield during a few growing seasons (e.g., 2002, 2006, 2009, and 2018) with anomalously low precipitation at the end of CC and/or start of the corn growing seasons. This is expected as precipitation amount is one of the leading factors that affects the performance of CCs and their impacts on subsequent crops (Blanco-Canqui et al., 2015). For the CC treatment, the effect of low precipitation was exacerbated by soil moisture depletion by the CC. Except for these years, simulated yield was comparable among NCC and CC treatments. On-field and simulation-based studies over the region (e.g., Basche, Archontoulis, et al., 2016; Basche, Kaspar, et al., 2016; Kaspar & Bakker, 2015; Malone et al., 2017) have also found similar corn yield differences between NCC and CC treatments. However, as in our study, some of these studies have reported a significant interaction between CC impact on subsequent corn yield and year (precipitation amount) where reduction in yield was relatively higher during years with low rainfall amounts.

It can also be noted that the reduction in corn yield due to CC increased under both RCP4.5 and RCP8.5 scenarios (i.e., 8.9% and 10.8%, respectively) relative to HIST period ($p < 0.05$). This is mainly the result of (1) soil moisture depletion by CC that showed more than 200% increase in biomass at the time of termination; (2) reduced net N mineralization due to increased carbon to nitrogen ratio (C:N ratio) of CC biomass; and (3) reduction in N availability for corn due to increased uptake by CC (Figure S3). Several studies (e.g., Joshi et al., 2023; Marcillo & Miguez, 2017) have shown the impact of late termination on corn yield. To assess if the

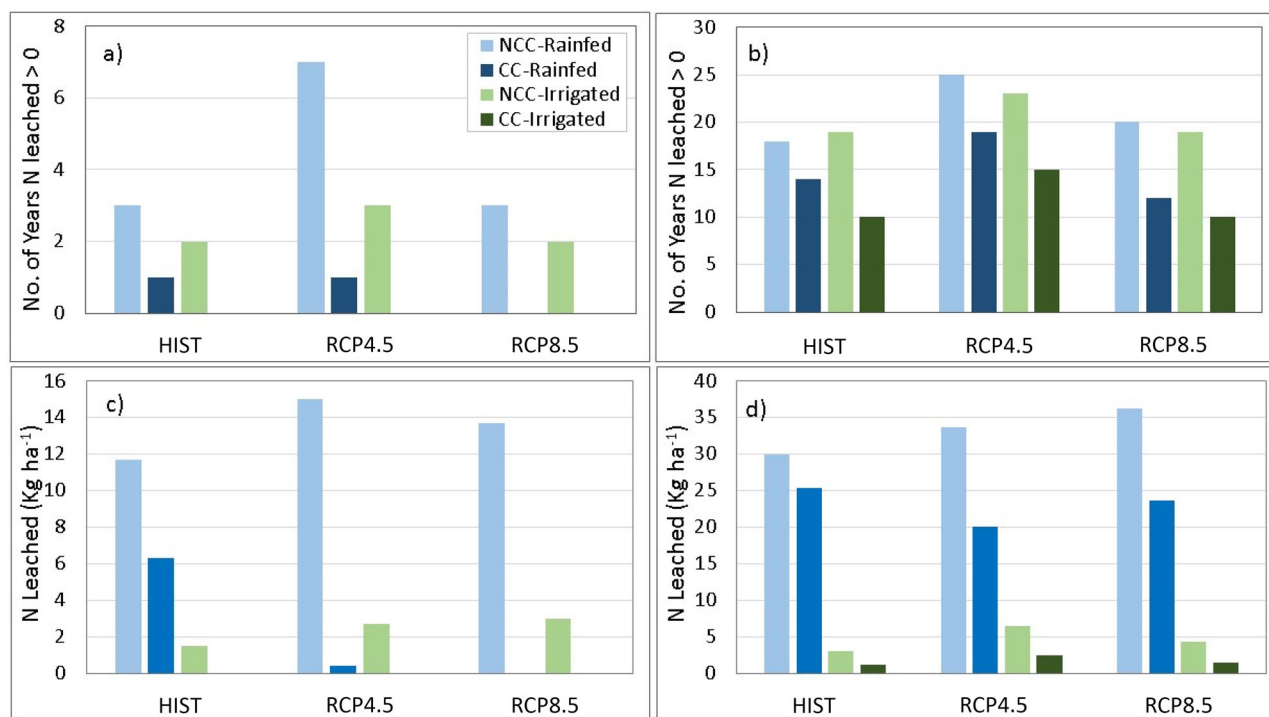


FIGURE 5 Number of years with a non-zero nitrogen (N) leached during (a) cover crop, (b) corn growing seasons and average N leached during (c) cover crop and (d) corn growing seasons with rainfed and irrigated conditions under historical simulations, representative concentration pathways (RCP) 4.5, and RCP8.5 scenarios. CC, cover crop; NCC, no cover crop.

10-day gap between CC termination and corn planting was sufficient, we conducted HIST with 5–20 days gap and found statistically significant ($p < 0.05$) reduction in corn yield only when gap was 5 days or shorter (not shown). This is likely attributed to the study site's location in a notably humid part of Nebraska. However, for RCP4.5 and RCP 8.5, results suggest that 10 days gap were too short for soil moisture to recover for corn planting.

Under the projected climate change conditions, mean corn yield is projected to decrease for irrigated treatments, while changes for rainfed treatments were not statistically significant ($p < 0.05$) (Figure 1b). The reduction in corn yield was higher for CC than NCC treatments (9.4% vs. 3.7%) and higher for irrigated corn compared to rainfed (10.6% vs. 2.5%). Furthermore, yield reduction in all treatments became more severe under RCP8.5 in comparison to RCP4.5 (2.7% vs. 10.4%).

One possible reason for yield reduction is the negative impact of high temperatures during grain filling period that is considerably above the optimum temperature (i.e., 22.5°C) for maximum dry matter accumulation in kernels (Wilhelm et al. 1999). This is evident from comparison of kernel weight (Figure S2), which showed a reduction of 25% (20.6%) under RCP4.5 and 30% (25.4%) under RCP8.5 scenarios compared to HIST for rainfed (irrigated) conditions. A growth chamber study by Badu-Apraku et al. (1983) showed a 42% loss

in grain weight per plant when day (night) temperature from post-silking to maturity was increased from 25 (15)°C to 35 (15)°C, 15°C rise in average daily temperature. Wilhelm et al. (1999) also found a 7% reduction in kernel dry weight with a 7.5°C increase in grain-filling temperature from 23.5°C to 31.8°C. In addition, the optimum temperature for corn growth in CERES-Maize model in DSSAT is set at 34°C, and with projected change in temperature, there are considerably more days during the growing season with temperature above 34°C that will likely put more stress on corn physiology leading to a possible yield reduction.

3.6 | Nitrogen leaching

Adoption of CC has resulted in substantial reduction in N leached under all treatments (i.e., rainfed/irrigated conditions and HIST/RCP scenarios) during both CC and corn growing seasons. During CC growing season, CC has reduced number of years with non-zero N leached (out of 30-year simulation) from 3 to 1 (2 to 0) for HIST rainfed (irrigated) conditions (Figure 5a). Under climate change conditions, there were almost no years with non-zero N leached for CC treatment. Similarly, during the corn growing season, CC reduced the number of years with non-zero N leached by 22%, 24%, and 40% under rainfed conditions and by 47%, 35%, and 47%

under irrigated conditions for HIST, RCP4.5, and RCP8.5 scenarios, respectively (Figure 5b).

In terms of amount, CC reduced N leached by 46% (5.4 kg ha^{-1}) and 76% (1.5 kg ha^{-1}) during CC season for HIST under rainfed and irrigated treatments, respectively (Figure 5c). Similarly, N leached during the corn growing season was reduced by 15% (5 kg ha^{-1}) and 63% (2 kg ha^{-1}) for HIST under rainfed and irrigated treatments, respectively (Figure 5d). The average N leached (on non-zero years) for NCC treatments under RCP4.5 (RCP8.5) were found to be around 15 kg ha^{-1} (13.7 kg ha^{-1}) for rainfed conditions and around 3 kg ha^{-1} for irrigated conditions, and adoption CC entirely eliminated N leached through subsurface flow. The high N leached reduction in future scenarios compared to HIST was due to increased CC N uptake. For example, N uptake during CC season increased by 137% (122%) for RCP4.5 (RCP8.5) compared to HIST periods for rainfed conditions (Figure S1).

The reduction of N leached with CC is mainly due to an increased retention of N in the CC biomass, the reduction of the $\text{NO}_3\text{-N}$ concentration in the percolating water, and/or the reduction of the percolating water flux (Kramberger et al., 2014). These mechanisms can be directly attributed to the reduction in N leached during the CC growing season. However, for the corn growing season, as there are no live CCs on the field, the reductions in N leached are likely the result of changes in soil physical properties resulting from CC biomass (above and below ground) that reduces fluxes of percolating water.

Comparing N content in CC above ground biomass, we found 30-year average N content of 1.24%, 0.66%, and 0.67% for HIST, RCP4.5, and RCP8.5 scenarios. The N content for RCP scenarios is lower as N content decreases (C:N ratio increases) with growth stage (Holste et al., 2016), and CC has progressed to its later stages due to accelerated growth induced by increased temperature (Figure S4). Furthermore, despite having three times more aboveground biomass than HIST, RCP4.5 and RCP8.5 scenarios were found to have a cumulative seasonal average net N mineralization (N mineralization-N immobilization) relatively close (i.e., 72, 89, and 80 kg ha^{-1} for HIST, RCP4.5, and RCP8.5, respectively). Holste et al. (2016) investigated whether the age of the CC affected the C:N ratio and N content in the aboveground biomass at a similar location in Nebraska and found C:N ratio of 25:1 (22:1) and N content 1.6% (2.1%) for early (late) planted cereal rye. These differences were found to have further implications on N dynamics (i.e., N mineralization and immobilization) during the corn season after CC is terminated. This suggests that terminating CC early may serve better under climate change conditions in terms of increasing N available to corn.

4 | CONCLUSION

In this study, we conducted long-term simulations using DSSAT to assess the performance of cereal rye CC in terms of subsequent corn yield, CC biomass, soil hydrology, N leached, and SOC under historical (1991–2020) and future climate conditions (2041–2070) in eastern Nebraska. Weather data during historical period were drawn from Mead Station, while climate change projections were based on CanESM2 GCM dynamically downscaled using CanRCM4 under RCP4.5 and RCP8.5. Our simulation results showed that CC had no significant impact on corn yield under HIST and RCP scenarios for rainfed and irrigated treatments. The change in climate has created a more favorable condition for CC growth and resulted in more than 200% increase in CC biomass compared to the historical average biomass of around 871 kg ha^{-1} (720 kg ha^{-1}) for rainfed (irrigated) conditions. As a result, CC managed to eliminate N leached through subsurface flow during the CC growing season under RCP scenarios compared to an average reduction of 60% (7 kg ha^{-1}) during HIST period.

In terms of soil moisture, CC resulted in 6% (27 mm) reduction in total water in the soil profile and 22% (27 mm) reduction in PAW compared to NCC during HIST period. These reductions further increased to 12% (55 mm) and 13% (60 mm) for total water in the soil profile and 38% (56 mm) and 46% (60 mm) for PAW under RCP4.5 and RCP8.5 scenarios, respectively. However, we found that the 10-day period between CC termination and corn planting was able to slightly recover soil moisture. In addition, moisture recovery under CC treatment was higher than NCC owing to soil property improvements from CC. CC also managed to reduce cumulative seasonal surface runoff and soil evaporation during CC and corn growing seasons under both HIST and RCP scenarios. Without CC, loss of SOC due to increased rate of soil organic matter decomposition resulted in reduction in the rate of SOC buildup in the future, despite higher amount of corn biomass. Such information can give insights on likely consequences of climate change and inform crop-management improvement programs, risk management, and strategic planning within farm-scale operations.

AUTHOR CONTRIBUTIONS

Girma Birru: Conceptualization; funding acquisition; investigation; methodology; supervision; validation; writing—original draft; writing—review and editing. **Andualem Shiferaw:** Conceptualization; data curation; formal analysis; investigation; methodology; software; validation; visualization; writing—original draft; writing—review and editing. **Tsegaye Tadesse:** Conceptualization; funding acquisition; investigation; project administration; resources; super-

vision; writing—review and editing. **Brian Wardlow:** Conceptualization; funding acquisition; project administration; resources; supervision; writing—review and editing. **Virginia L. Jin:** Conceptualization; funding acquisition; methodology; project administration; resources; supervision; writing—review and editing. **Marty R. Schmer:** Conceptualization; funding acquisition; investigation; project administration; resources; supervision; writing—review and editing. **Tala Awada:** Conceptualization; project administration; supervision; writing—review and editing. **Tulsi Kharel:** Conceptualization; validation; writing—review and editing. **Javad Iqbal:** Conceptualization; writing—review and editing.

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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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