frontiers in Agronomy

TYPE Original Research
PUBLISHED 23 March 2026
DOI 10.3389/fagro.2026.1761663

OPEN ACCESS

EDITED BY
Isabel Martínez-Alcalá,
Catholic University San Antonio of Murcia, Spain

REVIEWED BY
Joao Henrique Luz,
University of São Paulo, Brazil
Tianyi Qiu,
Wuhan University of Technology, China

*CORRESPONDENCE
Axel Garcia y Garcia
axel@umn.edu

RECEIVED 05 December 2025
REVISED 24 February 2026
ACCEPTED 27 February 2026
PUBLISHED 23 March 2026
CORRECTED 30 March 2026

CITATION
Liu S, Rusch HL, Johnson GA, Strock JS, Stahl L and Garcia y Garcia A (2026) Water use of interseeded cover crops in rainfed maize–soybean rotations in the Northern U.S. *Front. Agron.* 8:1761663.
doi: 10.3389/fagro.2026.1761663

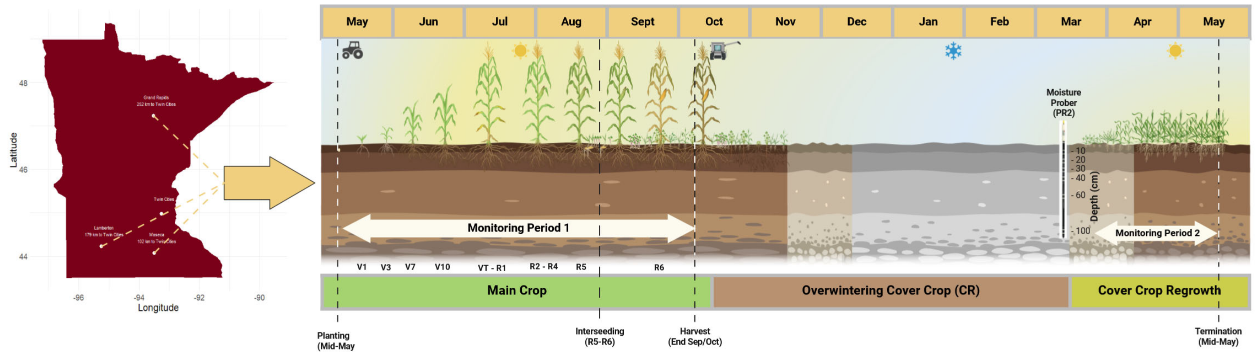
Water use of interseeded cover crops in rainfed maize–soybean rotations in the Northern U.S.

Shuhui Liu[1,2], Hannah L. Rusch[3], Gregg A. Johnson[3,4], Jeffrey S. Strock[2,5], Lizabeth Stahl[6] and Axel Garcia y Garcia[2,3]*

[1]College of Water Resources Science and Engineering, Taiyuan University of Technology, Taiyuan, China, [2]Southwest Research and Outreach Center, University of Minnesota, Lamberton, MN, United States, [3]Department of Agronomy and Plant Genetics, University of Minnesota, St. Paul, MN, United States, [4]Southern Research and Outreach Center, University of Minnesota, Waseca, MN, United States, [5]Department of Soil, Water, and Climate, University of Minnesota, St. Paul, MN, United States, [6]Extension, University of Minnesota, Regional Office, Worthington, MN, United States

Introduction: Cover crop adoption in U.S. crop rotations is steadily increasing. In the upper Midwest, where the conventional maize (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation is mostly rainfed, there is legitimate concern that cover crops may affect available soil water and the establishment of the subsequent main crop.
Methods: A study was conducted to evaluate 1) the effect of interseeded cover crops on soil moisture at seeding and termination, and subsequent maize and soybean yields, and 2) seasonal evapotranspiration (*ET*) or water use of the main crops and cover crops. Field trials were conducted from 2016 to 2019 at three locations in the upper Midwest using four treatments: monoculture cereal rye (*Secale cereale* L.), two-species rye + crimson clover (*Trifolium incarnatum* L.), three-species rye + clover + forage radish (*Raphanus sativus* L.), and a fallow (no-cover planted) as the control.
Results: The ET of cover crops varied between 52 and 110 mm, 70% of which was attributed to its evaporation component. Meanwhile the ET for maize and soybean ranged from 364–516 mm and 378–503 mm, respectively, 20% of which was attributed to evaporation. Regardless of the interseeding strategy, the biomass of cover crops was low in two out of the three experimental years due to weather conditions, resulting in little to no effect on soil water content or crop yield.
Discussion: Our findings suggest that late interseeded cover crops for conditions in the northern U.S. may have limited impact on soil available water or the productivity of the subsequent crop when cover crop growth is low.

KEYWORDS
corn, cover crop mixes, crimson clover, evapotranspiration, forage radish, soy, winter rye



GRAPHICAL ABSTRACT
Created in BioRender. Garcia y Garcia, A. (2026) https://BioRender.com/ytdt5q1.

1 Introduction

The conventional two-year maize (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation is the predominant cropping system in the U.S. Corn Belt (Grassini et al., 2014). The upper Midwest alone accounts for approximately 50% of the total U.S. grain production of both commodities (USDA, National Agricultural Statistics Service (NASS), 2026). Yet, this highly productive region generates environmental concerns like nutrient leaching, soil erosion, and declining ecosystem services (Mitsch et al., 2001; Syswerda et al., 2012).

Cover cropping is promoted as a sustainable practice to mitigate these concerns. The benefits of cover crops include soil erosion reduction, improved water infiltration, increased soil organic matter, reduced soil evaporation, and improved water retention (Gabriel et al., 2019; Unger and Vigil, 1998). The practice is a central component of climate-smart agriculture, aiming to enhance resilience of agroecosystem to increasing climate variability (Qiu et al., 2024). More broadly, these approaches integrate innovative management to sustain productivity despite rising biotic and abiotic stresses, all while reducing the overall environmental footpring (Raza et al., 2025).

The question is whether cover crop benefits include maintaining the hydrological buffer needed to sustain cash-crop productivity under such conditions. This is because cover crops can affect the soil-plant-atmosphere continuum by shifting the pathways of the evapotranspiration components (soil evaporation and plant transpiration) and influencing soil water infiltration and storage (Basche et al., 2016; Krstić et al., 2018; Unger and Vigil, 1998). Quantifying these fluxes is particularly relevant in rainfed crop production systems, where in-season dry spells and intense rainfall events can occur.

While these benefits are generally well documented, issues related to cover crop water use are less well-known in regions with climates where rainfed crop production is a common practice as in the upper Midwest. In rainfed cropping systems, cover cropping can enhance soil-water dynamics but in the short term may also compete with cash crops for water (Basche et al., 2016). At the same time, increased soil cover can reduce soil evaporation and improve infiltration, potentially offsetting increases in transpiration. This balance between building soil resilience and managing water competition is key to their adoption.

However, cover crop growth in the upper Midwest is limited by the colder temperatures and a shorter growing season, which may reduce their effect on soil water and the performance of the subsequent crop. For instance, rainfall during the growing season typically accounts for about 75% of the annual total precipitation in the upper Midwest, which is often enough to meet the water needs of maize and soybean (Garcia y Garcia and Strock, 2018). However, the year-to-year variability in rainfall occurrence and its intensity introduces uncertainty, especially when cover crops are added to the system. In addition, the magnitude and direction (positive or negative) of the effects of cover crop are both highly influenced by species, seeding and termination timing, and soil and weather conditions (Basche et al., 2016; Garba et al., 2022; He et al., 2025).

Cereal rye (*Secale cereale* L.), crimson clover (*Trifolium incarnatum* L.), and forage radish (*Raphanus sativus* L.) are widely used as cover crops in the U.S (CTIC-SARE-ASTA, 2023). All three species have been the subject of studies ranging from agronomy to environmental services, but less is known about their effects on soil moisture, water use, and impacts on the subsequent crop. In a maize-soybean rotation study conducted in central Iowa (Qi and Helmers, 2010), scientists reported that cereal rye increased soil water storage. Similarly, a study conducted in Maryland (Chen and Weil, 2011) reported that forage radish improved maize root penetration and enhanced surface soil water availability in compacted soils. In contrast, crimson clover was reported to reduce available soil moisture under certain conditions (Meyer et al., 2018). For conditions in Minnesota, cereal rye interseeded into maize as a monocrop cover crop or in mixtures with crimson clover and forage radish produced marginal biomass, which did not affect soil moisture at maize planting (Rusch et al., 2020). However, the study by Rusch et al. (2020) did not evaluate seasonal water use or the partitioning of water into evaporation and transpiration.

This study builds on earlier work (Rusch et al., 2020) by expanding to a third location, adding one more year of data and incorporating a dual-method approach to quantify seasonal water use of main crops and cover crops, partitioning the evapotranspiration into its evaporation and transpiration components. We hypothesized that the limited growth of interseeded cover crops in rainfed cropping systems in regions with short growing seasons would not affect soil moisture or the productivity of crops. To address this issue, we conducted a nine location-year study to 1) assess the effects of interseeded cover crops on soil moisture and crop productivity, and 2) quantify the water use of maize, soybean, and cover crops in rotation.

2 Methods

2.1 Site description

Field experiments were conducted from 2016 to 2019 within the University of Minnesota Long-Term Agricultural Research Network (LTARN; http://ltarn.cfans.umn.edu). The LTARN facilities are located at the University of Minnesota North Central Research and Outreach Center (NCROC) in Grand Rapids (GR; 47° 18'N, -93°53'W, 391 meters above sea level, *masl*), Southwest Research and Outreach Center (SWROC) near Lamberton (LA; 44°24'N, -95°31'W, 348 *masl*), and Southern Research and Outreach Center (SROC) in Waseca (WA; 44°06'N, -93°53'W, 351 *masl*). Soils at the experimental sites are characterized as well-drained Nashwauk loam (fine-loamy, mixed, superactive, frigid Oxyaquic Glossudalfs) at NCROC, moderately well drained Normania clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) at SWROC, and somewhat poorly drained Nicollet clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) at SROC (USDA-NRCS, 2022). Soil conditions, including texture, nitrate-N, organic matter, and pH also varied across locations (Table 1).

Prior to this study, all sites had been under continuous maize–soybean rotation since 2013 (LA and WA) or 2014 (GR), with no history of cover cropping. Long-term (1990–2015) weather data from NASA POWER (https://power.larc.nasa.gov/) indicate average annual precipitation of 700 mm, 708 mm, and 922 mm, and average annual maximum/minimum temperatures of 8/−2 °C, 13/1 °C, and 13/2 °C for GR, LA, and WA, respectively.

2.2 Experimental design and agronomic practices

Field experiments followed a randomized complete block design with four replications at LA and WA, and three replications at GR. Plots measured 3.0 m wide by 6.0 m long, and both phases of the maize–soybean rotation were present at each site in every year of the study (2016–2019).

Cover crop treatments included monoculture cereal rye (CR), two-species mix of cereal rye and crimson clover (CRCC), three-species mix of cereal rye, crimson clover, and forage radish (CRCCFR), and a fallow control (no cover crop planted) hereafter refer to as the no-cover crop (NC) treatment. These treatments are hereafter referred to as "cover crop strategies." All four strategies were implemented at each location in each study-year.

Cover crops were interseeded into maize at R5–R6 stages (kernel dough to physiological maturity) and into soybean at R7–R8 stages (beginning to full maturity). At all locations, cover crops were manually broadcast and lightly incorporated with a rake. Seeding rates were: 67 kg ha^{-1} for CR monoculture, 33.5 kg ha^{-1} CR + 22 kg ha^{-1} CC for CRCC, and 33.5 kg ha^{-1} CR + 16.5 kg ha^{-1} CC + 10 kg ha^{-1} FR for CRCCFR. All cover crops were seeded in early August to late September depending on location, stage of development of the main crop, and weather conditions.

Crimson clover and FR were winter-killed, while cereal rye—a winter-hardy species—was terminated in spring with glyphosate [N-(phosphonomethyl)glycine] applied at 0.84 kg ae ha^{-1} approximately 7 days before main crop planting. Spring termination occurred between late April and late May depending on location and year. Maize and soybean were managed according to University of Minnesota best management practices, with conventional tillage and no irrigation applied. Fertilizer rates, weed control, and planting dates were consistent with standard regional practices and are described in detail in Garcia y Garcia et al. (2020) and Rusch et al. (2020).

TABLE 1 Soil physical and chemical characteristics at the three experimental locations in Minnesota, U.S.

Location‡	Soil Layer	Particle-size distribution (%)			NO_3	OM	pH
	(cm)	Clay	Silt	Sand	ppm	%	
Grand Rapids	0-20	6.6	42.2	51.3	3.5	2.3	6.9
	20-40	7.2	40.2	52.6	4.8	1.1	6.4
	40-60	8.8	13.5	77.7	3.8	0.9	6.2
Lamberton	0-20	31.1	31.5	37.4	3.8	4.0	6.0
	20-40	34.1	31.6	34.3	2.9	3.2	6.6
	40-60	31.3	30.0	38.7	1.6	2.1	7.5
Waseca	0-20	31.7	38.6	29.8	2.5	4.8	6.4
	20-40	32.5	34.6	32.9	2.9	3.4	6.7
	40-60	33.9	34.1	32.0	2.2	2.2	7.0

‡North Central Research and Outreach Center at Grand Rapids, Minnesota (MN), U.S.; Southwest Research and Outreach Center near Lamberton, MN, U.S.; Southern Research and Outreach Center at Waseca, MN, U.S.

2.3 Data collection

2.3.1 Soil moisture measurements

Soil moisture was measured every 7–10 days using a PR2/6 profile probe (Delta-T Devices Ltd., Cambridge, UK). One access tube was installed per experimental unit, and the same portable probe was used across all three study locations. At each measurement event, the probe was rotated 120° within the tube to obtain three readings per depth, which were then averaged to represent soil water content at that depth.

The PR2 access tubes are made of polycarbonate with a 25.4 mm internal diameter. Soil moisture was recorded at 10, 20, 30, 40, 60, and 100 cm depths as volumetric water content (m^3 m^{-3}). Soil moisture readings at 60 and 100 cm depths were almost constant throughout the study period so here we report only the readings in the top 40 cm of soil, a layer reported to be within the influence of winter cover crops in the region, even under drought or semi-arid conditions (Barker et al., 2018; Daigh et al., 2014). We acknowledge, however, that maize and soybean can access water below 0.40 m; therefore, our soil-moisture results are most directly interpretable as treatment effects on near-surface soil water dynamics rather than whole-profile plant-available water. The PR2/6 probe was operated using the manufacturer's calibration equation for mineral soils. Although the sites differed in texture and drainage, the factory calibration was considered appropriate for the range of mineral soils present.

2.3.2 Yield of crops and cover crops

Maize and soybean grain yields were obtained each October by harvesting the center 18 m^2 of each plot using a small-plot combine. Grain yield was adjusted to 15.5% moisture for maize and 13% for soybean.

Cover crop biomass was measured twice per season: once in autumn following 2–3 consecutive frost days, and again in spring just prior to termination. Aboveground biomass was sampled by clipping plants at the soil surface within a 30 cm × 30 cm quadrat randomly tossed into the center of each plot. Two quadrats were collected per plot at each sampling event. Samples were oven-dried at 60°C until constant mass (typically within 72 hours), and dry biomass was expressed on a per hectare basis following the protocol of Rusch et al. (2020).

2.3.3 Water use of crops and cover crops

Water use or crop evapotranspiration (*ETc*) was obtained separately for maize, soybean, and cover crops using two approaches: (i) a simplified field water balance method (*ETc-wb*; Equation 2) and (ii) a weather-based crop coefficient method (*ETc-kc*; Equation 5) following FAO-56 guidelines (Allen et al., 1998). Soil moisture was measured every 7–10 days; however, ETc-wb was computed at a monthly time step to match the temporal resolution of effective precipitation (P_e). Accordingly, soil water storage was calculated at each measurement date and changes in storage were aggregated within months.

The general field water balance can be expressed as in Equation 1:

$$ET_c = P_e + I - RO - D + CR \pm \Delta S \quad (1)$$

Simplifications included irrigation (*I*) = 0 because our system was rainfed, runoff (*RO*) was ignored because the experimental sites were all flat (< 1% slope; nearly level) and no evidence of *RO* (ponding or flow paths) was observed, drainage (*D*) and capillary rise (*CR*) were not monitored and were both assumed to be negligible. This is consistent with Garcia y Garcia and Strock (2018), who used the same approach under similar cropping systems and soil conditions in Minnesota. Nevertheless, we acknowledge that drainage following high-intensity rainfall events could introduce uncertainty; if drainage occurred below 40 cm between measurement dates, ETc-wb would be biased upward because water losses from the profile would be attributed to evapotranspiration.

We recognize that ignoring RO and D could bias ETc-wb during extreme rainfall events; however, given the flat topography, lack of observed surface flow, and the focus on relative treatment comparisons within site-years, we expect any resulting error to be small and not systematically different among treatments.

Thus, and given our rainfed conditions and site characteristics, the simplified water balance in Equation 2 represents the field *ETc-wb* used in this study:

$$ET_{c-wb} = P_e \pm \Delta S \quad (2)$$

where P_e is effective precipitation and ΔS corresponds to the change in water storage in the top 40 cm of soil between two consecutive readings within a given growing season. The *Pe* was obtained using Equation 3, which corresponds to the USDA-SCS method (Smith, 1992):

$$P_e = P_{total} \times (125 - 0.2P_{total})/125 \quad (3)$$

for monthly precipitation $P < 250$ mm.

Soil water storage (ΔS) was calculated as:

$$\Delta S = (\bar{\theta}_{t2} - \bar{\theta}_{t1})z \quad (4)$$

where $\bar{\theta}$ is the depth-averaged volumetric water content and z = 0.40 m, a depth beyond which soil moisture is reported to have little effect on seasonal water use of rainfed crops in the region (Garcia y Garcia and Strock, 2018). For each interval between consecutive measurements (t1 to t2), soil water storage was calculated using Equation 4 and ΔS was obtained as the difference between storage at t2 and t1. Monthly ΔS was then calculated as the sum of all interval ΔS values occurring within that month. Because ΔS was computed for the upper 0.40 m, ETc-wb estimates are most robust for relative comparisons under our assumptions and may not fully capture deeper soil-water contributions during periods when crops extract water below 0.40 m.

To partition *ETc* into evaporation (*E*) and transpiration (*T*), the FAO dual crop coefficient (*Kc*) approach described in Equations 5 and 6 was used for $ET_{c\text{-}kc}$:

$$ET_{c-kc} = K_c ET_o \quad (5)$$

$$K_c = K_{cb} + K_e \tag{6}$$

where K_{cb} is the basal crop coefficient, Ke is the soil water evaporation coefficient (both dimensionless), and ET_o is the reference evapotranspiration calculated using the Penman–Monteith equation (Allen et al., 1998) as in Equation 7:

$$ET_o = \frac{0.408\ \Delta\ (R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{7}$$

where R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1}), G is the soil heat flux density (MJ m^{-2} d^{-1}), T is the daily air temperature (°C) at 2 m height, u_2 is the wind speed (m s^{-1}) at 2 m height, e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), Δ is the slope vapor pressure curve (kPa $°C^{-1}$) and γ is the psychrometric constant (kPa $°C^{-1}$).

Required daily weather data (solar radiation, wind speed, temperature, and humidity) were obtained from automated weather stations at each of the three experimental sites. Calculations were conducted using the SIMDualKc model (Rosa et al., 2012a, 2012b), which has been validated under different conditions for its ability to estimate *ET* and its components. The *E:T* ratios obtained from the SIMDualKc model were applied to partition total ET_{c_wb} into its E and T components for both the main and cover crops.

The water use of cover crop mixtures (CRCC and CRCCFR) or $ET_{c\text{-}mix}$ was calculated based on their biomass relative to the cereal rye monoculture using Equation 8:

$$ET_{c-mix} = Biomass_{mix} \frac{ET_{c-rmo}}{Biomass_{rmo}} \tag{8}$$

where $Biomass_{mix}$ refers to the biomass of cover crop mixtures (kg DM ha^{-1}) and $ET_{c\text{-}rmo}$ and $Biomass_{rmo}$ refer to the water use and biomass of the rye monoculture (kg DM ha^{-1}), a proportionality that has been used in water productivity studies (Garcia y Garcia et al., 2009; Steduto et al., 2007; Zwart and Bastiaanssen, 2004). Because the biomass of the interseeded cover crops was low in some site-years, the low cover-crop $ET_{c\text{-}mix}$ proportionality is consistent with the expectation that transpiration scales with canopy development.

2.4 Statistical analysis

Results were subjected to statistical analyses using SPSS 20.0 for Windows (IBM Corp., Armonk, NY) and R (version 4.3.1), and the ggplot2 package (Wickham, 2016) was used for visualization. Separate linear mixed models were used to evaluate cover crop biomass, maize and soybean grain yield, soil volumetric water content, water use (ET_c) of main crops and cover crops. For analyses of grain yield and water use, fixed effects included location, year, and cover crop strategy, while replication was treated as a random effect. For soil moisture, fixed effects included main crop (maize or soybean), soil depth, timing (seeding or termination), and cover crop strategy; replication was treated as a random effect as well. To account for site-year variability, we used a multilevel meta-analysis in R (*metafor*; (Viechtbauer, 2010) based on lnRR effect sizes (cover crop vs. NC) and sampling variances computed from group means, standard deviations, and sample sizes. Site-year (location × year) was included as a random effect, and correlation analyses evaluated consistency across years and between crops. The effect size represents the proportional yield response of maize and soybean to cover crop strategies relative to the NC control within each site-year.

Normality of residuals was assessed using Q–Q plots, and homoscedasticity was evaluated using residuals versus fitted values plots. Where interactions among main effects were significant, separate analyses of variance (ANOVA) were conducted by site and year. We used the Fisher's Least Significant Difference (LSD) test for mean separation.

Boxplots were used to visualize variability in soil volumetric water content, and the Pearson coefficient of correlation was used to assess agreement between the water balance ($ET_{c\text{-}wb}$) and crop coefficient ($ET_{c\text{-}kc}$) methods of obtaining the water use of crops.

3 Results

3.1 Weather conditions

Weather conditions during the study years (2016–2019) varied by year and location, which ultimately affected autumn establishment and spring regrowth of cover crops and the performance of both main crop and cover crops. Compared to long-term (1990–2015) averages, temperature and precipitation showed inter-annual differences in each of the three locations. Precipitation from mid-August to early October, the autumn growth period of cover crops, exceeded the long-term average by 12% and 18% at LA and WA, respectively, while GR was 6% drier. During the same period, air temperature was 0.5–1.2°C cooler than the long-term average at LA and WA but near average at GR. In contrast, the spring period (mid-March to early May) was slightly wetter at LA and WA (+5–9%) and warmer than average at GR (+1.5°C; Figure 1: upper and middle panels).

The growing season of maize and soybean (May to September) received approximately 75% of the annual precipitation across locations. The average total rainfall during the growing season was 455 mm in GR, 597 mm in LA, and 741 mm in WA. July, with an average of 66 mm, was the driest month at GR while June with an average of 114 mm was the driest at both LA and WA. Across locations, June was the warmest month, with average daily maximum temperatures of 28.1°C (GR), 30.2°C (LA), and 29.5°C (WA).

Across years and locations, daily ETo was often lower than daily precipitation. However, cumulative ETo exceeded rainfall in GR (2017) and LA (2018), suggesting temporary periods of water limitation (Figure 1: lower panel). Average daily ETo over the growing season was 2.8 mm d^{-1} at GR and 3.5 mm d^{-1} at LA and WA.

3.2 Seasonal fluctuations of soil moisture

We observed fixed sources of variation, including seeding and termination timing, main crop, soil depth and the timing of seeding and termination × soil depth interaction significantly ($0.05 > p < 0.0001$) affected soil moisture in all locations. Cover crop strategy, however, had no effect on soil moisture at any site (Table 2).

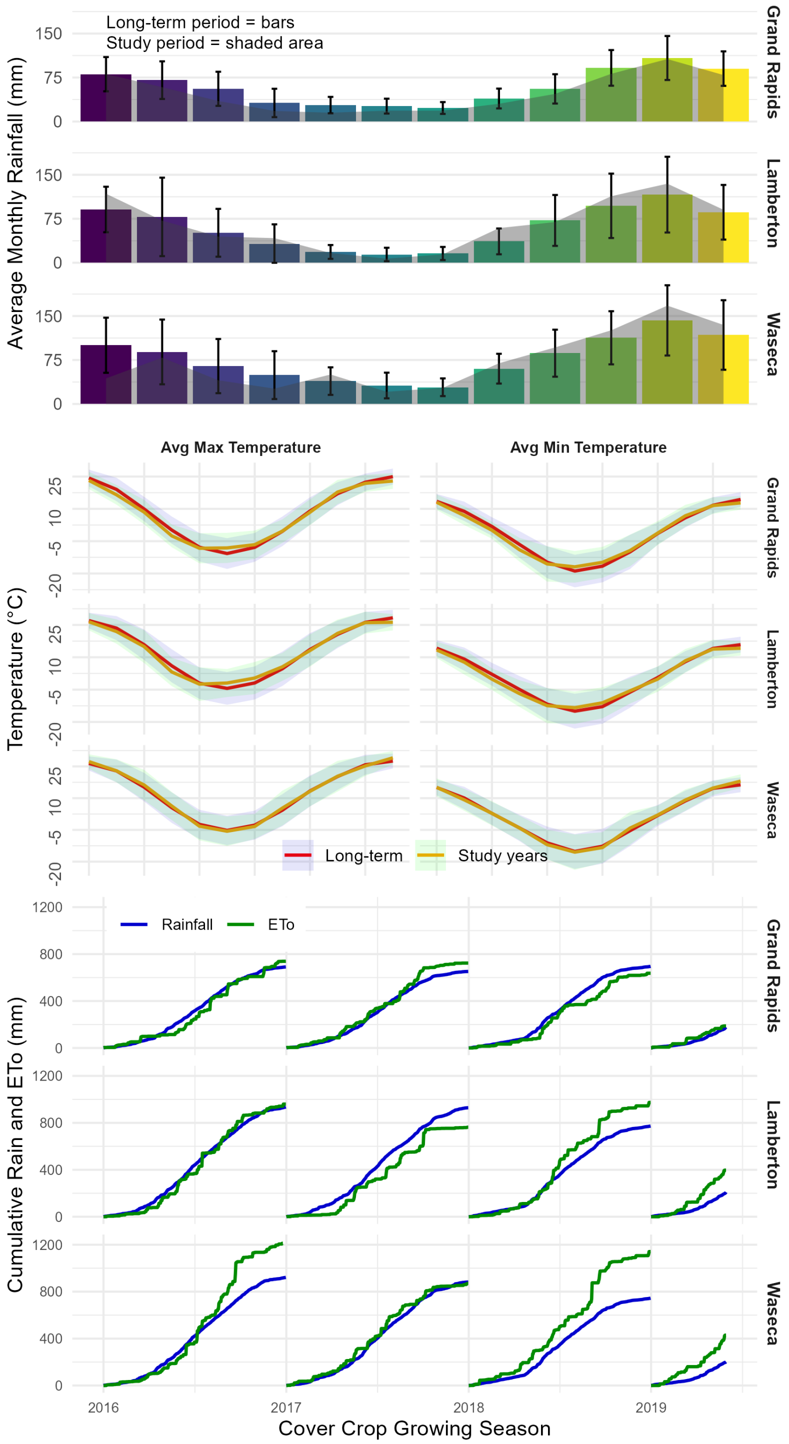


FIGURE 1
Long-term (1990–2015) and study-period (2016–2019) weather conditions at the experimental locations. The upper panel shows the monthly precipitation (mm; mean ± 1 SD as error bars), the middle panel shows the monthly mean air temperature (°C), and the lower panel shows the cumulative rainfall and reference evapotranspiration (ETo, mm) during the maize–soybean growing season (May–September).

Soil moisture generally increased with depth, particularly at the time of seeding, and was highest at the 40 cm layer. For example, in WA soil moisture in the top 40 cm of soil averaged around 0.45 m^3 m^{-3}, suggesting near-saturation during portions of the growing season (Figure 2). These patterns reflect both seasonal precipitation trends (Figure 1) and differences in soil texture and drainage: WA has a somewhat poorly drained clay loam, while GR has a coarser, well-drained loam (Table 1).

TABLE 2 **Significance of fixed sources ofvariation for soil volumetric water content in a maize-soybean rotation with cover crops.**

Fixed Source of Variation†	Grand Rapids	Lamberton	Waseca
		Pr > F‡	
Timing (T)	***	***	***
Main Crop (M)	***	*	***
Cover Crop Strategy (S)	ns	ns	ns
Depth (D)	***	***	***
T × M	ns	**	**
T × S	*	ns	ns
T × D	***	***	***
M × S	*	ns	ns
M × D	*	ns	ns
S × D	*	ns	ns
T × M × S	ns	ns	ns
T × M × D	**	ns	ns
T × S × D	ns	ns	ns
M × S × D	ns	ns	ns
T × M × S × D	ns	ns	ns

†T, seeding and termination; M, maize and soybean; S, cereal rye, cereal rye + crimson clover, cereal rye + crimson clover + forage radish, and no cover crop control; and D = 10, 20, 30, and 40 cm.
‡ ***, **, and *, denote significant effect at $p < 0.0001$, $p \leq 0.01$, and $p \leq 0.05$, respectively; ns denotes no effect at $p > 0.05$

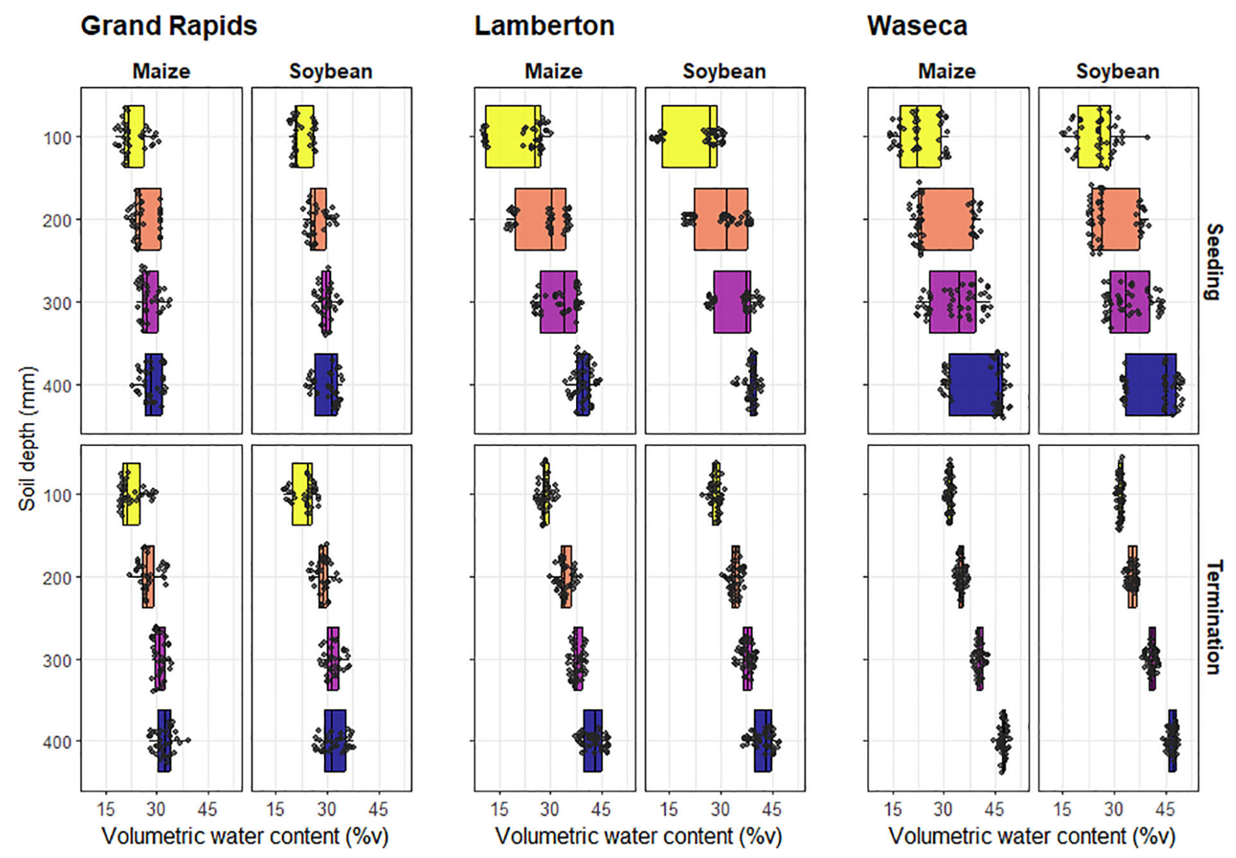


FIGURE 2
Soil volumetric water content (%v) at seeding (top) and termination (bottom) of cover crops at three locations in Minnesota, U.S.

3.3 Performance of crops and cover crops

Grain yield of maize and soybean was significantly affected by year, location, and the year × location interaction but was not affected by cover crop strategy (Table 3). In 2017 and 2018 the average maize yields ranged from 9,020 to 13,600 kg ha^{-1} across sites, with the highest yields observed at LA. The average soybean yields ranged from 2,580 to 5,380 kg ha^{-1} with the highest yields observed at LA. Yields of both maize and soybean were consistently lower at GR, the northernmost site, likely because of shorter-season genotypes selected for cooler growing conditions (Figure 3).

Maize and soybean yields were not significantly affected by cover crops (Figure 4; top panels). Pooled responses to cover crop strategies were negligible (near zero), and most site-year confidence intervals overlapped zero, with positive and negative responses observed across environments. Furthermore, yield responses also showed limited consistency between 2017 and 2018 (Figure 4; bottom-left) and little to no correspondence between crops (Figure 4; bottom-right), likely because cover crop growth (and thus potential yield effects) was low and highly variable among environments and years.

TABLE 3 Significance of fixed sources of variation for grain yield of maize and soybean and biomass yield of cover crops.

Fixed source of variation	Maize	Soybean	Cover crops
Location (L)	***	***	***
Year (Y)	*	***	***
Cover Crops (C)	ns	ns	.
L × Y	***	***	**
L × C	ns	ns	ns
Y × C	ns	ns	ns
L × Y × C	ns	ns	ns

“.”, *, **, *** denote effects significant at $p < 0.10$, < 0.05, < 0.01, and <0.001, respectively; *ns* denotes $p \geq 0.10$.

Across all locations and years, cover crops were interseeded near physiological maturity of the main crop (R5–R6 in maize, R7–R8 in soybean), resulting in seeding dates ranging from late August to mid-September, depending on location and seasonal weather conditions (Rusch et al., 2020). Most seeding dates were followed by rainfall within 1–3 days, except at GR in 2018, which received no rain for 11 days post-seeding. Biomass was measured in both autumn (after 2–3 consecutive frost days) and spring (prior to termination).

Biomass yield of cover crops was significantly affected by location, year, and the year × location interaction. The main effect of cover crop strategy was not significant ($p < 0.10$) nor was the interaction of strategy with location and year, indicating that differences among cover crop strategies were not consistent across environments (Table 3). Although cover crop mixtures were expected to produce more biomass than monocultures, no consistent advantage was observed. Overall, cover crop biomass was highest in the first year (autumn 2016 and spring 2017), but dropped sharply in subsequent years, mainly due to cooler and drier autumns in Grand Rapids and wetter springs in Lamberton and Waseca. Specifically, the average total biomass (autumn + spring) of cover crops at GR, LA, and WA was 474, 891, and 759 kg ha^{-1} in the first year; 106, 159, and 188 kg ha^{-1} in the second year; and only 12, 99, and 184 kg ha^{-1} in the third year (Table 4). This trend is consistent with weather conditions showing colder, longer winters and excessive spring moisture in 2017-2019. For example, average minimum air temperatures from September to May declined from –

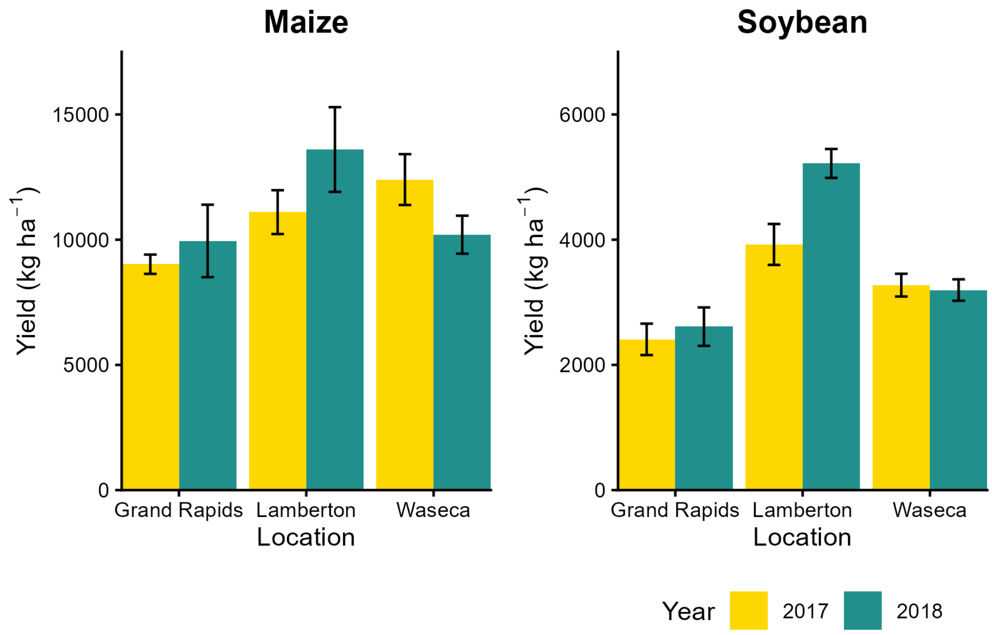


FIGURE 3
Yield of main crops during the experimental years.

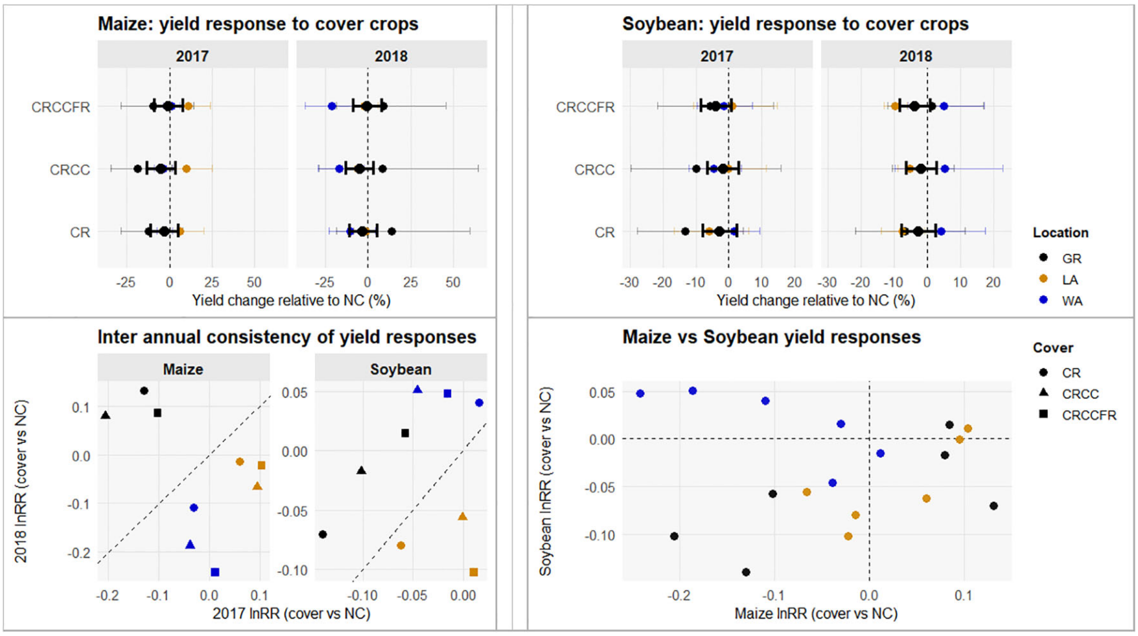


FIGURE 4
Response of maize and soybean yields to cover crop strategies across site-years. Top: yield change (%) relative to the no-cover control (NC). Bottom-left: interannual consistency (2017 vs. 2018 lnRR); points near the 1:1 line indicate more consistent responses. Bottom-right: maize vs. soybean lnRR; quadrants indicate aligned vs. divergent responses.

3.8°C (2016–2017) to −7.4°C and −7.1°C in the following years at GR, while spring rainfall over 130 mm were recorded at WA in both 2017 and 2018, evidencing the less than optimum conditions for cover crops growth.

The autumn to spring biomass trend of cover crops was highly variable across years. For example, in 2016–2017 the biomass generally increased from autumn to spring across sites, which reflected good establishment and winter survival of cereal rye. The opposite trend was observed in 2017–2018 and 2018-2019, when autumn biomass was greater than biomass at spring termination (Table 4). Treatment means (± SE) for the four cover crop strategies by site-year are provided in Supplementary Table 1. Since cereal rye is known for its tolerance to low temperatures, the reduction in spring biomass was likely due to a combination of poor autumn establishment and unfavorable spring conditions for growth. Precipitation in September and October 2017 was low at GR and WA, which may have affected establishment. An increase in rainfall was observed in early spring 2018, particularly at WA and LA, a condition that saturated soils (Figure 1) and likely delayed regrowth.

3.4 Water use of maize and soybean

The water use (ETc) of maize and soybean was significantly affected by location, year, and the location × year interaction while that of cover crops was unaffected (Table 5). These results reflect the combined effect of weather conditions, crop growth and development, and soil water holding capacity. The average ETc of maize ranged from 330 to 516 mm across years and sites; water use was lowest at GR and highest at LA. Soybean ETc ranged from 329 to 509 mm, following a similar spatial and temporal pattern (Figure 5).

3.5 Water use of cover crops

Cover crop ETc was significantly affected by location and year, as well as their interaction, in both autumn and spring (Table 5). However, ETc was not affected by cover crop strategy in either season, suggesting that monocultures and mixtures used similar amounts of water. These results are consistent with the low and variable biomass observed across treatments and years (Table 3), which likely limited transpiration regardless of species composition.

TABLE 4 Biomass of cover crops at autumn frost and spring termination at three locations during three growing seasons.

Location	2016-2017		2017-2018		2018-2019	
	Autumn	Spring	Autumn	Spring	Autumn	Spring
Grand Rapids	124a[$]	340ab	76b	30a	10c	2.3c
Lamberton	401b	490a	149a	10b	76b	23b
Waseca	329b	430a	158a	30a	134a	50a

[$] Columns with different letters differ significantly at $P < 0.05$.

TABLE 5 Significance of fixed sources of variation for water use of maize, soybean and cover crops ET_c (weather-based).

Fixed Source of Variation	Maize	Soybean	Cover Crop	
			Autumn	Spring
Location (L)	**	**	**	**
Year (Y)	**	**	**	ns
Cover Crop Strategy (S)	ns	ns	ns	ns
L × Y	**	**	**	**
L × S	ns	ns	ns	ns
Y× S	ns	ns	ns	ns
L × Y × S	ns	ns	ns	ns

**Highly significant difference ($P < 0.01$); * significant difference ($P < 0.05$); ns denotes no difference.

The total water use of cover crops ranged from 52 to 110 mm across locations and years, with less ETc in GR and more in WA (Figure 6). Most of the ETc occurred as evaporation from the soil surface, mainly in autumn when ground cover was sparse. On average, evaporation accounted for 70% and 60% of total ETc in autumn and spring, respectively, most likely due to the marginal growth of cover crops.

4 Discussion

4.1 Seasonal fluctuations of soil moisture

The interaction between cover crop strategy and other factors (e.g., main crop, timing) marginally affected soil moisture at GR only, but differences were small and inconsistent. Our findings agree with prior studies in similar systems that have reported minimal or no effect of interseeded cover crops on soil moisture (Barker et al., 2018; Daigh et al., 2014).

Across locations, soil moisture at the time of seeding (late summer/early autumn) was more variable and generally lower than at cover crop termination (spring), consistent with high growing season evapotranspiration and soil-water recharge from precipitation accumulation over winter (Hussain et al., 2019). These results also support our decision to limit the analysis to the top 40 cm of soil, as deeper layers showed little variation and are unlikely to be influenced by shallow-rooted cover crops. However, because deeper soil water was not incorporated into ΔS, sub-surface water uptake by maize/soybean from lower soil layers could buffer treatment differences in some site-years; thus, conclusions are strongest for near-surface dynamics.

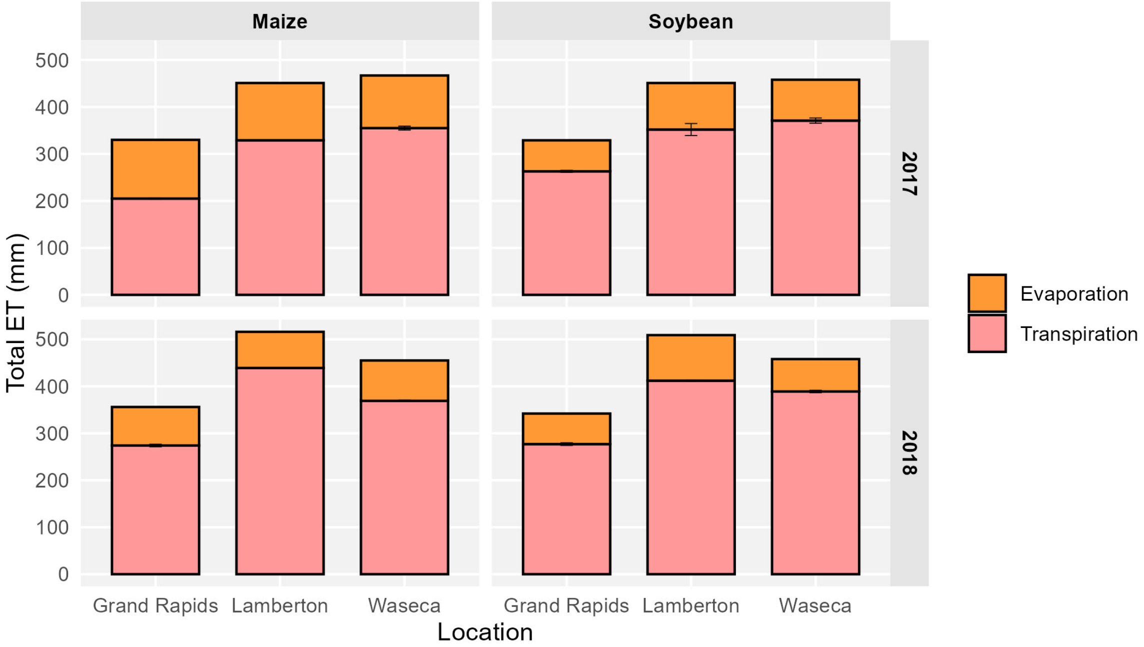


FIGURE 5
Evapotranspiration (E + T) of maize and soybean during the experimental years.

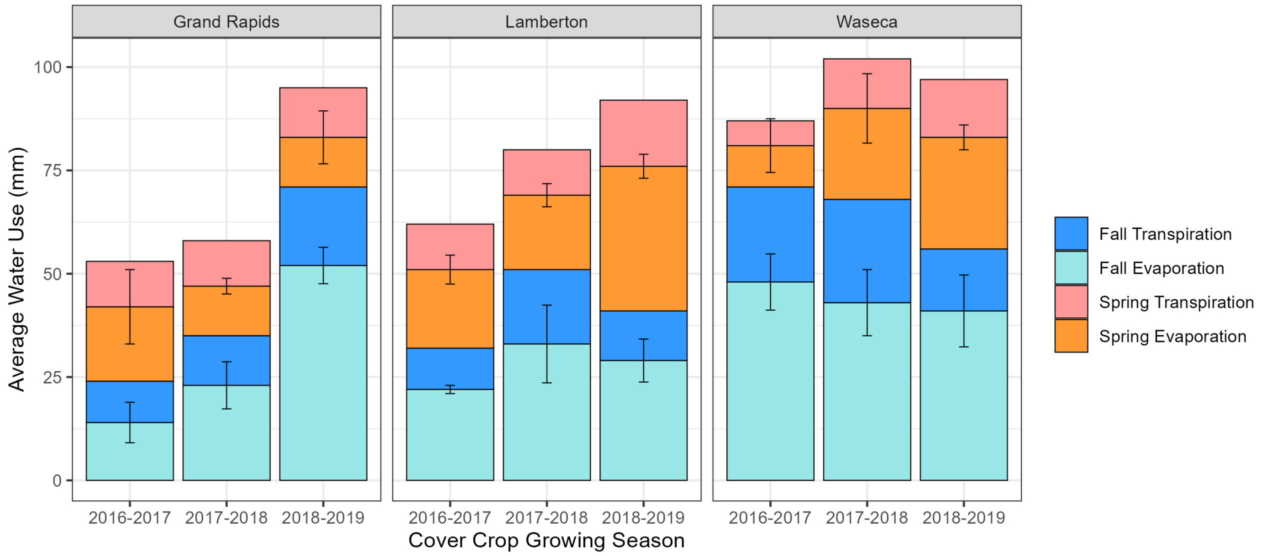


FIGURE 6
Evapotranspiration (E + T) of interseeded cover crops in maize-soybean during the experimental years.

4.2 Performance of crops and cover crops

Maize and soybean yields were 3% and 1% higher, respectively, in the NC than with cover crops, but differences were not significant ($P > 0.05$). These minor differences are not enough evidence of yield reduction, especially considering the marginal biomass of cover crops in the second and third study years (Table 4). The lack of yield effects is consistent with the temporal separation of transpiration between the cash crops and cover crops. Peak transpiration for maize and soybean occurs in mid-summer, whereas cover crops interseeded late into main crops remain small and their transpiration contribution is negligible until after cash-crop senescence. Consequently, cover crop water use is largely displaced to the post-harvest and early spring periods. Under this framework, the net effect of late interseeding on water use depends on whether cover crop biomass is sufficient to shift the water balance from soil evaporation toward cover crop transpiration during these off-season windows (Figure 7). Overall, the results suggest that under the conditions of this study, including relatively low cover crop biomass and short growing seasons, interseeded cover crops did not affect maize and soybean grain yield.

4.3 Water use of maize and soybean

Of the total ETc of maize and soybean, approximately 20% was attributed to soil evaporation, a contribution reflecting an increasingly shaded soil from mid to late growing season. Our findings agree with previous studies in maize production systems

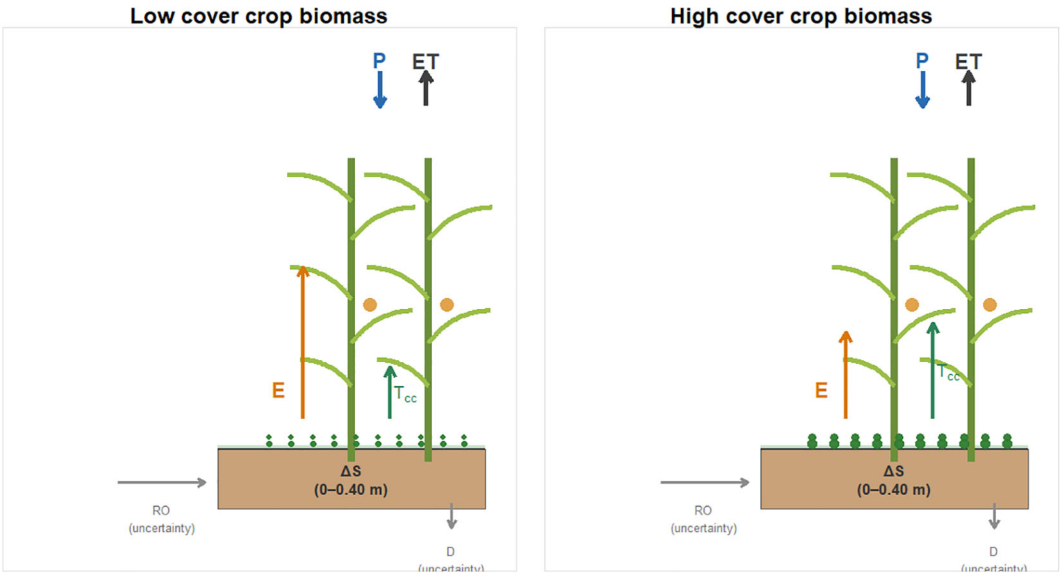


FIGURE 7
Evapotranspiration partitioning as a function of biomass of late-interseeded cover crops.

with similar conditions reporting evaporation loss of 13% (Xinhua et al., 2016) and 19% (Wang et al., 2021). A synthesis of a systematic review further supports our findings, noting that while E/ET ratios above 30% are possible in sparse-canopy or surface-irrigated systems, many well-vegetated cropping systems like maize and soybean show moderate evaporation losses (Kool et al., 2014).

The observed variation in crop ET_c was primarily driven by differences in seasonal weather and site conditions, with little evidence that cover crops affect the water use of the subsequent crop. Our results are consistent with ET_c reported for rainfed maize and soybean in the upper Midwest (Garcia y Garcia and Strock, 2018; Irmak et al., 2014), further supporting that the main driver of variation in crop water use in our study was seasonal weather and site conditions rather than the presence of cover crops.

4.4 Water use of cover crops

These seasonal evaporation rates reflect the fact that cover crops in this study established late and accumulated minimal canopy biomass, especially in years two and three. The relatively low transpiration and high evaporation is a clear indication of bare soil for much of the autumn and spring period. Our results of high evaporation fractions are consistent with findings reported in studies involving low-biomass systems (Silva et al., 2012; Ward et al., 2012). Although this study did not perform a formal economic analysis, the low risk of yield penalties suggests economic feasibility for late-interseeded cover crops. Further, utilizing sufficient biomass for forage can offset costs (Blanco-Canqui et al., 2021).

Interseeded cover crops can, in principle, increase transpiration while simultaneously reducing soil evaporation by increasing surface cover and residue. Although we did not directly measure soil evaporation suppression as a function of residue cover, our E:T partitioning indicates that, when cover crop biomass was marginal, soil evaporation represented a relatively large share of cover crop ET. This is consistent with limited canopy development and limited soil shading, which constrains cover crop transpiration while allowing evaporation to remain high. The dual crop coefficient approach (SIMDualKc) supported this interpretation by indicating a high fraction of ET attributable to soil evaporation during periods of limited cover crop canopy development.

Because the ETc of cover crops was not significantly different from the ETc of the NC, the observed values should not be interpreted as definitive proof of resource competition. Instead, they likely reflect background seasonal soil water fluxes, modulated by weather and soil properties. These findings are in line with previous studies showing that interseeded cover crops, particularly under poor establishment, have limited effects on overall soil water dynamics (Barker et al., 2018; Daigh et al., 2014; Qi and Helmers, 2010).

A correlation analysis of ETc-wb and ETc-kc resulted in a strong association ($R = 0.99$), indicating consistency in the seasonal pattern and magnitude from both ETc approaches used. Although having different assumptions and requirements, the strong correlation found supports the use of the ETc-kc method to partition ETc-wb into its evaporation and transpiration components. Similar agreement has been reported by others using the SIMDualKc model and simplified water balance approaches in rainfed cropping systems (Paredes et al., 2017; Rolim et al., 2007), therefore suggesting that ETc-kc provided a robust and pragmatic approach for studying the dynamics of evapotranspiration in our study.

From a management perspective, our results indicate that when interseeded cover crops produce marginal biomass, within the range observed in this study (typically < 200 kg DM ha^{-1}), soil water storage and cash-crop yields are unlikely to be negatively affected. These findings support interseeding as a low-risk option in short-season rainfed systems, particularly when establishment occurs under a dense canopy and cover crop growth remains limited.

Considering the framework of this study (late-season interseeding), it is important to highlight that our findings are specific to such management practice and conditions. We did not evaluate the effects of alternative management practices like earlier interseeding dates, delayed termination (including planting green), precision seeding, or different cover crop species, all of which could greatly affect soil moisture availability, grain yields, and water use of main crops and cover crops. During the study period, late-season interseeding was relatively uncommon in the upper Midwest; practices such as aerial seeding have shown potential and align well with the short growing seasons and weather limitations in the region. Yet, these results may be a valuable guide for farmers considering or currently adopting similar cover cropping practices under similar environmental conditions.

5 Conclusions

In this study we evaluated the soil moisture dynamics, yields, and water use of main crops and cover crops from a rainfed maize–soybean rotation interseeded with cover crops late in the growing season across three locations in the upper Midwest. Our results showed that under such conditions, cover crops did not affect soil moisture dynamics, grain yield, or water use of maize and soybean. Marginal autumn growth and spring weather conditions resulted in limited cover crop growth, especially during the second and third years, explaining why soil moisture and main crop yields were not affected by the practice. Such conditions are typical of regions with humid continental climates and short growing windows for cover crops. These outcomes may not apply to systems with earlier seeding and late spring termination timings, systems with improved establishment technologies, or different species better suited to overwintering and early spring growth.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

SL: Data curation, Formal analysis, Writing – original draft. HR: Data curation, Investigation, Writing – review & editing. GJ: Supervision, Writing – review & editing. JS: Data curation, Writing – review & editing, Resources, Supervision. LS: Writing –

review & editing. AG: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This work has been supported, in part, by the farm families of Minnesota and their check-off investment though the Minnesota Corn Research and Promotion Council (award # 4142-18SP; www.mncorn.org/) and the Minnesota Department of Agriculture (award #109825; www.mda.state.mn.us/). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Acknowledgments

We thank Nathan Dalman, Mark Coulter, Matt Bickell, and Kara Anderson for assistance with field operations, data collection, and laboratory analysis portions of this research.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author JS declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Correction note

This article has been corrected with minor changes. These changes do not impact the scientific content of the article.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2026.1761663/full#supplementary-material

References

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). "Crop evapotranspiration—guidelines for computing crop water requirements—FAO irrigation and drainage paper 56," in *Irrigation and drainage*. Rome: Food and Agriculture Organization of the United Nations. doi: 10.1016/j.eja.2010.12.001

CTIC-SARE-ASTA. (2023). *National cover crop survey report*. College Park, MD: Sustainable Agriculture Research and Education. 83. Available online at: https://www.sare.org/resources/national-cover-crop-survey-reports/ (Accessed December 2, 2025).

USDA, National Agricultural Statistics Service (NASS). (2026). *Crop production 2025 summary*. Washington, DC: U.S. Department of Agriculture. 114. Available online at: https://release.nass.usda.gov/reports/cropan26.pdf (Accessed January 14, 2026).

USDA-NRCS. (2025). *National cooperative soil survey characterization database*. Washington, DC: U.S. Department of Agriculture, Natural Resources Conservation Service. Available online at: https://ncsslabdatamart.sc.egov.usda.gov/ (Accessed December 3, 2025).

Barker, J. B., Heeren, D. M., Koehler-Cole, K., Shapiro, C. A., Blanco-Canqui, H., Elmore, R. W., et al. (2018). Cover crops have negligible impact on soil water in Nebraska maize–soybean rotation. *Agron. J.* 110, 1718–1730. doi: 10.2134/agronj2017.12.0739

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

Blanco-Canqui, H., Drewnoski, M. E., and Rice, D. G. (2021). Does harvesting cover crops eliminate the benefits of cover crops? Insights after three years. *Soil Sci. Soc. Am. J.* 85, 146–157. doi: 10.1002/saj2.20175

Chen, G., and Weil, R. R. (2011). Root growth and yield of maize as affected by soil compaction and cover crops. *Soil Tillage Res.* 117, 17–27. doi: 10.1016/j.still.2011.08.001

Daigh, A. L., Helmers, M. J., Kladivko, E., Zhou, X., Goeken, R., Cavdini, J., et al. (2014). Soil water during the drought of 2012 as affected by rye cover crops in fields in Iowa and Indiana. *J. Soil Water Conserv.* 69, 564–573. doi: 10.2489/jswc.69.6.564

Gabriel, J. L., Quemada, M., Martín-Lammerding, D., and Vanclooster, M. (2019). Assessing the cover crop effect on soil hydraulic properties by inverse modelling in a 10-year field trial. *Agric. Water Manage.* 222, 62–71. doi: 10.1016/j.agwat.2019.05.034

Garba, I. I., Bell, L. W., and Williams, A. (2022). Cover crop legacy impacts on soil water and nitrogen dynamics, and on subsequent crop yields in drylands: A meta-analysis. *Agron. Sustain. Dev.* 42, 1–21. doi: 10.1007/s13593-022-00760-0

García y García, A., Persson, T., Guerra, S., and Hoogenboom, G. (2020). Response of continuous soybean to variable irrigation and nitrogen management. *Agrosyst Geosci Environ* 3:e20070. Burnsville, MN: Wiley. doi: 10.1002/agg2.20070

García y García, A., and Strock, J. S. (2018). Soil water content and crop water use in contrasting cropping systems. *Trans. ASABE* 61, 75–86. doi: 10.13031/trans.12118

García y García, A., Strock, J., Johnson, G., Potter, B., Vetsch, J., Sadok, W., et al. (2020). *Impact of cover crop strategies on productivity of corn*. Burnsville, MN: Minnesota Corn Research & Promotion Council. Available online at: https://www.mncorn.org/research-item/impact-of-cover-crop-strategies-on-productivity-of-corn-2/ (Accessed December 2, 2025).

Grassini, P., Specht, J. E., Tollenaar, M., Ciampitti, I., and Cassman, K. G. (2014). "High-yield maize-soybean cropping systems in the US Corn Belt," in *Crop physiology: applications for genetic improvement and agronomy* (Elsevier Inc). London, UK: Elsevier. doi: 10.1016/B978-0-12-417104-6.00002-9

He, Q., Lu, C., Cowie, A., Zhao, S., Liu, D. L., Yi, B., et al. (2025). Optimizing cover cropping application for sustainable crop production. *NPJ Sustain. Agric.* 3, 1–11. doi: 10.1038/s44264-025-00050-8

Hussain, M. Z., Hamilton, S. K., Bhardwaj, A. K., Basso, B., Thelen, K. D., and Robertson, G. P. (2019). Evapotranspiration and water use efficiency of continuous maize and maize and soybean in rotation in the upper Midwest U.S. *Agric. Water Manage.* 221, 92–98. doi: 10.1016/j.agwat.2019.02.049

Irmak, S., Specht, J. E., Odhiambo, L. O., Rees, J. M., and Cassman, K. G. (2014). Soybean yield, evapotranspiration, water productivity, and soil water extraction response to subsurface drip irrigation and fertigation. *Trans. ASABE* 57, 729–748. doi: 10.13031/trans.57.10085

Kool, D., Agam, N., Lazarovitch, N., Heitman, J. L., Sauer, T. J., and Ben-Gal, A. (2014). A review of approaches for evapotranspiration partitioning. *Agric. For. Meteorol.* 184, 56–70. doi: 10.1016/j.agrformet.2013.09.003

Krstić, Đ., Vujić, S., Jaćimović, G., D'Ottavio, P., Radanović, Z., Erić, P., et al. (2018). The effect of cover crops on soil water balance in rain-fed conditions. *Atmosphere* 9 (12):492. doi: 10.3390/atmos9120492

Meyer, N., Constantin, J., Bergez, J.-E., and Justes, E. (2018). Impact of different cover crops management on soil water profile and dynamics. *Proc. Eur. Soc. Agron.* 116.

Mitsch, W. J., Day, J. W., Gilliam, J. W., Groffman, P. M., Hey, D. L., Randall, G. W., et al. (2001). Reducing nitrogen loading to the gulf of Mexico from the Mississippi River Basin: Strategies to counter a persistent ecological problem. *BioScience* 51, 373–388. doi: 10.1641/0006-3568(2001)051[0373:RNLTTG]2.0.CO;2

Paredes, P., Pereira, L. S., Rodrigues, G. C., Botelho, N., and Torres, M. O. (2017). Using the FAO dual crop coefficient approach to model water use and productivity of processing pea (Pisum sativum L.) as influenced by irrigation strategies. *Agric. Water Manage.* 189, 5–18. doi: 10.1016/j.agwat.2017.04.010

Qi, Z., and Helmers, M. J. (2010). Soil water dynamics under winter rye cover crop in Central Iowa. *Vadose Zone J.* 9(1):53–60. doi: 10.2136/vzj2008.0163

Qiu, T., Shi, Y., Peñuelas, J., Liu, J., Cui, Q., Sardans, J., et al. (2024). Optimizing cover crop practices as a sustainable solution for global agroecosystem services. *Nat. Commun.* 15, 10617. doi: 10.1038/s41467-024-54536-z

Raza, A., Khare, T., Zhang, X., Rahman, M. M., Hussain, M., Gill, S. S., et al. (2025). Novel strategies for designing climate-smart crops to ensure sustainable agriculture and future food security. *J. Sustain. Agric. Environ.* 4, 1–25. doi: 10.1002/sae2.70048

Rolim, J., Godinho, P., Sequeira, B., Paredes, P., and Pereira, L. S. (2007). "Assessing the SIMDualKc model for irrigation scheduling simulation in Mediterranean environments," in *Water saving in Mediterranean agriculture and future research needs*, vol. 56. Eds. N. Lamaddalena, C. Bogliotti, M. Todorovic and A. Scardigno (CIHEAM, Bari, Italy), 49–61.

Rosa, R. D., Paredes, P., Rodrigues, G. C., Alves, I., Fernando, R. M., Pereira, L. S., et al. (2012a). Implementing the dual crop coefficient approach in interactive software. 1. Background and computational strategy. *Agric. Water Manag.* 103, 8–14. doi: 10.1016/j.agwat.2011.10.013

Rosa, R. D., Paredes, P., Rodrigues, G. C., Fernando, R. M., Alves, I., Pereira, L. S., et al. (2012b). Implementing the dual crop coefficient approach in interactive software. 2. Model testing. *Agric. Water Manag.* 103, 62–77. doi: 10.1016/j.agwat.2011.10.018

Rusch, H. L., Coulter, J. A., Grossman, J. M., Johnson, G. A., Porter, P. M., and García y García, A. (2020). Towards sustainable maize production in the U.S. upper Midwest with interseeded cover crops. *PLoS One* 15:e0231032. doi: 10.1371/journal.pone.0231032

Silva, V. P. R., Borges, C. J. R., Farias, C. H. A., Singh, V. P., Albuquerque, W. G., and Silva, B. B. (2012). Water requirements and single and dual crop coefficients of sugarcane grown in a tropical region, Brazil. *Agric. Sci.* 3, 274–286. doi: 10.4236/as.2012.32032

Smith, M. (1992). "CROPWAT: A computer program for irrigation planning and management," in *FAO irrigation and drainage paper 46*. Rome: Food and Agriculture Organization of the United Nations.

Steduto, P., Hsiao, T. C., and Fereres, E. (2007). On the conservative behavior of biomass water productivity. *Irrig. Sci.* 25, 189–207. doi: 10.1007/s00271-007-0064-1

Syswerda, S. P., Basso, B., Hamilton, S. K., Tausig, J. B., and Robertson, G. P. (2012). Long-term nitrate loss along an agricultural intensity gradient in the Upper Midwest USA. *Agric. Ecosyst. Environ.* 149, 10–19. doi: 10.1016/j.agee.2011.12.007

Unger, P. W., and Vigil, M. F. (1998). Cover crop effects on soil water relationships. *J. Soil Water Conserv.* 53, 200–207. doi: 10.1080/00224561.1998.12457219

Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *J. Stat. Softw.* 36(3):1–48. doi: 10.18637/jss.v036.i03

Wang, Y., Horton, R., Xue, X., and Ren, T. (2021). Partitioning evapotranspiration by measuring soil water evaporation with heat-pulse sensors and plant transpiration with sap flow gauges. *Agric. Water Manage.* 252:106883. doi: 10.1016/j.agwat.2021.106883

Ward, P. R., Flower, K. C., Cordingley, N., Weeks, C., and Micin, S. F. (2012). Soil water balance with cover crops and conservation agriculture in a Mediterranean climate. *Field Crops Res.* 132, 33–49. doi: 10.1016/j.fcr.2011.10.017

Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis*. New York, NY: Springer-Verlag.

Xiao, X., Sauer, T. J., Horton, R., Ren, T., Wang, Y., Zhao, Y., et al. (2016). Partitioning evaporation and transpiration in a maize field using heat-pulse sensors for evaporation measurement. *Trans. ASABE* 59, 591–599. doi: 10.13031/trans.59.11059

Zwart, S. J., and Bastiaanssen, W. G. M. (2004). Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agric. Water Manage.* 69, 115–133. doi: 10.1016/j.agwat.2004.04.007