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Abstract: Cover crops (CCs) offer ecosystem benefits, yet their impact on subsequent crop yields varies with climate, soil, and management practices. Using the Decision Support System for Agrotechnology Transfer (DSSAT) at the University of Nebraska-Lincoln’s Eastern Nebraska Research, Education, and Extension Center (ENREEC), we identified optimal cereal rye management strategies focusing on planting, termination, and the intervals between CC termination and corn planting. Results showed minimal impact of CC management variations on corn yield, underscoring corn’s resilience to management changes. Delayed planting notably decreased CC biomass, nitrogen uptake, and biomass nitrogen content on average by 8.8%, 11%, and 9.2% for every five-day delay from 25 September. Every 5-day increase in the interval between CC termination and corn planting reduced biomass by 19.3%. Conversely, each 5-day delay in CC termination from 10 September to 10 October increased biomass by 30%, enhancing SOC accumulation. SOC changes over the 30-year simulation ranged from 5.8% to 7.7%, peaking with late May terminations. The earliest termination showed the highest nitrogen content in biomass (3.4%), with the lowest (0.69%) in mid-May. Our results demonstrate that strategic CC management supports soil health without negatively impacting corn yield in Eastern Nebraska, providing valuable insights for farmers and practitioners aiming to implement sustainable CC practices while preserving crop productivity.

Keywords: crop modeling; cover crops; cereal rye; DSSAT; ecosystem services

1. Introduction

In the pursuit of sustainable and resilient agricultural systems, the integration of cover crops has become increasingly recognized for its potential to enhance soil health and optimize crop productivity [1–6]. Cereal rye (*Secale cereale* L.), due to its robust adaptability, has emerged as a popular choice within Nebraska’s corn production framework, prized for its straightforward fall establishment, resilience over winter, and vigorous growth in early spring [7,8]. However, to harness the full spectrum of benefits from cereal rye and

minimize the negative impact on main crop yield, it is crucial to understand and apply management practices specifically tailored to local conditions.

The impact of CC planting date is one such critical aspect under examination. Several studies (e.g., [9–13]) have demonstrated how planting dates can influence biomass accumulation and the subsequent soil water and nitrogen dynamics, thereby affecting the following main crop's performance. By optimizing planting dates, farmers can maximize the ecological benefits rendered by CCs without compromising the yield of subsequent main crops. Equally important is the determination of the optimal CC termination date that directly influences the amount of biomass produced and its subsequent effects on soil properties and main crop yields. Several studies (e.g., [14–16]) have underscored the balance between maximizing CC growth for soil benefits while ensuring THAT it does not adversely impact the subsequent main crop through excessive soil moisture depletion or nutrient competition with delayed termination. Similarly, the interval between CC termination and main crop planting is another critical element shaping the effectiveness of cover cropping approaches and their influence on the subsequent crop's yield. The length of this interval not only affects the availability of soil moisture, essential for the germination and early growth of the main crop, but also impacts key agricultural factors such as nutrient cycling, the regulation of soil temperature, and the management of pests and weed populations [17].

Although the cited studies underscore the significance of CC planting date, termination date, and termination-planting interval on cover cropping outcomes and their impact on the main crop, it is noteworthy that their findings exhibit variability, underscoring the premise that optimal CC management practices necessarily differ across contrasting environments influenced by distinct climate, soil, and related factors [15]. This variability highlights the critical need for region-specific research to tailor CC management strategies that accommodate the unique environmental conditions of a given area. Although field experiments stand as the gold standard for agricultural research, they are not always feasible for exploring all potential scenarios due to constraints such as high costs, extensive time requirements, and the practical challenges of replicating diverse environmental conditions. In this context, integrating field experiments with crop simulation models serves as an effective tool to optimize CC management strategies. By simulating diverse environmental and management scenarios, this approach not only aims to maximize the benefits of CCs but also minimizes their impact on main crop productivity. Furthermore, crop simulation models are particularly useful, as they facilitate the understanding of mechanistic pathways in cover cropping outcomes by simulating intermediate variables that are typically difficult to measure in field experiments. These experiments often focus only on final variables such as cash crop yield and cover crop biomass, thereby limiting mechanistic insights.

Several studies (e.g., [15,18–22]) have validated the potential use of crop simulation models to dissect the dynamics between CCs and main crops. However, these studies are very few and limited in both technical (i.e., covering only specific aspects of cover cropping) and geographic scope. Thus, much remains to be researched to fully understand and optimize these systems to be an integral part of CC decision-making. Consequently, this study employs the Decision Support System for Agrotechnology Transfer (DSSAT, [23]) crop modeling system to explore three key areas within CC management: the planting date, termination date, and the interval between CC termination and corn planting. This investigation is conducted at ENREEC (Figure 1). Furthermore, this study aims to demonstrate how crop simulation modeling can ideally complement traditional field experiments, providing a robust method for identifying optimal management practices for cereal rye CC within corn production systems.

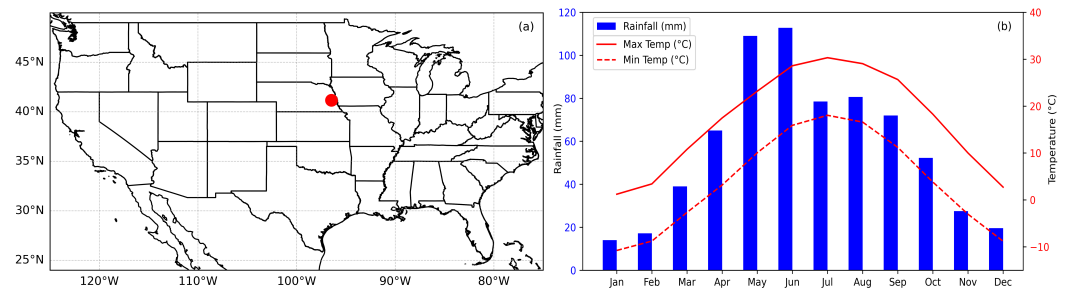


Figure 1. (a) Location of the study site, and (b) monthly climatology of rainfall (mm), minimum and maximum temperature (°C) climatology at the site based on 30-year (1991–2020) data from Mead station (Station ID: MEAD 4S; 41°10′12″ N, 96°28′12″ W).

2. Data and Methods

2.1. Crop Models (and Cultivars)

The CERES-Maize and CERES-Wheat crop models in DSSAT version 4.7 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. In this study, previously calibrated and validated cultivar-specific parameters for 111-day maturity corn hybrid (i.e., P1197) and Elbon cereal rye variety were used [18]. Model calibration/validation for P1197 was undertaken using grain yield, unit kernel weight, kernel number, and emergence date, while for the Elbon cereal rye variety, biomass and biomass N content data collected from 10 sites across the United States were used. For further details on calibration/validation statistics and final cultivar-specific parameters for P1197 corn hybrid and Elbon cereal variety, see [18].

DSSAT generates simulation outputs for crop growth and dynamic soil parameters on daily timescales as well as aggregated values at the season's end for both CC and the main crop. This study focused on a select subset of parameters to evaluate the effects of management practices on crop outcomes and soil health. For cover crops, we examined biomass at termination, biomass nitrogen content, and growth stage; these parameters were critical in assessing the impacts of delayed termination on nitrogen dynamics in the soil, including total soil net mineralization and immobilization during the corn growing season. Furthermore, CC growth stage and canopy height at termination were used to assess termination efficiency, which is strongly influenced by these parameters. For corn, yield at harvest maturity was considered alongside determinants such as unit kernel weight, kernel number per cob, and the duration of the grain-filling phase, which are crucial for understanding the implications of shifts in climatic conditions due to delayed cover crop termination. Total SOC changes were analyzed over a 30-year simulation period to capture the long-term effects of different termination dates on SOC accumulation. Soil moisture within the top 56 cm at corn planting was also studied to understand the impact of the intervals between CC termination and corn planting on soil moisture availability.

2.2. Crop Model Input Data

The crop model simulations were conducted under a rainfed continuous corn cropping system with (CC) and without (NCC) winter cereal rye cover crop at ENREEC, Mead, NE. The simulations cover the period 1991–2020. Soil profile data for the site were collected from the National Cooperative Soil Survey Soil Characterization database (<https://ncsslabsdatamart.sc.egov.usda.gov/> (accessed on 10 May 2023)). The soil series at the site was Tomek silt loam (fine, smectitic, mesic Pachic Argiudolls), and data were available to a depth of 140 cm. Historical daily weather data for an on-site station (Figure 1) at ENREEC were acquired from the Nebraska State Climate Office's Nebraska Mesonet (<https://mesonet.unl.edu/> (accessed on 10 May 2023)). 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.

2.3. Agronomic Management Scenarios

For all simulations, corn was planted using a “no-till planter” at a depth of 5 cm, 76 cm row spacing, and at a rate of 6.5 plants m^{-2} . Corn was fertilized using equally split applications of 75 N kg ha^{-1} anhydrous ammonia at planting and 75 N kg ha^{-1} 30 days after planting (i.e., an approximate time when corn is at the V8 stage) at a depth of 10 cm. Cereal rye was planted after corn harvest using a “no-till drill” at a depth of 3 cm and a rate of 300 seeds m^{-2} . No fertilizer was applied to the CC.

2.3.1. Cover Crop Planting Date

To assess the impact of fall planting date on CC performance and corn yield, simulations were run for six planting dates immediately after corn harvest (i.e., 25 September, 30 September, 5 October, 10 October, 15 October, and 20 October). All six simulations had the same CC termination date (i.e., 1 May), corn planting date (i.e., 11 May), and other agronomic management, such as seeding rate, planting depth, fertilizer amount, and application time.

2.3.2. Cover Crop Termination-Corn Planting Interval

The impact of the length of the interval between CC termination and corn planting was assessed for the 11 May corn planting. The intervals considered were 1-, 5-, 10-, 15-, and 20-days before 11 May (i.e., 21 April, 26 April, 1 May, 6 May, and 10 May termination dates).

2.3.3. Cover Crop Termination Date

We tested 15 different termination dates with 5-day intervals starting on 22 March and ending on 31 May. Corn planting for these 15 termination dates was moved accordingly while keeping the 10-day intervals between termination and respective corn planting dates. Termination dates were compared and evaluated based on corn yield, CC biomass, CC growth stage, and CC biomass nitrogen content averaged over a 30-year simulation period (1991–2020).

2.4. Statistical Analysis

To determine if the differences in corn yield, cover crop biomass, and other parameters across the six CC planting dates, fifteen termination dates, and five termination-planting intervals were statistically significant, a one-way Analysis of Variance (ANOVA) was initially conducted. ANOVA is suitable for comparing means across multiple groups simultaneously and is appropriate for identifying if at least one group mean significantly differs from the others in scenarios involving more than two groups. Upon obtaining a significant result from the ANOVA, a Tukey’s Honestly Significant Difference (HSD) test was performed as a post hoc analysis. Tukey’s HSD test was used to conduct pairwise comparisons between group means to specifically identify which means differ from each other while controlling for the Type I error rate associated with multiple comparisons. To assess the impact of CC on subsequent corn yield, paired *t*-tests were conducted for each interval (i.e., 1 day, 5 days, 10 days, 15 days, 20 days) comparing yields between fields with (CC) and without a cover crop (NCC). This approach was chosen to isolate the effect of the cover crop on corn yield by directly comparing the treated and control conditions at each specified termination interval.

3. Result and Discussion

3.1. Cover Crop Planting Date

The overall performance and winter survival of fall-established CCs is strongly affected by the planting date [24]. Planting cereal rye early in the fall led to increased biomass production, primarily attributed to a longer growing period, allowing for better establishment before winter dormancy (Figure 2). The earliest (latest) CC planting date of 25 September (20 October) resulted in the highest (lowest) simulated biomass of 1.92 Mg ha^{-1} (1.202 Mg ha^{-1}), a 37.4% reduction in biomass with 25-day delay in planting date ($p < 0.05$).

For every 5-day delay in planting, CC biomass was reduced on average by 8.8%, with reductions being more pronounced for later planting dates. Several studies (e.g., [24–27]) have documented the impact of different fall planting dates on CC biomass production. For example, in Michigan, [26] found that planting hairy vetch (*Vicia villosa* L.)—a cereal rye CC mix—in late August to early September increased biomass production by 54–65% compared to planting in mid-September. Similar increases in biomass production were observed by [24,27]. Ref. [28] found 29, 51, 69, and 79% declines in cereal rye biomass for 1-, 2-, 3-, and 4-week delays from the critical planting date (mid-August to early October) in Massachusetts.

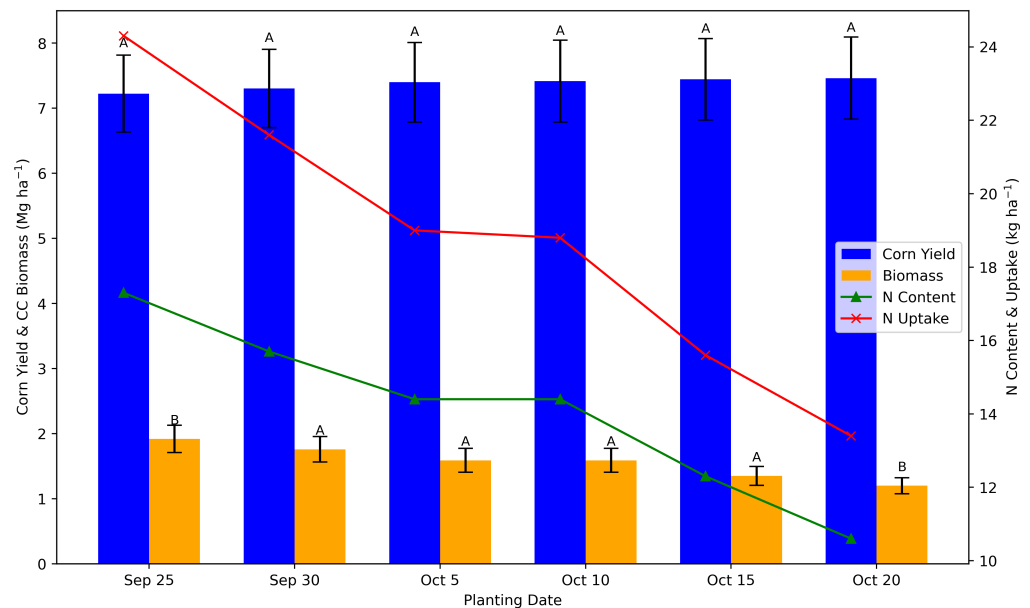


Figure 2. Corn yield (Mg[Dry] ha⁻¹), CC biomass (Mg[Dry] ha⁻¹), CC N uptake (kg[N] ha⁻¹), and CC biomass N content (kg ha⁻¹) for six different planting dates. The bars represent mean values with standard error bars indicating variability within each planting date. Letters above the bars denote significant differences between dates as determined by Tukey’s HSD test, where different letters indicate statistically significant differences ($p < 0.05$).

The reduction in CC biomass due to delayed planting was associated with a significant reduction in N uptake and biomass N content (Figure 2), which in turn will affect N lost through leaching and N availability for the following crop from the decomposing cover crop [10]. Total N uptake by CC showed a gradual reduction with delayed planting with an average reduction of 11% (2.2 Kg N ha⁻¹) for every 5-day delay in planting date starting from 25 September. The earliest planting date (i.e., 25 September) resulted in 24.3 kg N ha⁻¹, while the latest date had an average N uptake of 13.4 kg N ha⁻¹. Consequently, above ground biomass N content at termination followed a similar pattern to N uptake. The earliest (latest) planting date had the highest biomass N content of 17.3 kg (10.6 kg) with an average reduction of 9.2% for every 5-day delay in planting date.

Compared to the effects on CC biomass, the impact of the CC planting date on subsequent corn yield was marginal and did not achieve statistical significance ($p > 0.05$) (Figure 2). The maximum yield difference noted across varied planting dates, particularly between 25 September and 20 October, was 0.238 Mg ha⁻¹. Additionally, each five-day postponement in CC planting correlated with a modest average yield increase of 0.65%. This minimal yield fluctuation for earlier planting dates could potentially be attributed to premature harvest instances. Specifically, simulation data indicated that corn harvested prematurely—before attaining full maturity—occurred in 6, 4, and 2 out of 30 years for 25 September, 30 September, and 5 October planting dates respectively, compared to only once across 30 years for planting dates of 10, 15, and 20 October. This indicates that while

yield differences were not statistically significant, early harvesting due to earlier cover crop planting can pose a risk to corn yield.

3.2. Termination-Planting Interval

Corn Yield

The impact of different termination-planting intervals on corn yield and CC biomass is illustrated in Figure 3 for the 11 May corn planting date. There was a significant reduction in CC biomass with increasing the termination-planting interval, with 0.952 Mg ha^{-1} and 2.256 Mg ha^{-1} for 20- and 1-day intervals, respectively. For every 5-day increase in the interval, CC biomass was reduced by an average of 19.3% (0.33 Mg ha^{-1}). This was expected, as longer intervals between CC termination and corn planting resulted in earlier termination of the rye, allowing less time for rye growth and biomass accumulation.

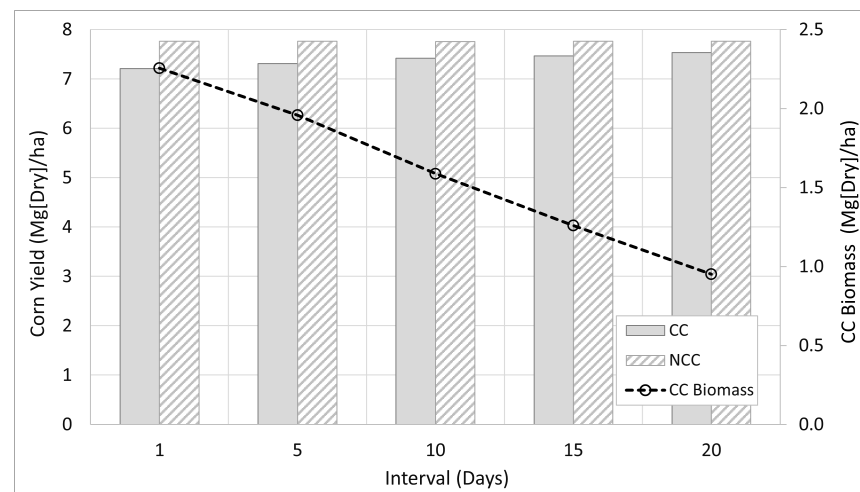


Figure 3. Corn yield (kg[Dry]/ha) and cover crop biomass (kg[Dry]/ha) for five different intervals between cover crop termination and corn planting dates (NCC-corn yield for simulations without cover crop).

However, differences in yield between intervals were minimal. Although the long-term average corn yield exhibited a slight progressive increase from 1- to 20-day intervals, these differences were not statistically significant ($p < 0.05$). The largest difference between intervals (i.e., 20-day vs. 1-day) was only 0.325 Mg ha^{-1} . This is in agreement with the USDA Natural Resources Conservation Service (NRCS) Cover Crop Termination Guidelines ([29]) that recommend terminating CC at or before planting the main crop. Similarly, other studies (e.g., [30,31]) on termination-planting interval have also found little to no negative effect on corn productivity with shorter intervals. However, [30] reported an increased risk of root disease with shorter intervals, which is beyond the capabilities of the modeling system used in this study. The minimal differences in yield suggest that the timing of termination, within the range of days studied, was not a critical factor for corn yield under the conditions simulated.

The rate of increase in yield changed with the intervals, starting at 1.45% when moving from a 1-day to a 5-day interval, then slightly decreasing to 1.43% from a 5-day to a 10-day interval. This increasing rate diminished further to 0.69% from a 10-day to a 15-day interval and slightly rose again to 0.86% from a 15-day to a 20-day interval. The diminishing rate of yield gain could suggest that while there are benefits to extending the termination interval, these benefits may have diminishing returns as the interval lengthens. This might be due to a plateauing effect where the initial changes in termination timing have a more pronounced impact on yield, but as the CC is terminated earlier and earlier, the additional benefits to the corn yield become less significant.

We conducted a regression analysis to quantitatively assess the relationship between yield changes at specified intervals using annual percentage changes in yield between

intervals of 1 day and 5 days, 5 days and 10 days, 10 days and 15 days, and 15 days and 20 days over a 30-year period. The analysis aimed to determine the statistical significance and strength of relationships between earlier interval changes and their impacts on subsequent intervals. The regression model ($R^2 = 0.614$) revealed that approximately 61.4% of the variability in the yield changes between the 15-day and 20-day intervals could be explained by the changes in earlier intervals. Specifically, changes between the 10-day and 15-day intervals demonstrated a strong and statistically significant positive relationship with changes between the 15-day and 20-day intervals (coefficient = 0.912, $p < 0.001$), indicating a robust influence on yield outcomes. Visual inspection of the scatter plots (Figure 4) reinforced these findings, with changes between the 10-day and 15-day intervals showing a clear positive trend, suggesting that increases in this interval significantly impact the yield changes in the subsequent interval. In contrast, changes between the 1-day and 5-day intervals did not show a significant influence on the yield changes in the 15-day to 20-day interval, consistent with its non-significant statistical indicator in the regression analysis. The results underscore the importance of strategic CC termination timing, particularly highlighting the interval between 10 days and 15 days as critical for influencing subsequent yield outcomes. These insights suggest that management practices should focus on optimizing conditions during this interval to potentially enhance yields. Additionally, the variability in yield responses across different intervals indicates that adaptive management strategies, responsive to annual and situational conditions, may be necessary to maximize the yield benefits.

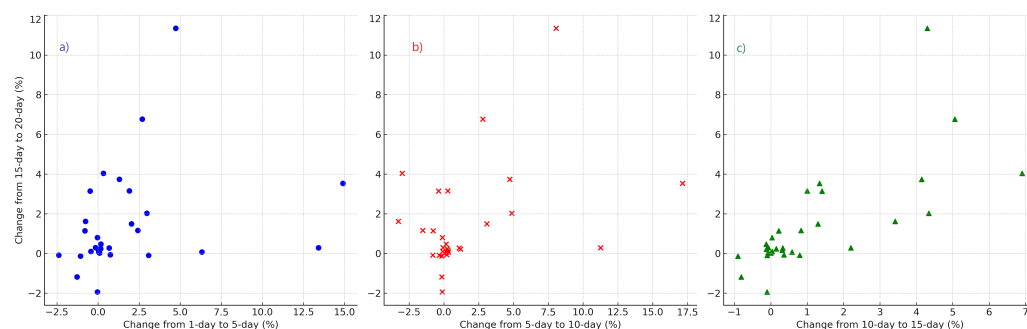


Figure 4. Relationship between CC termination corn planting interval changes and subsequent corn yield changes, (a) change from 1-day to 5-day vs. 15-day to 20-day yield change, (b) change from 5-day to 10-day vs. 15-day to 20-day yield change, and (c) change from 10-day to 15-day vs. 15-day to 20-day yield change.

The corn yields for the five intervals were further compared with respective simulations without cover crop (NCC). The NCC yield was consistently higher than CC across all intervals, with differences increasing in magnitude with the shortening of the termination-planting interval (Figure 3). However, the differences between CC and NCC yields were small (ranging from 0.23 Mg ha^{-1} (3%) for the 20-day interval to 0.56 Mg ha^{-1} (7.2%) for the 1-day interval) and statistically insignificant ($p < 0.05$), suggesting that the use of CC, regardless of termination timing, has a minimal negative impact on corn yield. This could be interpreted as evidence of the successful integration of cover cropping into the corn production system with negligible yield penalties at the study site.

The evaluation of corn yield in relation to the interval between CC termination and corn planting, stratified by seasonal rainfall conditions, presents nuanced insights. The division of the 30-year seasonal rainfall into three categories, below normal (BN), near normal (NN), and above normal (AN), helps contextualize yield responses under varying moisture regimes (Figure 5). Contrary to initial assumptions, the analysis revealed a non-linear relationship between the intervals and corn yield across different rainfall scenarios. Under BN conditions, yield did not consistently decrease with shorter intervals, challenging the expectation that reduced intervals would exacerbate moisture deficits. Notably, the 20-day interval under NN conditions demonstrated the highest yield, which diminishes

progressively towards the shorter intervals, a trend aligning with the conventional wisdom that adequate moisture availability coupled with longer intervals may enhance yield. However, this pattern does not hold uniformly across all scenarios, indicating that other factors beyond soil moisture may influence yield outcomes. In AN years, the interval length had minimal impact on yields, suggesting that in periods of ample rainfall, the CC water consumption has negligible effects on the subsequent corn crop. These findings suggest a degree of flexibility in the timing of CC termination, which could prove beneficial for farmers navigating variable weather conditions. Importantly, while the intervals appear to have some effect on yield, particularly in NN conditions, the overall minimal differences across intervals and rainfall categories underscore that the strategic length interval can be balanced with other agronomic and environmental benefits provided by CCs without resulting in significant yield penalties.

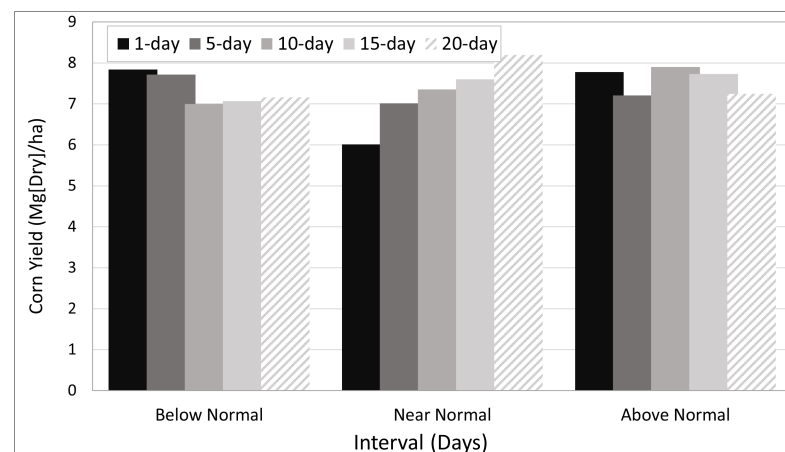


Figure 5. Corn yield (kg/ha) for five different intervals disaggregated by rainfall during the cover crop growing season.

The lack of significant yield differences between termination-planting intervals could be related to several factors such as soil moisture, availability of nitrogen, and soil temperature directly or indirectly related to CC management practices [32]. To explore the minor variations in corn yield between different intervals, we analyzed the volumetric water content at corn planting within the top 56 cm of the soil profile (Figure 6). The simulation results confirmed our initial hypothesis: soil moisture declines as the termination-to-planting interval decreases. Notably, the 20-day interval displayed the highest moisture at all depths, diminishing as intervals reduced to 1 day, suggesting decreased moisture is a consequence of shorter intervals due to continued water uptake by an active CC. Although these differences in soil moisture were not statistically significant, they highlight an important trend that longer intervals may be beneficial for maintaining soil moisture at the time of corn planting, particularly during relatively drier years.

On the other hand, the lack of a statistically significant difference in soil moisture between intervals might be explained by the increased organic matter from greater biomass accumulation in shorter intervals. The considerable biomass generated when the CC is terminated closer to corn planting can improve soil structure, increase porosity, and enhance moisture retention, offsetting potential moisture deficits from shorter termination intervals. Therefore, the similar soil moisture levels across intervals may result from the beneficial effects of organic matter on soil hydrological properties, mitigating the expected differences due to CC water usage. Several studies, (e.g., [33–35]) underscore the transformative role of soil organic carbon (SOC) from cover crops in enhancing soil physical properties. These studies have documented how increases in SOC improve macroaggregation, reduce soil compaction risks, and elevate water retention capabilities. Consequently, these improvements stabilize soil moisture levels across different cover crop management practices, despite variations in biomass. This is particularly relevant, as our

findings suggest that considerable biomass generated when the CC is terminated closer to corn planting can enhance soil structure, increase porosity, and boost moisture retention, effectively mitigating potential moisture deficits from shorter termination intervals. These enhancements contribute to maintaining consistent soil moisture levels, supporting the notion that strategic cover crop management can profoundly influence the soil hydrological properties without adversely affecting corn yield. This insight aligns with the concept that while soil moisture is crucial for corn growth, specific management practices of cover crops can significantly influence these dynamics without adversely affecting corn yield. By enhancing soil physical properties through increased SOC as demonstrated in these studies, the optimal management of cover crops can ensure effective soil moisture conservation. These results provide valuable guidance on the management of cover crops to enhance soil health and water dynamics, thereby supporting sustainable agricultural practices without compromising yield.

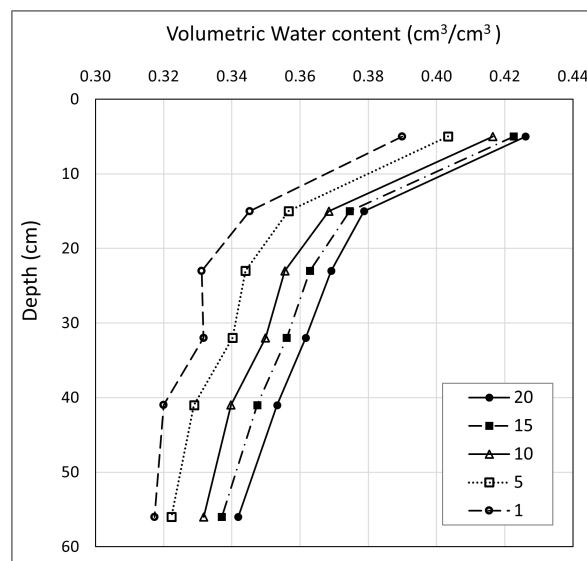


Figure 6. Volumetric water content at corn planting for top 56 cm of soil profile for five different intervals between cover crop termination and corn planting.

3.3. Cover Crop Termination Date

3.3.1. Corn Yield

The comprehensive evaluation of long-term average corn yields across 15 distinct CC termination dates reveals a yield spectrum ranging from 6.86 Mg ha^{-1} for a 31 May termination to a peak of 7.49 Mg ha^{-1} for an 26 April termination (Figure 7). This variation underscores a critical insight: the timing of CC termination exerts a minimal influence on corn yield, with the most notable yield discrepancy among simulations being a modest 0.64 Mg ha^{-1} . Contrary to initial expectations, early termination dates did not uniformly translate to enhanced yields. Instead, yields exhibit relative stability across early termination dates (22 March to 16 April), peak around 26 April, and then demonstrated a mild decline thereafter. This observed variation in yields, with notable increases for terminations in late April, can likely be linked to the favorable climatic conditions prevalent in May. This period is marked by warmer temperatures and higher levels of rainfall, conditions that are advantageous for the early growth stages of corn and facilitate the replenishment of soil moisture that may have been depleted by the cover crop. However, corn yields began to decline for terminations after 6 May.

The yield pattern was partly the result of the complex interaction between CC termination and corn yield determinants such as unit kernel weight, kernel number per cob, and grain-filling duration, which are tied to climatic conditions. The delay in CC termination resulted in a significant shift in the average onset of the corn grain-filling period from 19 July for the earliest termination gradually to 27 August for the latest termination date.

The long-maturing corn variety used in this study (with a CRM of 111 days) and the local climatology characterized by decreasing rainfall from June to October and a temperature peak in July (Figure 1) suggest a narrowing window for optimal grain development with a delayed corn planting date. The shift to cooler temperatures and reduced rainfall in September and October can potentially stress the plants, resulting in altering the duration of the grain-filling period and the kernel number and weight. The length of the grain-filling period increased significantly from 37.3 to 45.8 days; the number of kernels per cob decreased from 425 to 372, while the unit kernel weight increased from 0.245 g to 0.302 g for the earliest and latest termination dates, respectively.

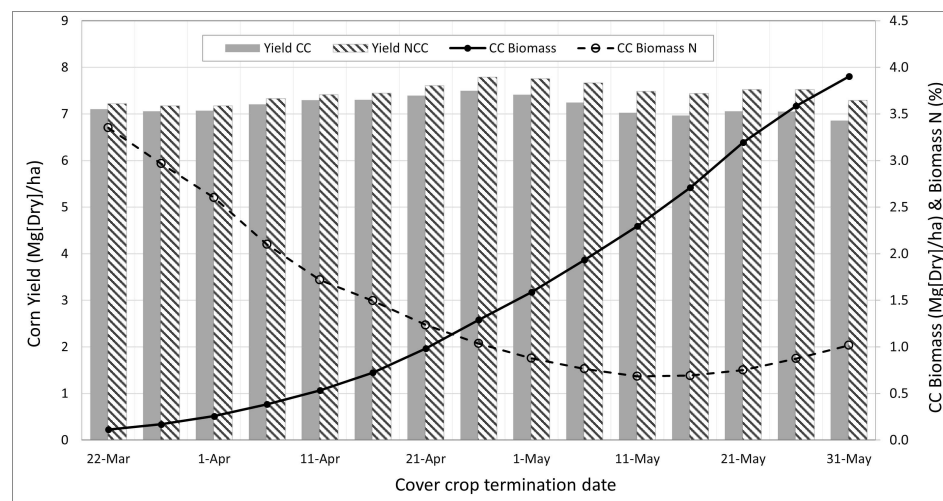


Figure 7. Long-term average (1991–2020) CC biomass, CC biomass N content, and corn yield for different CC termination dates. Yield CC and Yield NCC represent corn yield with and without a cover crop, respectively. For all simulations, corn was planted 10 days after CC termination.

Despite the above observed pattern, yield differences among the termination dates studied did not reach statistical significance ($p < 0.05$), affirming the minimal impact of CC termination timing on corn yield. However, a comparative analysis between cover crop (CC) and no cover crop (NCC) simulations indicated a slight yield decrement attributable to CC, ranging from approximately 0.11 Mg ha^{-1} (1.5%) for 1 April termination to about 0.48 Mg ha^{-1} (6.4%) for 16 May termination date ($p < 0.05$). This reduction in yield remained below 0.15 Mg ha^{-1} until 16 April and became more pronounced ($>0.4 \text{ Mg ha}^{-1}$) after the 1 May termination date. This may suggest the increased negative impacts of CCs as they progressed to later growth stages, potentially depleting critical resources such as soil moisture and nitrogen to a degree that adversely affected corn yield.

Choosing a termination date based solely on corn yield considerations, the 26 April termination with a yield of 7.5 Mg ha^{-1} might seem marginally preferable. Nonetheless, the yield advantage over the 1 and 6 May was very small ($<0.25 \text{ Mg ha}^{-1}$), while CC biomass increased by 0.30 Mg ha^{-1} and 0.64 Mg ha^{-1} for these dates compared to 26 April. The observed increase in CC biomass with similar grain yield indicated that extending the termination date to 1 May or 6 May may offer an optimal balance, maximizing both yield efficiency and biomass accumulation.

To optimize cover cropping with an emphasis on maximizing biomass, it is crucial to tailor management strategies that address the potential reductions in corn yield stemming from delayed development, especially when grain filling occurs under less than ideal conditions. For instance, in scenarios where the CC termination date is 31 May, postponing the corn harvest date by ten and twenty days from 10 October, has been observed to enhance corn yield by 5.5% and 6.9%. Nevertheless, these increases in yield come at a significant cost of respective 13.4% and 25.6% reductions in CC biomass. Thus, while extending the harvest period can bolster yield, it requires a careful consideration of the trade-off with CC biomass production.

3.3.2. Cover Crop Biomass

The long-term average CC biomass, as expected, showed a steady rise from 0.113 Mg ha⁻¹ for 22 March termination to 3.9 Mg ha⁻¹ by the 31 May termination, a trend that was statistically significant ($p < 0.05$) (Figure 7). Notably, biomass accumulation accelerated by an average of 30% with each five-day postponement in termination, exhibiting pronounced surges of approximately 50% in late March and moderating to about 10% by the end of May. This pattern reflects a rapid uptick in biomass growth from the end of February into early March, likely spurred by the transition to warmer and more humid conditions following winter dormancy.

The accumulation of CC biomass is intrinsically linked to its ecological benefits, with increased biomass from delayed termination poised to influence various environmental parameters. Chief among these is the build-up of Soil Organic Carbon (SOC)—a cornerstone of soil health and fertility. The total SOC at the end of the 30-year simulation period showed a clear trend: as CC biomass increased, there was a corresponding build-up in SOC, reaching its zenith when the termination date was set at May 16. The change in total SOC ranged from 5.8% for late march termination to 7.7% for late May termination dates (Figure 8). The highest SOC was recorded for the May 16 termination despite the total biomass (sum of corn and CC biomass) reaching its peak for the May 31 termination date suggests plateauing effect as the season progresses. This might indicate that while CC biomass contributes to SOC, the interplay with corn biomass and its residue as well as climate factors such as rainfall and temperature also play a crucial role in carbon dynamics. Adequate moisture and favorable temperatures not only enhance biomass production through improved photosynthesis and growth rates but also influence the decomposition rate of plant residues, which in turn affects SOC accumulation. The growth stage of the cereal rye at termination is equally important. As rye matures, the carbon to nitrogen ratio of its biomass increases, potentially slowing down the decomposition process and extending the period over which carbon is sequestered in the soil.

Therefore, while the 16 May termination leverages the vigorous growth phase of cereal rye, maximizing nitrogen content and contributing to SOC, the subsequent slight declines in SOC despite increased total biomass could be attributed to shifts in the C:N ratio and altered residue decomposition rates under evolving late-spring climatic conditions. This interplay suggests that the maximum SOC build-up is achieved not merely by biomass quantity but also by the quality and decomposition characteristics of the biomass, modulated by the growth stage and prevailing weather patterns [36,37].

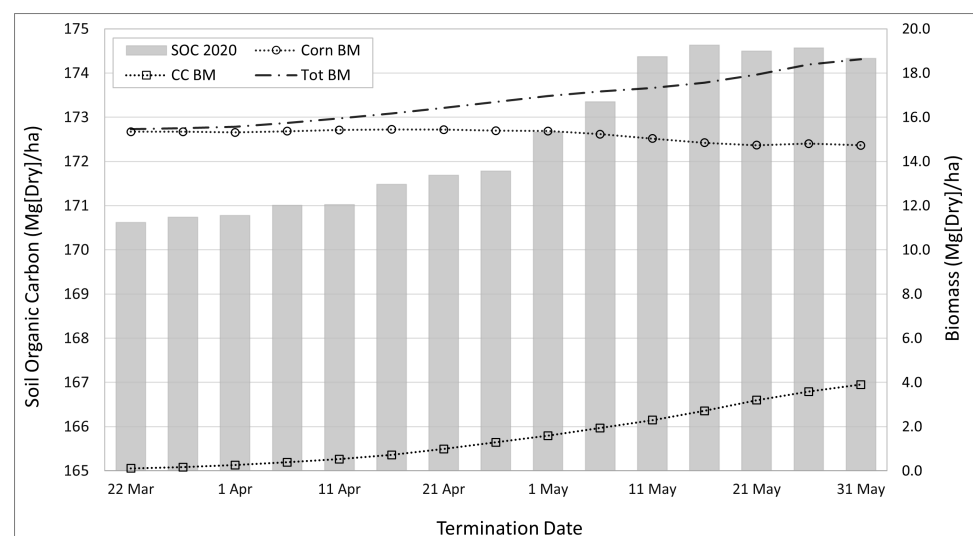


Figure 8. Total soil organic carbon (SOC) in soil profile at the end of 30-year simulation period (bars), 30-year average cover crop (dashed line with square marker), and corn (circle markers) and total biomass (dashed line) for 15 termination dates.

3.3.3. Cover Crop Biomass Quality

The timing of CC termination influences the amount of nitrogen uptake by cereal rye, as well as the subsequent nitrogen released through CC decomposition, which in turn determines nitrogen uptake by the cash crop. Analysis of the CC growth stage for each termination date showed that CC progressed further into its later growth stages with each 5-day delay in termination (Figure 9). The CC growth stage ranged from “beginning of tillering stage” (20 in zodok scale) for 22 March to “past early dough stage” (84 in zodok scale) for 31 May termination. Consequently, CC biomass N content decreased consistently with each successive 5-day delay in termination. The earliest termination date, 22 March, yielded the highest N content of 3.35% in CC biomass, while the lowest N content, 0.69%, corresponded to a mid-May termination date (Figure 7). This trend, a decrease in N concentration with advancing shoot growth and maturity, corroborates the findings from other research on winter cereal crops [3,38]. As a consequence, later termination dates result in a higher carbon to nitrogen (C:N) ratio, influencing the rate at which nitrogen is released from decomposing CC residues and subsequently available for corn uptake.

Seasonal patterns of cumulative net nitrogen mineralization, examined from cover crop termination through to corn harvest, reveal the implications of the diminishing nitrogen content (increasing C:N ratio) in CC biomass (Figure 10). Interestingly, despite a marginal uptick in biomass N percentage for late-May termination dates, net mineralization exhibited a marked increase, suggesting that abiotic factors such as soil temperature and moisture, perhaps coupled with the heightened microbial activity associated with warmer conditions, can enhance nitrogen mineralization, offsetting the effects of lower biomass nitrogen content [39].

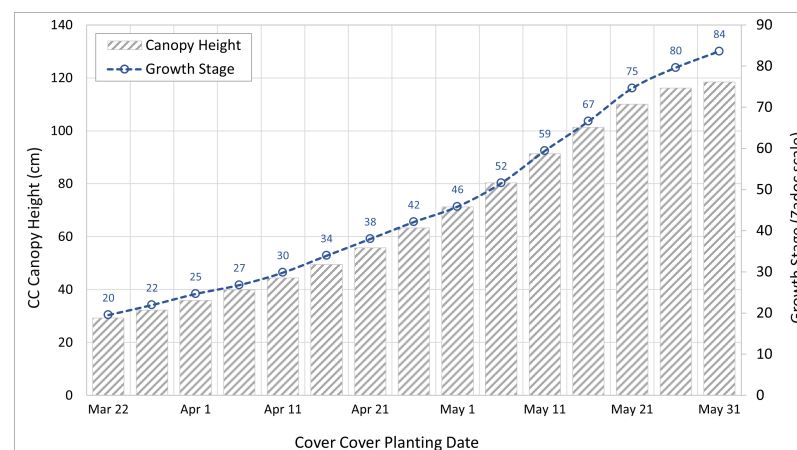


Figure 9. Cover crop growth stage (Zadoks scale) and canopy height (cm) for different termination dates.

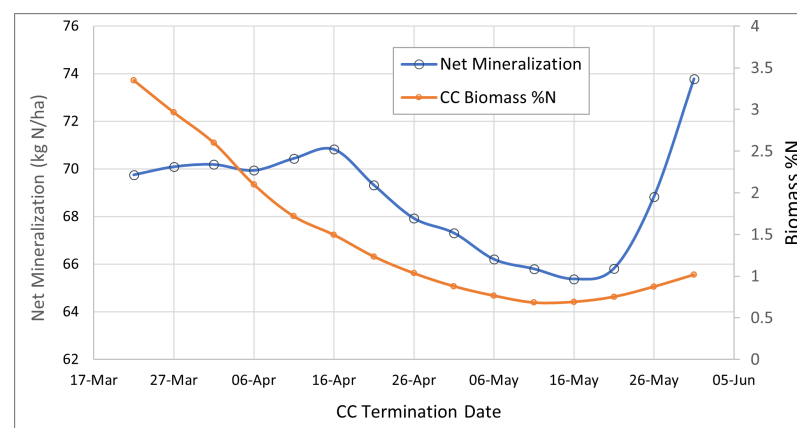


Figure 10. Cover crop above ground biomass N content (%) at termination and net mineralization in a season (kg N/ha).

3.4. Termination Efficiency

In this analysis, our exploration into the dynamics of cover crop termination in no-till systems is primarily informed by secondary data sources. The crop simulation modeling system applied in our study does not directly offer metrics related to termination efficiency. Consequently, we rely on secondary datasets, particularly those detailing growth stage and canopy height at various termination dates, alongside established recommended practices, to infer termination efficiency across different scenarios. The efficiency of herbicide termination—the most common technique in no-till systems—is significantly influenced by the growth stage of the CC at the time of herbicide application [40].

In this simulation study, average growth stage by the time of termination showed that on average, for 6 May and subsequent termination dates, CC has consistently reached or surpassed the heading (≥ 50 Zadoks stage) or flowering stages (≥ 60 Zadoks stage). For optimal control, it is generally recommended to apply herbicides before the CC begins its reproductive growth, as mature CCs present a greater challenge for herbicidal control [41]. Consequently, termination dates beyond early May might be less suitable due to the increased risk of diminished herbicide efficiency and potential regrowth.

Despite the conventional consensus that terminating cereal rye before the end of the boot stage is the best practice, there are instances where high herbicide efficiency has been observed during the heading stage. For example, Ref. [42] found that cereal rye cover crops could be controlled with 98% efficiency using glyphosate (N-(phosphonomethyl) glycine), administered when the rye was approximately 99 cm tall and transitioning between the boot and heading stages. Thus, while 1 May is typically recommended to avoid reduced termination efficiency and prevent competition with the subsequent corn crop, on-field studies suggest the 6 May termination, where the CC on average reached the early heading stage, could still be viable, albeit with specific considerations.

3.5. Practical Considerations in the Use of Simulation Outputs

The employment of DSSAT models in our study highlights the critical need for a nuanced approach to simulation-based research. While significant attention has been given to the input data and management practices representative of the study site, it is essential to consider both the limitations and the critical factors that enhance the reliability and applicability of model outputs when using these simulations for decision-making.

3.5.1. Model Calibration and Validation

Our models were previously calibrated and validated using data collected from several sites across the US, which included a diverse range of management practices, soil characteristics, and historical weather patterns. However, further validation against a new set of observed field data is crucial not only to affirm the models' capability to simulate realistic agricultural outcomes but also to continually update and refine model parameters to maintain accuracy, thus bolstering their utility for strategic decision-making. It should also be noted that this study only considered one long-maturing corn hybrid with a CRM of 111 days (i.e., P1197) and one cereal rye variety (i.e., Elbon). Employing different corn hybrids with varying CRMs or distinct genetic traits, as well as exploring different cover crop species or cereal rye varieties other than Elbon, can significantly alter the outcomes of cover cropping and its impacts on subsequent corn production. Thus, future research should consider these variables to broaden the understanding of CC benefits across a wider range of agricultural scenarios.

3.5.2. Addressing Uncertainties in Simulation Inputs

Accurate simulation outcomes depend heavily on the reliability of input data. Strategies to mitigate uncertainties in key inputs such as soil characteristics, weather data, and management practices are crucial for enhancing the validity of model predictions. Although our study utilized the best available soil data with several parameters representing soil physical and chemical properties at different depths, these datasets were collected several

years ago. Some soil parameters are dynamic and may not accurately represent the actual conditions at the time of simulation. Therefore, initiating models with the most recent soil testing data whenever possible is advantageous. Moreover, incorporating sufficient 'spin-up' time within the simulation process allows the model to reach equilibrium based on the initial conditions, thus enhancing the reliability of the simulation outcomes. Another significant source of variability in simulation models stems from the management practices. Practices such as crop and variety selection, planting and harvest dates, and fertilizer application rates introduce uncertainties. In this study, these management practices were uniformly applied throughout the entire simulation period. However, in real-world scenarios, farmers often adjust these practices annually in response to climatic variability. Recognizing the implications of such static assumptions is crucial for interpreting the outcomes of cover cropping strategies. Simulating a range of management scenarios can help identify robust outcomes across different strategies and highlight sensitive parameters crucial for informing adaptive and resilient agricultural practices.

3.5.3. Integration with Other Data Sources

To enhance decision-making, model outputs should be integrated with other reliable data sources, such as local weather forecasts, soil health assessments, and crop condition reports. This holistic approach helps in forming a more accurate assessment of the situation and planning appropriate management strategies.

4. Conclusions

Optimal cover crop management in Eastern Nebraska and elsewhere hinges on achieving a balance between maximizing cover crop benefits and minimizing negative impacts on the subsequent cash crop. This study examined three crucial cover crop management practices: CC planting date, CC termination-to-corn planting interval, and CC termination date. Our findings indicate that variations in these management practices did not significantly affect corn yield, demonstrating the adaptability of corn production under diverse cover crop scenarios.

Specifically, delayed CC planting resulted in an average reduction in biomass of 8.8% for each five-day delay beyond 25 September, emphasizing the importance of timely planting for optimal biomass production. Moreover, extending the interval between CC termination and corn planting led to a noticeable average reduction in CC biomass by 19.3% (0.33 Mg ha^{-1}) for every five-day extension in the interval, suggesting that longer intervals can significantly influence biomass dynamics while enhancing soil moisture conservation. Testing 15 different CC termination dates from 22 March to 31 May indicated that the optimal termination for balancing corn yield and soil benefits occurs approximately on 26 April. Extending CC growth slightly into early May proved to be a viable compromise, effectively maintaining corn yield while enhancing soil benefits. This finding underscores the significance of strategic termination timing, particularly in late April, for optimizing both sustainability and productivity within the farming system.

The results of this study are particularly relevant for farmers and agronomists seeking to optimize cover crop strategies in corn–soybean rotations. The early planting of cover crops is crucial for maximizing biomass production, which in turn can improve soil structure and fertility. The findings suggest that managing the timing of cover crop termination can significantly impact soil moisture levels, with later terminations allowing greater moisture retention which is beneficial during the planting of the subsequent cash crop. By adhering to an optimal termination date around late April, practitioners can ensure that soil health is bolstered without sacrificing the yield of the following corn crop. Additionally, while these guidelines provide a strong foundation, local agronomists should be consulted to tailor these strategies to specific field conditions, ensuring that management practices align with local soil types, weather patterns, and specific farming objectives. These strategies not only contribute to better crop performance but also enhance

sustainable agricultural practices by improving soil organic matter and reducing the need for additional water inputs.

Continued research is encouraged to explore the long-term effects of different cover crop management strategies on both soil health and crop productivity across varied climatic conditions. Advances in crop simulation models, like the DSSAT used in this study, will continue to be crucial in predicting outcomes under different scenarios and can help in fine-tuning cover crop management for various environmental settings. This study is part of a larger initiative aimed at developing a cover crop decision support system designed to be easily accessible and user friendly for farmers. Such a tool will integrate the insights gained from our research and others, providing tailored recommendations that help farmers make informed decisions about cover crop management based on specific local conditions.

Additionally, integrating economic analyses into future studies will assess the cost-effectiveness of different cover crop strategies, ensuring that the recommended practices are not only agronomically sound but also economically viable. By including farmer experiences and field-level data, future research could offer a more comprehensive understanding of the practical challenges and benefits associated with cover cropping. This holistic approach will continue to support the development of sustainable agricultural practices that meet both ecological and production goals, ultimately benefiting farmers globally.

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References

1. Blanco-Canqui, H.; Lal, R. Mechanisms of carbon sequestration in soil aggregates. *Crit. Rev. Plant Sci.* **2004**, *23*, 481–504. [\[CrossRef\]](#)
2. Blanco-Canqui, H. Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils. *Agron. J.* **2015**, *107*, 2449–2474. [\[CrossRef\]](#)
3. Kaspar, T.C.; Bakker, M.G. Biomass production of 12 winter cereal cover crop cultivars and their effect on subsequent no-till corn yield. *J. Soil Water Conserv.* **2015**, *70*, 353–364. [\[CrossRef\]](#)
4. Baligar, V.C.; Fageria, N.K.; Bailey, B.A. Role of Cover Crops in Improving Soil and Row Crop Productivity. *Commun. Soil Sci. Plant Anal.* **2005**, *36*, 2733–2757. [\[CrossRef\]](#)
5. Phatak, S.; Sumner, D.; Chalfant, R.; Gay, J.; Chandler, L.; Bugg, R.; Brunson, K. Managing Cover Crops Profitably. *HortScience* **1995**, *30*, 429f–429. [\[CrossRef\]](#)
6. Malone, R.; Kersebaum, K.; Kaspar, T.; Ma, L.; Jaynes, D.; Gillette, K. Winter rye as a cover crop reduces nitrate loss to subsurface drainage as simulated by HERMES. *Agric. Water Manag.* **2017**, *184*, 156–169. [\[CrossRef\]](#)
7. Oliveira, M.C.; Butts, L.; Werle, R. Assessment of Cover Crop Management Strategies in Nebraska, US. *Agriculture* **2019**, *9*, 124. [\[CrossRef\]](#)
8. Wallander, S.; Smith, D.; Bowman, M.; Claassen, R. Cover crop trends, programs, and practices in the United States. In *Economic Information Bulletin*; US Department of Agriculture: Washington, DC, USA, 2021.
9. Eash, L.; Berrada, A.F.; Russell, K.; Fonte, S.J. Cover Crop Impacts on Water Dynamics and Yields in Dryland Wheat Systems on the Colorado Plateau. *Agronomy* **2021**, *11*, 1102. [\[CrossRef\]](#)

10. Hashemi, M.; Farsad, A.; Sadeghpour, A.; Weis, S.A.; Herbert, S.J. Cover-crop seeding-date influence on fall nitrogen recovery. *J. Plant Nutr. Soil Sci.* **2013**, *176*, 69–75. [\[CrossRef\]](#)
11. Krueger, E.S.; Ochsner, T.E.; Porter, P.M.; Baker, J.M. Winter Rye Cover Crop Management Influences on Soil Water, Soil Nitrate, and Corn Development. *Agron. J.* **2011**, *103*, 316–323. [\[CrossRef\]](#)
12. Ruis, S.J.; Blanco-Canqui, H.; Elmore, R.W.; Proctor, C.; Koehler-Cole, K.; Ferguson, R.B.; Francis, C.A.; Shapiro, C.A. Impacts of cover crop planting dates on soils after four years. *Agron. J.* **2020**, *112*, 1649–1665. [\[CrossRef\]](#)
13. Wells, M.S.; Reberg-Horton, S.C.; Mirsky, S.B. Planting Date Impacts on Soil Water Management, Plant Growth, and Weeds in Cover-Crop-Based No-Till Corn Production. *Agron. J.* **2016**, *108*, 162–170. [\[CrossRef\]](#)
14. Almeida, T.F.; Robinson, E.; Matthiesen-Anderson, R.; Robertson, A.E.; Basche, A. Effect of cover crop species and termination timing on corn growth and seedling disease. *Agron. J.* **2024**, *116*, 1792–1803. [\[CrossRef\]](#)
15. Qin, Z.; Guan, K.; Zhou, W.; Peng, B.; Villamil, M.B.; Jin, Z.; Tang, J.; Grant, R.; Gentry, L.; Margenot, A.J.; et al. Assessing the impacts of cover crops on maize and soybean yield in the U.S. Midwestern agroecosystems. *Field Crops Res.* **2021**, *273*, 108264. [\[CrossRef\]](#)
16. Rosa, A.T.; Creech, C.F.; Elmore, R.W.; Rudnick, D.R.; Lindquist, J.L.; Fudolig, M.; Butts, L.; Werle, R. Implications of cover crop planting and termination timing on rainfed maize production in semi-arid cropping systems. *Field Crops Res.* **2021**, *271*, 108251. [\[CrossRef\]](#)
17. Martinez-Feria, R.A.; Dietzel, R.; Liebman, M.; Helmers, M.J.; Archontoulis, S.V. Rye cover crop effects on maize: A system-level analysis. *Field Crops Res.* **2016**, *196*, 145–159. [\[CrossRef\]](#)
18. Birru, G.; Shiferaw, A.; Tadesse, T.; Schmer, M.R.; Jin, V.L.; Wardlow, B.; Koehler-Cole, K.; Awada, T.; Beebout, S.; Tsegaye, T.; et al. Simulated impacts of winter rye cover crop on continuous corn yield and soil parameters. *Agron. J.* **2023**, *115*, 1114–1130. [\[CrossRef\]](#)
19. Birru, G.; Shiferaw, A.; Tadesse, T.; Wardlow, B.; Jin, V.L.; Schmer, M.; Awada, T.; Kharel, T.; Iqbal, J. Cover crop performance under a changing climate in continuous corn system over Nebraska. *J. Environ. Qual.* **2024**, *53*, 66–77. [\[CrossRef\]](#) [\[PubMed\]](#)
20. Chatterjee, N.; Archontoulis, S.V.; Bastidas, A.; Proctor, C.A.; Elmore, R.W.; Basche, A. Simulating winter rye cover crop production under alternative management in a corn-soybean rotation. *Agron. J.* **2020**, *112*, 4648–4665. [\[CrossRef\]](#)
21. Jones, C. Predicting the Impacts of Cover Crop Management Practices on Corn Yield: A Simulation Modeling Approach. *J. Agric. Sci. Technol.* **2021**, *23*, 837–851.
22. Li, Y. Modeling the Long-Term Effects of Cover Crops on Crop Production and Soil Health. *Agric. Syst.* **2019**, *172*, 42–52.
23. Jones, J.; Hoogenboom, G.; Porter, C.; Boote, K.; Batchelor, W.; Hunt, L.; Wilkens, P.; Singh, U.; Gijsman, A.; Ritchie, J. The DSSAT cropping system model. *Eur. J. Agron.* **2003**, *18*, 235–265. [\[CrossRef\]](#)
24. Duiker, S.W. Establishment and Termination Dates Affect Fall-Established Cover Crops. *Agron. J.* **2014**, *106*, 670–678. [\[CrossRef\]](#)
25. Baron, V.S.; Dick, A.C.; Salmon, D.F.; Mcleod, J.G. Fall Seeding Date and Species Effects on Spring Forage Yield of Winter Cereals. *J. Prod. Agric.* **1999**, *12*, 110–115. [\[CrossRef\]](#)
26. Hayden, Z.D.; Ngouajio, M.; Brainard, D.C. Planting Date and Staggered Seeding of Rye–Vetch Mixtures: Biomass, Nitrogen, and Legume Winter Survival. *Agron. J.* **2015**, *107*, 33–40. [\[CrossRef\]](#)
27. Lawson, A.; Cogger, C.; Bary, A.; Fortuna, A.M. Influence of Seeding Ratio, Planting Date, and Termination Date on Rye-Hairy Vetch Cover Crop Mixture Performance under Organic Management. *PLoS ONE* **2015**, *10*, e0129597. [\[CrossRef\]](#)
28. Farsad, A.; Randhir, T.O.; Herbert, S.J.; Hashemi, M. Spatial Modeling of Critical Planting Date for Winter Rye Cover Crop to Enhance Nutrient Recovery. *Agron. J.* **2011**, *103*, 1252–1257. [\[CrossRef\]](#)
29. NRCS. *Cover Crop Termination Guidelines Version 4*; USDA Natural Resources Conservation Service: Washington, DC, USA, 2019.
30. Acharya, J.; Bakker, M.G.; Moorman, T.B.; Kaspar, T.C.; Lenssen, A.W.; Robertson, E.A. Time Interval Between Cover Crop Termination and Planting Influences Corn Seedling Disease, Plant Growth, and Yield. *Plant Dis.* **2017**, *101*, 591–600. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Dittlinger, D.; Green, V.; Brown, E.; Massey, J. Effect of Cover Crop Termination Timing on Corn Population and Yield. In *University of Arkansas Research Series*; Division of Agriculture, University of Arkansas System: Fayetteville, AK, USA, 2021; p. 43.
32. Ball Coelho, B.R.; Roy, R.C.; Bruin, A.J. Long-term effects of late-summer overseeding of winter rye on corn grain yield and nitrogen balance. *Can. J. Plant Sci.* **2005**, *85*, 543–554. [\[CrossRef\]](#)
33. Blanco-Canqui, H.; Shapiro, C.A.; Wortmann, C.S.; Drijber, R.A.; Mamo, M.; Shaver, T.M.; Ferguson, R.B. Soil organic carbon: The value to soil properties. *J. Soil Water Conserv.* **2013**, *68*, 129A–134A. [\[CrossRef\]](#)
34. Irmak, S.; Sharma, V.; Mohammed, A.; Djaman, K. Impacts of cover crops on soil physical properties: Field capacity, permanent wilting point, soil-water holding capacity, bulk density, hydraulic conductivity, and infiltration. *Trans. ASABE* **2018**, *61*, 1307–1321. [\[CrossRef\]](#)
35. Rankoth, L.M.; Udawatta, R.P.; Anderson, S.H.; Gantzer, C.J.; Alagele, S. Cover crop influence on soil water dynamics for a corn–soybean rotation. *Agrosyst. Geosci. Environ.* **2021**, *4*, e20175. [\[CrossRef\]](#)
36. Finney, D.M.; White, C.M.; Kaye, J.P. Biomass Production and Carbon/Nitrogen Ratio Influence Ecosystem Services from Cover Crop Mixtures. *Agron. J.* **2016**, *108*, 39–52. [\[CrossRef\]](#)
37. Zhang, Z.; Kaye, J.P.; Bradley, B.A.; Amsili, J.P.; Suseela, V. Cover crop functional types differentially alter the content and composition of soil organic carbon in particulate and mineral-associated fractions. *Glob. Chang. Biol.* **2022**, *28*, 5831–5848. [\[CrossRef\]](#)

38. Muldoon, D.K. Dry matter accumulation and changes in forage quality during primary growth and three regrowths of irrigated winter cereals. *Aust. J. Exp. Agric.* **1986**, *26*, 87–98. [[CrossRef](#)]
39. Russelle, M.P. Nitrogen cycling in pasture and range. *J. Prod. Agric.* **1992**, *5*, 13–23. [[CrossRef](#)]
40. Kumar, V.; Singh, V.; Flessner, M.L.; Haymaker, J.; Reiter, M.S.; Mirsky, S.B. Cover crop termination options and application of remote sensing for evaluating termination efficiency. *PLoS ONE* **2023**, *18*, e0284529. [[CrossRef](#)]
41. Heggenstaller, A. Managing Winter Cover Crops in Corn and Soybean Cropping Systems. *Crop Insights Pioneer Agron. Sci.* **2023**, *23*, 4–5.
42. Pittman, K.B.; Cahoon, C.W.; Bamber, K.W.; Rector, L.S.; Flessner, M.L. Herbicide selection to terminate grass, legume, and brassica cover crop species. *Weed Technol.* **2020**, *34*, 48–54. [[CrossRef](#)]

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