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Interseeded cover crop mixtures influence soil water storage during the corn phase of corn-soybean-wheat no-till cropping systems

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ABSTRACT

Cover crops (CC) have the potential to increase water storage by reducing runoff, increasing infiltration, and decreasing evaporation. Interseeding CC into a summer cash crop can increase CC biomass production essential for maximizing beneficial services. Effects of interseeded CC on soil water content during the following cash crop has not been fully evaluated in the Mid-Atlantic USA. Soil water content was measured during the corn (*Zea mays* L.) phase of four no-till rotations at the USDA Beltsville Agricultural Research Center, Beltsville, MD from 2017 through 2020. All systems included corn-soybean (*Glycine max* L.)-wheat (*Triticum aestivum* L.) rotations, and Systems 3, 4 and 5 added double crop soybean (DCS) after wheat. In System 5, a mix of rye (*Secale cereale* L.)-hairy vetch (*Vicia villosa* Roth)-crimson clover (*Trifolium incarnatum* L.) was interseeded into DCS. In System 6, red clover (*rc*, *Trifolium pratense* L.) was interseeded into wheat and rye was planted into *rc* after wheat harvest. In 2017 and 2018, season average soil water storage was 20 mm greater in systems with CC before corn compared to no CC before corn (NC). A similar, but non-significant, trend was present in 2019 and 2020 (11 mm). Estimated evapotranspiration was lower for CC compared to NC systems in 2018, while greater estimated infiltration was observed for CC compared to NC systems in 2019. Four-year average corn yields were greater for CC compared to NC systems (12.1 vs 10.6 Mg ha^{-1}). Similarly, average corn water use efficiency (WUE) was greater in CC compared to NC systems (5.55 vs 4.70 kg m^{-3}). The returns from increased yield more than offset the cost of CC establishment. The combination of greater yields and WUE demonstrate the benefits of interseeded CC in humid regions of the US.

1. Introduction

Crop productivity in Northeastern and Mid-Atlantic agriculture is expected to be negatively impacted by future patterns of increased evapotranspiration (ET) driven by higher summer temperatures (Boesch et al., 2008; Dupigny-Giroux et al., 2018). Precipitation intensity in the Northeastern United States has increased in recent decades (Guilbert et al., 2015; Hoerling et al., 2016) resulting in increased risk of runoff and reducing potential contributions to soil water storage (SWS). Predicted regional temperature increases (Lynch et al., 2016) will place greater demand on available soil moisture, potentially negatively impacting crops during critical periods of anthesis and grain-filling. To adapt, producers need improved management practices that increase rainfall infiltration and reduce surface evaporation to maintain soil water availability for crop growth.

Long-term use of winter cover crops (CC) affects soil physical properties and has been demonstrated to increase soil porosity, water infiltration and SWS (Basche et al., 2016; Blanco-Canqui and Ruis, 2020; Daigh et al., 2014; Leuthold et al., 2021; Qi et al., 2011a). In a meta-analysis Blanco-Canqui and Ruis (2020) report an 1.5% increase in macroporosity and a 62% increase in water infiltration due to CC. However, the authors note the magnitude of the effect on infiltration was highly variable among the studies indicating that effects are site and management specific. For example, in Maryland a rye (*Secale cereale* L.) CC in no-till continuous corn (*Zea mays* L.) generally decreased bulk density at Coastal Plain sites but not at a Piedmont site and had no effect on growing season infiltration after 12–13 years (Steele et al., 2012). Although CC may reduce soil water at planting (Alonso-Ayuso et al., 2014; Unger and Vigil, 1998), in humid regions spring rainfall is usually sufficient to overcome any deficit (Basche et al., 2016; Clark et al., 2007,

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1997). Given predicted regional increases in late winter and early spring precipitation (Thibeault and Seth, 2014) CC water use may even improve conditions for planting in wet years (Li et al., 2021). In years with insufficient summer rainfall, increased infiltration and reduced soil evaporation can increase soil water availability to crops, particularly during critical reproductive phases (Clark et al., 2007; Leuthold et al., 2021).

During the cropping season, water moves from the soil to the atmosphere through both crop transpiration and evaporation from the soil surface thus reducing water stored in the soil profile (Dingman, 1994). Cover crop residues lower soil temperatures (Dabney, 1998) and slow surface evaporation during drying cycles (Alonso-Ayuso et al., 2014; Clark et al., 2007), particularly during the early growing season prior to canopy closure (Balwinder-Singh et al., 2011). However, the mulching effect of surface CC residues on soil water is variable (Unger and Vigil, 1998). For example, Qi et al. (2011a) report greater average weekly SWS in the top 60 cm of soil in an Iowa no-till corn crop which they attribute to reduced soil surface evaporation and increased infiltration due to surface rye CC residues. In contrast, in a Minnesota study where there was limited rye biomass production and below average rainfall, the rye CC resulted in no effect on SWS relative to no CC in a continuous corn silage system (Krueger et al., 2011). When drought occurs during the cash crop production period, the favorable effects of rye residues on SWS depends on capturing early season rainfall and having sufficient rye biomass to reduce evaporation (Daigh et al., 2014). Clark et al. (2007) reported greater soil moisture for late-killed rye and rye-vetch CC compared to late-killed vetch, early-killed rye or mixtures, and no cover controls, which the authors attribute to greater residue cover with the late-killed rye and rye vetch.

Cover crop growth and biomass production can be limited following double crop soybean (*Glycine max* L.) (DCS) harvest in the Mid-Atlantic region due to the limited window for CC establishment prior to cold weather (Curran et al., 2018). By seeding CC into a growing main crop, relay intercropping can increase successful establishment and growth leading to greater spring biomass production, as well as increasing the diversity of potential CC species (Caswell et al., 2019). Intercropping CC can also potentially reduce weed pressure and nutrient losses (Bybee-Finley and Ryan, 2018; Teasdale, 1996; Thapa et al., 2018). The effects on soil water balances and water use efficiency of corn following interseeded CC mixtures have not been fully investigated in the Mid-Atlantic region. To evaluate the potential management implications of interseeded legume-rye CC mixtures on soil temperature, SWS, evapotranspiration, infiltration, corn yield and water use efficiency, we compared systems where CC were planted into wheat (*Triticum aestivum* L.) or DCS to systems where no CC was grown prior to the following corn crop.

2. Materials and methods

2.1. Experimental site and management

This investigation was conducted in the long-term Cover Crop Systems Project (CCSP) (39°00′ 51.3"N, 76°56′ 29.0"W) at the Beltsville Agricultural Research Center in Beltsville, MD USA from 2017 through 2020. Soils at the study site are mapped as Codorus (fine-loamy, mixed, active, mesic Fluvaquentic Dystrudept) and Hatboro (fine-loamy, mixed, active nonacid, mesic Fluvaquentic Endoaquept) silt loams (NRCS Web Soil Survey, accessed 11/2/2021) with slopes less than one percent. The Codorus and Hatboro series consist of very deep, moderately well drained to somewhat poorly drained soils formed in recently deposited alluvium on floodplains. Saturated hydraulic conductivity is moderately high to high. The site is underlain by drain tiles located 0.8–1.25 m below the soil surface and spaced approximately 15 m apart. Those under replications 1, 2 and 3 run northwest to southeast while those under replication 4 run northeast to southwest. The drain tiles were installed in the early 1950′s and remain functional although the output from the research field is not monitored. The locations of the drain lines were confirmed using ground penetrating radar in the fall of 2017 (Allred et al., 2018).

The prior study on this site (2011–2013) evaluated CC termination management in organic corn-soybean-wheat production systems (Keene et al., 2017; Wallace et al., 2018). The site was transitioned to the current study in the spring of 2014 when the entire area was planted to corn. In the fall of 2014 and spring of 2015, cover crop treatments were initiated as in Table 1. The first cash crops of the CCSP study were harvested in 2015.

The CCSP experiment is laid out as a randomized split-plot experiment with four replications (blocks). Whole plots are crop phase (corn, soybean or wheat, each crop is grown every year) and split-plots are CC systems (3 through 6 described below, Table 1). Soybean in interseeded systems and corn in all systems were planted in 76 cm rows with a four-row planter. Soybean in non-interseeded treatments was planted in 38 cm rows with an eight-row planter. Wheat was planted in 19 cm rows with a grain drill. Interseeded cover crops were planted in three 19 cm rows between two cash crop 76 cm rows with the Penn State University Interseeder (Curran et al., 2018). Other cover crops were planted in 19 cm rows with a grain drill. All cash crops were planted at University of Maryland Extension recommended rates.

Cropping systems 3, 4, and 5 consist of no-till corn–soybean–wheat—DCS rotations while System 6 is a no-till corn–soybean–wheat rotation (Table 1). In Systems 3 and 4, there is no cover crop (NC) prior to corn; however, System 4 includes a cereal rye CC between corn and the following full season soybean. The other two systems (CC, Systems 5 and 6) focus on interseeding legumes and rye into the cash crop preceding corn. In System 5, a rye + legume mix [hairy vetch (*Vicia villosa* Roth) + crimson clover (*Trifolium incarnatum* L.)] is interseeded into DCS prior to canopy closure in mid-August. The System 5 rye + hairy vetch + crimson clover was interseeded at 36 + 12 + 6 kg ha^{-1} (2017), 48 + 36 + 6 kg ha^{-1} (2018), 36 + 24 + 6 kg ha^{-1} (2019 and 2020). In 2017, this CC mixture also included 6 kg ha^{-1} red clover (*Trifolium pratense* L.). In System 6, red clover was interseeded into wheat in March at 30, 16, 18 or 19 kg ha^{-1} and rye was interseeded into the red clover in the fall at 145, 145, 135 or 36 kg ha^{-1} 2017 through 2020 respectively. The rye seeding rate was reduced in 2020 to allow more vigorous growth of the red clover in the fall and following spring.

The rye CC prior to full season soybean was terminated at boot stage with a mixture of 1.26 kg ha^{-1} glyphosate (N-(phosphonomethyl) glycine), 0.35 kg ha^{-1} metribuzin (4-amino-6-tert-butyl-3-(methylthio)– 1,2,4-triazin-5(4 H)-one), and 1.49 kg ha^{-1} S-metolachlor ((S)–2-chloro-N-(2-ethyl-6-methyl-phenyl)-N-(1-methoxypropan-2-yl)acetamide). The rye-legume mixtures prior to corn were terminated with

Table 1
Three-year main crop and cover crop rotation sequences in the Cover Crop Systems Project.

Cover crop†	System	Phase 1	Phase 2	Phase 3
NC	3	CORN‡	SOYBEAN	WHEAT-DCS§
NC	4	CORN-*rye*	*rye*-SOYBEAN	WHEAT-DCS
CC	5	CORN-*rye*	*rye*-SOYBEAN	WHEAT-DCS-*interseeded rye+hairy vetch+crimson clover*
CC	6	CORN-*rye*	*rye*-SOYBEAN	WHEAT-*interseeded red clover+fall planted rye*

† Designation of presence or absence of cover crop treatment at the end of phase 3 prior to the corn phase. NC indicates no cover crop, CC indicates cover crop.
‡ Cash crops are designated with capital letters while cover crops are in lowercase and italics letters. The rye cover crop in phase 1 following corn is the same rye cover crop in phase 2 prior to soybean.
§ DCS double cropped soybean is soybean planted in late June following wheat harvest.

0.84 kg ha^{-1} glyphosate, 0.42 kg ha^{-1} dicamba (3,6-dichloro-2-methoxybenzoic acid), and 0.28 kg ha^{-1} 2,4-D (2,4-Dichlorophenoxy-acetic acid). Once terminated, CC residues remained standing until the corn planting operation flattened the majority of the residues creating a mulch layer on the soil surface. Cover crop aboveground biomass samples were harvested just prior to termination (Table 2). Samples were collected from two representative 0.5 m^2 sub-areas in each plot. Biomass was clipped at the soil surface and dried for 10–14 days at 60 °C and weighed. Harvested biomass samples included CC species plus any weeds present (usually none).

An experimental objective at CCSP is to manage each system based on farmer practices in the Mid-Atlantic states. Many producers in the region do not use CC or kill their CC early to be able to plant near the end of April or beginning of May. Growers who maximize CC biomass production usually plant 10–15 days later than producers who do not use CC. Corn in the NC systems (3 and 4) was planted in early May usually 10–20 days prior to the CC systems (5 and 6), except in 2020 when all systems were planted on the same day (Table 2). The corn variety from 2017 through 2020 was Pioneer P0506AM. Documentation indicates it has a comparative relative maturity rating of 105 and requires 3150 heat units to reach maturity. Corn in all systems received 28 kg N ha^{-1} as starter fertilizer at planting. Corn in Systems 3 and 4 was sidedressed with 134, 157, 134 and 134 kg N ha^{-1} in 2017, 2018, 2019 and 2020, respectively. Corn in Systems 5 and 6 was sidedressed with 86, 134, 134 and 134 kg N ha^{-1} in 2017, 2018, 2019 and 2020, respectively.

Soil water measurements in the corn phase of the rotation began in the spring of 2017. Because we only focus on the corn phase, our experimental design reduces to a completely randomized block with 2 (2017) or 3 (2018–2020) replications. Because all rotation phases are present every year, each crop is grown in different plots over three consecutive years. In the fourth year, cash crops return to the same plots they were grown on in year one.

2.2. Weather data, corn growth stages, and potential evapotranspiration

Weather data were collected at a weather station located less than 80 m from CCSP. Air temperature, rainfall, relative humidity, solar radiation at the surface of the ground and windspeed data from the weather station were used to calculate daily values. Air temperature data were used to calculate growing degree days (GDD °C) as described in Abendroth et al., 2011. Corn development stages were estimated based on the accumulation of GDD using 10 °C and 30 °C as minimum and maximum optimum temperatures for corn growth and development (Abendroth et al., 2011). Developmental stages were adjusted to include emergence occurring at 105 GDD from planting. Daily GDD values were summed to give cumulative GDD (CumGDD °C). Daily growing degree days were calculated as follows:

$$GDD = [(TMIN + TMAX)/2] - 10,$$

TMIN = minimum daily air temperature (if temperature is less than 10 °C, use 10 as TMIN) and TMAX = maximum daily air temperature (if temperature is greater than 30 °C, use 30 as TMAX).

Weather data were also used as inputs to calculate daily potential evapotranspiration (PET) based on the Penman Montieth method using ETCalc, an online evapotranspiration calculator (Danielescu, 2021 and 2022).

2.3. Soil water and temperature measurements

Soil volumetric water content (m^3 m^{-3}) and temperature (°C) were measured at four depths in two (2017) or three (2018 – 2020) of the four field replications using time-domain reflectometry (TDR) sensors (Table 3). Data were collected at 5-minute intervals and stored as hourly (2017) or 15 min (2018–2020) averages using Campbell Scientific CR206X and CR1000 dataloggers (Campbell Scientific Inc., Logan, UT). Sensors were installed in non-traffic rows halfway between corn rows. They were installed in a vertical orientation and spaced 80–120 cm apart. The locations for sensor placement were established using GPS so that they were approximately halfway between mapped drain tiles (Allred et al., 2018) to minimize effects of drainage on soil water measurements as much as possible. Installation of soil water sensors occurred as soon as possible after corn planting.

2.4. Data QAQC

Raw volumetric water content data were evaluated for quality using routines from the International Soil Moisture Network QAQC approach

Table 2
Corn planting and harvest dates, cumulative growing degree days (CumGDD °C), rainfall, and sensor measurement periods for NC and CC systems during the corn growing season.

									Soil Water Measurement Period				
Year	CC Treat	CC Kill Date	Planting Date	PET† total mm, daily average mm, days	PET Period Rainfall mm	Harvest Date	CumGDD‡°C	Rainfall§mm	Sensor Install	Begin Date	End Date‖	Begin CumGDD¶	End CumGDD
2017	NC	–	2-May			5-Oct	1760	507	1-Jun	2-Jun	1-Sep	205	1452
2017	CC	4-May	18-May	148, 8.7, 17	63	5-Oct	1688	426	1-Jun	10-Jun	12-Sep	205	1455
2018	NC	–	10-May			20-Oct	2094	805	14-May	1-Jun	26-Aug	278	1467
2018	CC	10-May	30-May	217, 10.3, 21	122	20-Oct	1868	652	20-June	22-Jun	7-Sep	277	1463
2019	NC	–	4-May			24-Sep	1877	297	8-May	20-May	23-Aug	128	1504
2019	CC	8-May	17-May	163, 11.6, 14	17	24-Sep	1801	236	22-May	27-May	30-Aug	127	1505
2020	NC&CC	29-Apr	13-May	0		6-Oct	1812	495	20-May	26-May	1-Sep	77	1557

† PET is potential evapotranspiration estimated from 10 days after planting of corn in Systems 3 and 4, to 10 days after planting corn in Systems 5 and 6.
‡ CumGDD, Cumulative growing degree days °C at harvest
§ Rainfall is estimated from planting to harvest.
‖ End date indicates the calendar day equivalent for the final CumGDD used in the estimation of cumulative ET. End date for estimating cumulative infiltration was September 1 for all years.
¶CumGDD at beginning and end of soil water measurement period

Table 3
Soil sensor numbers per plot, waveguide lengths, depths measured, and horizon thickness for estimating water volume during the corn growing season.

Sensor	Number per plot	Wave guide Length mm	Sensor Measured Depth Top mm	Bottom mm	Estimated Horizon Boundary (Depth)† Top mm	Bottom mm	Horizon Thickness mm
2017							
CWS655‡	3	120	0	120	0	187	187
TDR310§	2	100	254	354	187	431	244
TDR310	2	100	508	608	431	685	254
TDR310	1	100	762	862	685	862	177
2018–2020							
TDR315	2#	150	0	150	0	202	202
TDR310	2	100	254	354	202	431	229
TDR310	2	100	508	608	431	685	254
TDR310	1	100	762	862	685	862	177

† Each horizon was considered to extend to halfway between the bottom of the upper sensor and the top of the next lower sensor.
‡ CWS655 is the Campbell Scientific wireless soil water content reflectometer (Campbell Scientific Inc., Logan, UT).
§ TDR310 and TDR315 are the Acclima TDR310 (S or H) and TDR315 (L or H) soil water content sensors (Acclima Inc., Meridian, ID). A mix of the S, L and H versions of the sensors were used with more of the later versions used in the later years.
# In 2019 and 2020 two areas in each plot were measured, doubling the listed number of sensors per plot and depth.

(Dorigo et al., 2021, 2013). The procedure applied simple threshold checks and evaluated trends in the time series data and their first and second derivatives. Spurious data were flagged and compared to nearby data. In addition, all data were graphed and evaluated visually. Short periods of missing data that occurred when no rainfall fell were replaced using the EXPAND procedure in SAS 9.4 (SAS Institute, Inc., Cary, NC; SAS Inst. Inc., 2019) to interpolate missing values with a linear function. Where missing data occurred in association with rainfall events, data from the other treatments in the same replication were used to estimate the missing data based on regressions estimated from the entire cropping season. This approach was used for missing surface sensor data in Systems 5 and 6 in 2017 for the period from 23 July to 10 August that occurred due to the failure of a data logger in replication 3. All other times when sensors or a data logger failed were of sufficiently short duration that interpolation was used to fill in the missing data. Interpolations were carried out for individual sensors prior to averaging data for the day.

2.5. *Estimation of soil water storage, estimated evapotranspiration and estimated infiltration*

Daily averages of volumetric water content and soil temperature were calculated from hourly (2017) or 15-minute data (2018 through 2020). Data from multiple sensors within a depth were averaged after data cleaning. Soil water storage was estimated by multiplying daily volumetric water content times the horizon depth to get millimeters of water. Calculation of SWS assumed that measurements within a depth interval were representative of that horizon depth interval. Millimeters of water for each depth were summed to obtain whole profile (0–862 mm) SWS.

The daily change in SWS was used to estimate evapotranspiration (ETe) and infiltration (INFe) as described by Sadeghi et al. (2007). This simple approach is based on the change in SWS for the soil profile between the current and previous day. Each day is considered to start at 5 am. Daily negative change in SWS was designated as ETe (daily losses

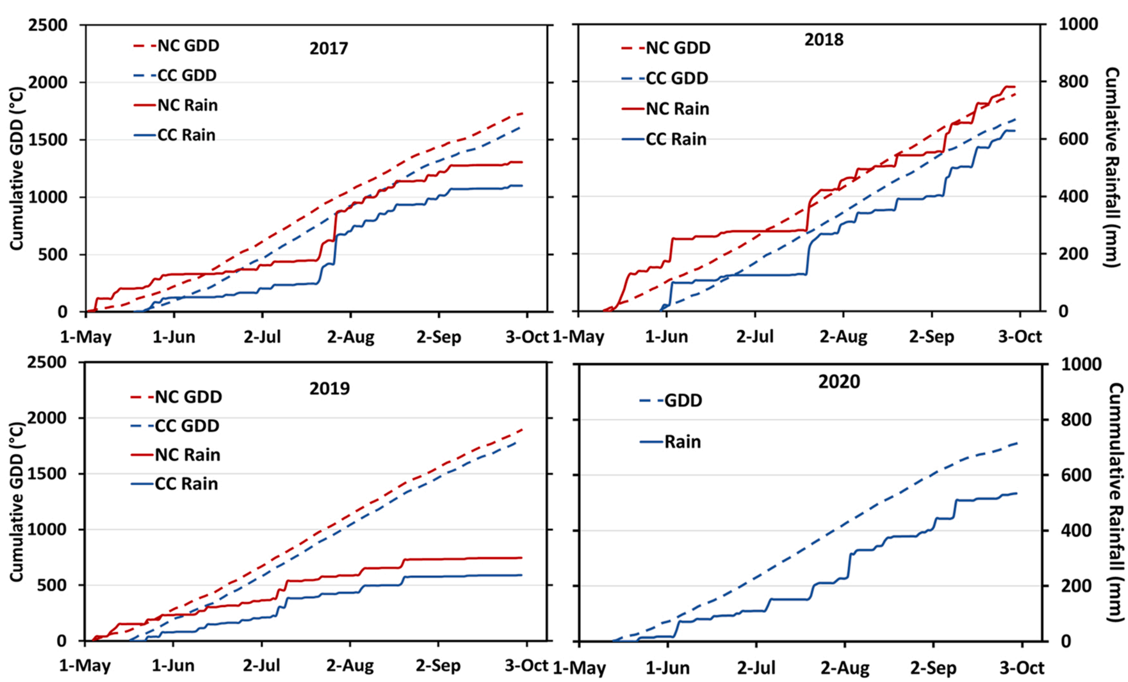

Fig. 1. Cumulative growing degree days (GDD) (dashed lines) and rainfall (solid lines) for the corn growing seasons in 2017 through 2020. Red (upper) lines are for Systems 3 and 4 (NC) and blue (lower) lines are for Systems 5 and 6 (CC). Only one set of lines are shown for 2020 because the planting date for all four systems was the same. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

which are an indication of actual ET). Positive changes were considered infiltration (gains in SWS, which because they are based on daily values may slightly underestimate actual infiltration). Runoff and deep percolation losses were considered negligible for the rainfall conditions in 2017, 2019 and 2020. In 2018, losses to drainage most likely occurred in the later part of the growing season when rainfall exceeded the monthly average for September by 142 mm (Fig. 1). At this point in the growing season, CC residues probably had limited influence on evaporation and we assumed losses to drainage would be similar among all the systems. Therefore, drainage losses this late in the growing season were considered to have little impact on our analysis in 2018.

2.6. Statistical analysis

Statistical analysis was conducted within the SAS Enterprise Guide platform (Version 8.3) (SAS Institute Inc. 2020). Cover crop biomass, corn yield and water use efficiency were analyzed using a mixed models approach with PROC MIXED in SAS/STAT 15.1 (SAS Institute, Inc., 2019). Year, system, and their interaction were considered fixed effects and replication and the replication by year interaction were considered random effects. The analysis of CC biomass included only Systems 5 and 6. Differences among systems were evaluated within a year using the SLICE option of the LSMEANS statement. Differences were considered significant at $\alpha \leq 0.05$ ($P \leq 0.05$).

Statistical analysis of system effects on soil temperature, SWS, ETe and INFe were conducted using a generalized linear mixed models approach with PROC GLIMMIX in SAS/STAT 15.1 (SAS Institute, Inc., 2019). Analyses were carried out separately for each year. System was considered a fixed effect, and replication and the replication by system interaction were included as random effects. Replication variance was allowed to be zero when computed to be so. Date was treated as a repeated measures effect in the analysis of soil temperature, SWS and INFe. Thermal units (CumGDD) were used as the repeated effect in the analysis of ETe. The RESIDUAL option was included in the RANDOM statement to model the R-side covariance where appropriate. Compound symmetry, autoregressive, and spatial power covariance structures were compared to determine the best covariance structure based on the one with lowest corrected Akaike's information criterion and where PROC GLIMMIX computed variance for all covariance parameters (except the replication and replication by system terms) (Stroup et al., 2018).

LSMEANS statements were used to estimate corn growing season average soil temperature and SWS and determine their differences among CC systems in each growing season. Differences in ETe and INFe among systems at specific stages of corn development were evaluated using LSMESTIMATE statements. For ETe, differences were evaluated at approximately V6, V10, VT, and R1 based on cumulative GDD values of approximately 575, 840, 1235 and 1400, respectively. These development stages represent early, mid, and late vegetative, and silking periods. For INFe, differences among systems were evaluated on July 1, August 1, and September 1. In addition to the direct comparisons among systems, a test was constructed to compare NC versus CC e.g. (System 3 + System 4)/2 vs (System 5 + System 6)/2. Differences were considered significant at $\alpha \leq 0.10$ ($P \leq 0.10$) for soil sensor related measurements due to the inherent spatial variability of soils.

3. Results and discussion

3.1. Weather

Monthly average temperature and rainfall data are provided in Table 4. In general, monthly average air temperatures for June through September during the four years were similar to the 10-year average. Average air temperatures in May were slightly below normal for 2017 and 2020 and slightly above average for 2018 and 2019. Rainfall amounts varied considerably from the 10-year average depending on the month and year. Rainfall was below the 10-year average in June and September 2017, June, August and September 2019, and May 2020. In 2018, monthly rainfall was above 10-year averages in all four months. However, the monthly rainfall totals do not adequately identify the long periods of limited rainfall in each year. In particular in 2018 limited rainfall is apparent in Fig. 1 from June 1 to July 21. From May 10, the date of corn planting in the NC systems, through May 31, the day after planting in the CC systems, there was 174 mm rainfall. In contrast, from June 1 through July 20, 108 mm rain fell with a majority of that (76 mm) occurring on June 3. Because of this, critical early stages of corn growth and development occurred during a period of limited, infrequent rainfall and higher temperatures. Similar early growing season periods of limited rainfall were observed in 2017 and 2019. The impact on crop yields were greater in 2018 than in the other years (see below).

Cumulative GDD and cumulative rainfall from corn planting to harvest for the four years are shown in Fig. 1. Patterns for CumGDD illustrate the effects of delaying corn planting in Systems 5 and 6 compared to Systems 3 and 4. Cumulative GDD for silking (~1400) occurred in mid-August to early September. Accumulation of heat units during the two weeks following corn planting was slower for Systems 3 and 4 compared to Systems 5 and 6 due to the earlier planting date. Accumulation of GDD for CC and NC systems was the same in 2020 when all systems were planted on the same date. Differences in rainfall amounts and distribution during the corn growing seasons depended on planting date differences. Rainfall during the corn growing season ranged from 236 mm (2019) to 805 mm (2018) (Table 2 and Fig. 1). Rainfall in 2018 was more than two times greater than the 10-yr average of 347 mm with much of that rain occurring after late July. Rainfall in 2019 was 86% of the 10-yr average for NC systems and 68% of the 10-yr average for CC systems (estimated from the date of planting).

3.2. Cover crop biomass at corn planting

Cover crop biomass in Systems 5 and 6 ranged from less than

Table 4
Monthly average temperature and rainfall at the Cover Crop Systems Project, Beltsville MD for the corn growing season. The 10-yr averages were calculated with data collected at the same weather station from 2011 through 2020.

	May	June	July	August	September
Average Air Temp °C					
2017	17.0	23.4	25.4	22.8	19.8
2018	20.5	22.7	24.9	24.9	22.3
2019	19.7	23.0	25.9	24.2	22.0
2020	16.3	23.1	26.6	24.6	19.5
10YR AVG	**18.5**	**23.0**	**25.6**	**23.9**	**20.6**
Average Rain mm					
2017	131.3	**17.2**	203.2	123.7	46.2
2018	175.5	104.7	147.6	126.5	229.2
2019	107.9	50.0	91.7	57.9	5.3
2020	40.8	92.0	117.5	174.6	132.0
10YR AVG	**87.2**	**89.5**	**93.9**	**104.8**	**82.2**

500 kg ha^{-1} to over 6000 kg ha^{-1} during the four years. In System 5, (rye+vetch+crimson clover), CC biomass prior to corn planting was 3248 (SD=323), 3697 (SD=838), 463 (SD=362) and 1611 (SD=416) kg ha^{-1} in 2017, 2018, 2019 and 2020, respectively. For the same years, CC biomass prior to corn planting in System 6 (red clover+rye) was 3939 (SD=533), 4279 (SD=344), 4478 (SD=847) and 6011 (SD=64) kg ha^{-1}. Cover crop establishment in Systems 5 and 6 in 2017 and 2018 was good and they produced similar amounts of biomass. In contrast, there were differences in biomass production in 2019 and 2020 that were due to the composition of the species mixtures and weather-related challenges planting the interseeded CC. Planting the rye-legume mixture into DCS in System 5 was difficult in 2018 due to wet conditions and in 2019 due to dry conditions both negatively impacting stand establishment and subsequent biomass production. Spring interseeding (March) of red clover in System 6 helped facilitate better stand establishment and growth in all four years. Wheat and soybean crop residue biomass on the soil surface at the time of corn planting in Systems 3 and 4 was not determined; however, visual observations found these to be limited. Wheat straw is baled after summer harvest and soybean residues tend to decompose rapidly under the mild humid winters of the Mid-Atlantic region. Residues from these crops provided less than 30% soil cover at the time of corn planting.

3.3. Soil temperature

Surface soil temperatures in the four systems are shown in Fig. 2 for each of the four years. Reponses across the growing season were similar for the four systems with variations in the data related primarily to sunny and cloudy days (Table 5). Significant system and system by date interactions were present in 2018 and 2019 (Table 6). Soils were noticeably warmer in CC systems compared to NC systems early in the corn growing season in 2018. This was due to less corn canopy in the CC systems (a result of the later planting date) during the extended dry period discussed above. In contrast, soil temperatures in 2019, the driest year of the study, tended to be lower in CC systems compared to NC systems later in the growing season. This may have been a result of greater corn canopy in the CC system.

The vertical orientation of our sensors reduced our ability to detect influences of the cover crop residues on temperatures near the soil surface (0–5 cm). Our sensors integrated temperature measurements for the 0–12 cm or 0–15 cm soil depth. Others have shown that CC residues have a small but variable effect on seasonal average summer soil temperatures (Blanco-Canqui and Ruis, 2020; Vann et al., 2018) with effects occurring early in the growing season (Daigh et al., 2014; Horton et al., 1996). Z. Wang et al. (2021) used a process-based model to simulate rye residue mulch effects on diurnal soil surface water and thermal dynamics. Soil surface temperatures (0–5 cm) with a mulch layer were reduced by 1–5 °C compared to the air temperature, and ~10 °C compared to the bare soil surface. The model indicated that the residue mulch attenuated shortwave radiation and maintained a relatively higher water content, which increased soil heat capacity and limited increases in surface soil temperature compared to the bare soil. However, nighttime surface soil temperatures were similar for bare soil and soil under the residue mulch.

Although, corn canopy closure would be expected to overshadow CC effects on soil temperature, CC residues could help reduce warming of the soil surface during periods of water stress later in the growing season. Corn leaves roll or curl in response to water stress to reduce light interception, transpiration and leaf dehydration (Kadioglu and Terzi, 2007) thereby allowing more solar radiation to reach the soil surface. As soil water continues to be depleted, leaf roll begins earlier each day extending the duration of soil surface exposure to direct solar radiation. Shading of the soil surface and low thermal conductivity of CC residues inhibit heat transfer between the soil and the atmosphere and act as a physical barrier to vapor transfer from the soil to the overlying air layer (Sauer et al., 1998) the combined effects would keep soils cooler compared to soils without CC residues.

3.4. Soil water storage

Soil water storage, the total amount of water in the soil profile, was used to compare responses among systems. Crop available water is the

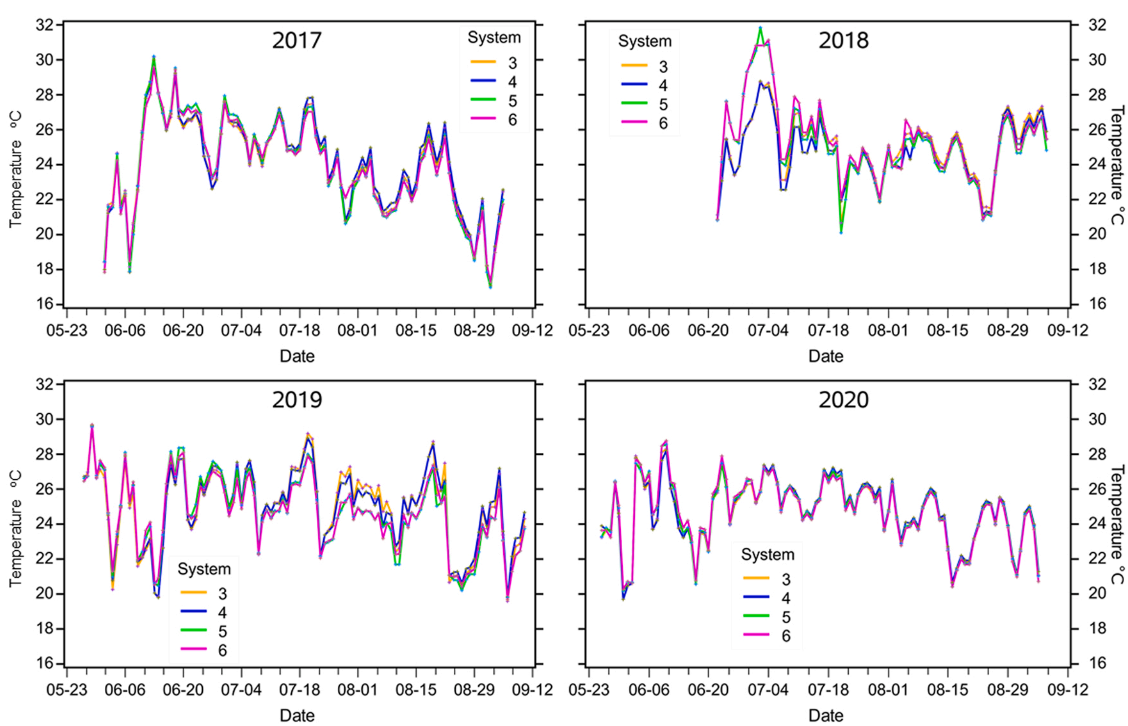

Fig. 2. Soil temperature in the upper soil layer (0–12 cm, 2017; 0–15 cm 2018 through 2020) during the corn growing season for the four cropping systems in 2017 through 2020.

Tablee 5

Mixed models analysis for upper soil layer soil temperature† and whole profile soil water storage as influenced by cover crop system, date and their interaction.

Year	2017		2018		2019		2020	
Effect	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F
Soil Temperature								
System	0.69	0.5717	**8.24**	**0.0001**	**9.5**	**< .0001**	0.58	0.635
Date	**404.4**	**< .0001**	**105.8**	**< .0001**	**220.2**	**< .0001**	**930.1**	**< .0001**
System*Date	1.17	0.1066	**1.63**	**< .0001**	**1.3**	**0.0025**	1.07	0.2326
Soil Water Storage								
System	2.08	0.2277	2.03	0.1763	0.15	0.9255	0.44	0.7318
Date	**86.48**	**< .0001**	**57.05**	**< .0001**	**77.12**	**< .0001**	**137.34**	**< .0001**
System*Date	1.13	0.1514	0.96	0.6286	**2.1**	**< .0001**	1.1	0.1499

†Soil surface temperature depth measured in 2017 is 0–12 cm and in 2018 through 2020 is 0–15 cm.

Table 6

Estimates of mean soil temperature (upper soil layer) and mean whole profile soil water storage in the four cover crop systems during the corn growing season each year and differences in responses between NC and CC systems.

	Year							
System	2017		2018		2019		2020	
	Temperature °C							
3	24.0	a†	25.1	ab	25.0	a	24.7	a
4	24.1	a	24.8	b	25.0	a	24.8	a
5	23.9	a	25.2	ab	24.7	b	24.7	a
6	23.9	a	25.4	a	24.6	b	24.7	a
NC vs CC	-0.08	ns‡	0.37	* *	-0.38	* *	0.02	ns
	Soil Water Storage mm							
3	251.8	a	260.4	a	205.8	a	277.5	a
4	259.4	a	245.4	a	203.6	a	263.9	a
5	277.4	a	271.8	a	221.1	a	276.2	a
6	275.2	a	274.0	a	209.7	a	286.6	a
NC vs CC	20.7	*	20.0	*	10.7	ns	10.7	ns

† Letters indicate differences among systems within a year.

‡ ns indicates the comparison is not significant at $P < 0.10$; * indicates the comparison is significant at $P < 0.10$ and * * indicates the comparison is significant at $P < 0.01$.

amount of soil water between the lower limit of crop soil water extraction and the drained upper limit. Using measurements of volumetric water content during extended dry periods, we estimated the lower limit of extractable water to be about 59 mm for the soil profile (0–862 mm). Similarly using extended wet periods, we determined the drained upper limit to be about 342 mm of water. Thus, the amount of plant available water at the drained upper limit is about 283 mm. Soil water storage occasionally exceeded the drained upper limit (Fig. 3). Those occasions were mostly during rainfall events late in the corn growing season. Periods where the whole profile was approaching the lower limit of crop extractable water occurred near the end of 2019. Profile SWS remained above the lower limit during the growing season in all years. Within this context, the remaining discussion on SWS provides an indication of system effects on plant available water.

Profile SWS was variable across the corn growing season each year (Fig. 3). The system level means for SWS are presented for each year in Table 6. Differences due to time were significant (Table 5) with weather variability and crop development through time contributing factors to this effect. Average SWS was not different among systems in 2017, 2018 and 2020. The interaction between system and date in 2019 were due to system differences at variable times in this drought year. In 2017 and 2018 CC systems had 20 mm greater SWS compared to NC systems; in 2019 and 2020 similar trends were observed but were not significant (Table 6). The average 10–20 mm greater water storage for CC systems would be expected to help delay crop water stress by 2.5–5 days during prolonged periods without rainfall (Anapalli et al., 2019).

Variable effects of CC on SWS in no-till corn have been reported by others. For example, rye CC before corn have generally been found to increase SWS but effects vary over the growing season (Basche et al., 2016), among years (Qi et al., 2011a), and between study sites (Daigh et al., 2014). In Maryland, CC treatments (rye, vetch, rye+vetch or no CC control) – with comparable termination and corn planting dates to our study – generally maintained greater surface SWS in Coastal Plain silt loams beginning in early summer relative to NC controls (Clark et al., 2007, 1997). They found 20–80 mm greater SWS with CC when corn reached the ~V5 growth stage (Clark et al., 2007, 1997). However, differences in seasonal average SWS were small ranging from − 26–37 mm over two years (Clark et al., 1997).

Profile SWS changes over time for each of the CC systems are shown in Fig. 3. The data reveal early season drying of the soil profile in June and July of each year as the combination of limited rainfall and corn water use depleted a large portion of the stored soil water. During the period of soil water depletion, SWS in Systems 3 and 4 (NC) reached a lower level compared to Systems 5 and 6 (CC) in 2017 and 2018 prior to rain recharging the soil profile (Figs. 1 and 3). Soil profile recharge occurred in late July in 2017, 2018, and 2020. The more even distribution of rainfall for 2020 (Fig. 1) buffered the depletion of soil profile water compared to the other years (Fig. 3). Similar trends in SWS were observed in corn-soybean rotations in Iowa following extended periods of below average rainfall followed by soil water recharge with increased precipitation (Qi et al., 2011a). They reported greater average SWS when a rye CC was grown prior to corn or soybean. As observed in our study, the buffering effect of CC residues on the seasonal minimum SWS was variable; however, presence of the rye CC resulted in greater values

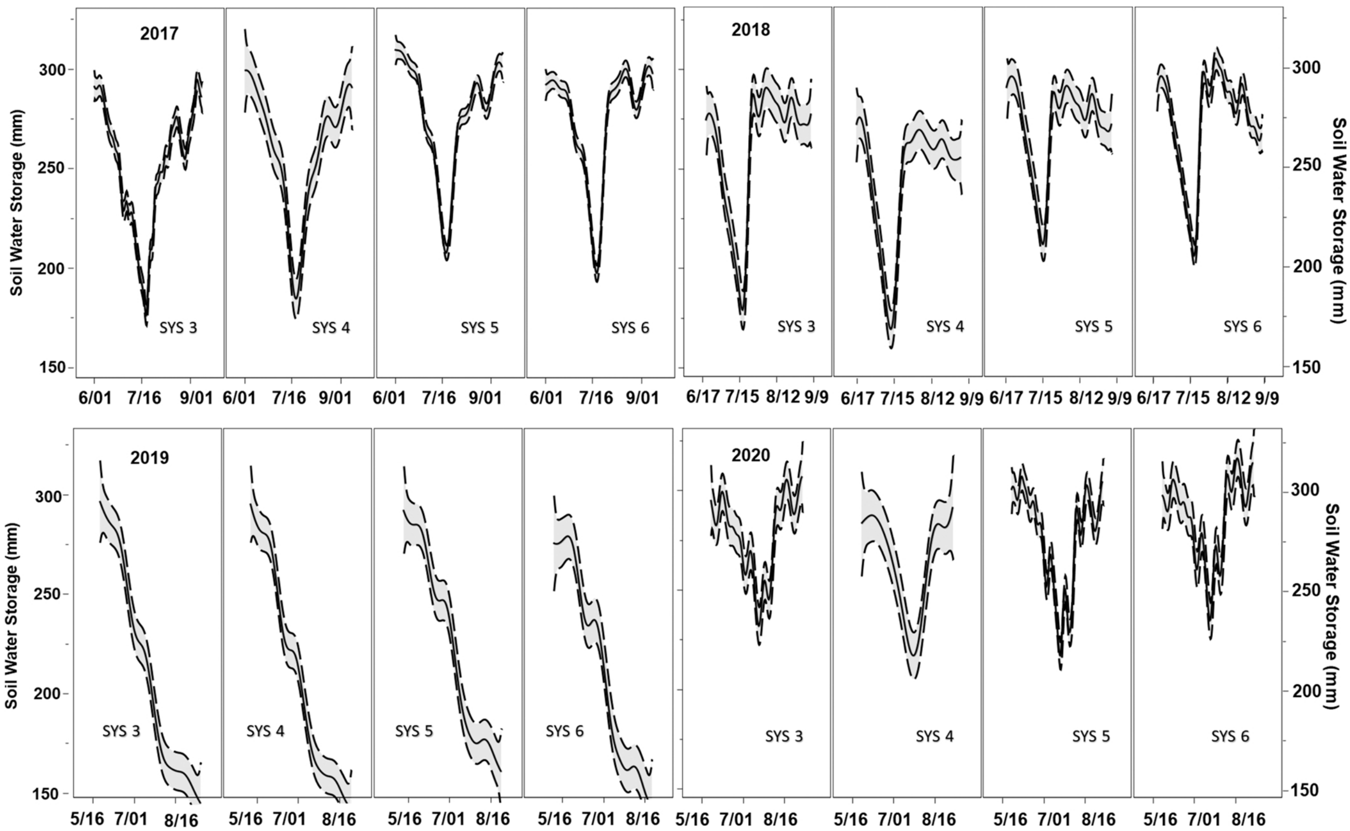

Fig. 3. Changes in whole profile soil water storage for the four cropping systems during the corn growing season in 2017 through 2020. The solid line is a penalized bspline fit of the data and the shaded areas illustrate the outer bounds at 95% confidence limits.

of minimum SWS in 2 of 3 years of their study. In contrast, CC residues had no effect on SWS in Minnesota during two years of corn silage production, which the authors attributed to early growing season rainfall replenishing CC water use in one year and insufficient CC biomass production or too little growing season rainfall in the other (Krueger et al., 2011).

The severity of drought conditions in 2019 are apparent from the continuous decline in SWS (Fig. 3). In 2019, a trend for more rapid

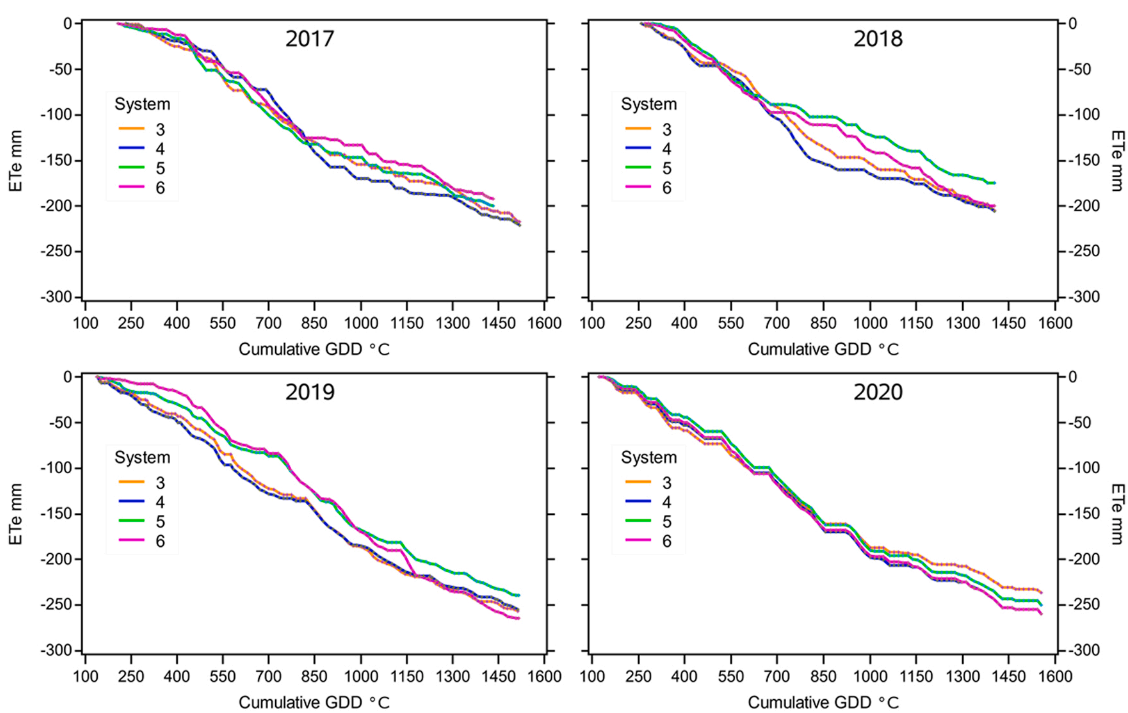

Fig. 4. Estimated cumulative evapotranspiration (ETe) during the corn growing season for the four cropping systems in 2017 through 2020.

drying of the soil profile earlier in the growing season was observed for Systems 3 and 4 (NC) compared to Systems 5 and 6 (CC) which may reflect both the later planting date in the CC systems and CC residues decreasing evaporation from the soil surface. The slight increase in SWS in mid-July 2019 appears to be greater in the CC systems which may reflect more favorable infiltration. A similar pattern of SWS depletion was observed in Minnesota during a season with below average growing season precipitation (Krueger et al., 2011). In contrast, during the Midwest drought in 2012, rye CC residues maintained greater SWS during the early growing season (Daigh et al., 2014). Qi et al. (2011a) attributed increased SWS with a rye CC to root growth possibly increasing soil porosity and infiltration and to soil surface cover by rye residue reducing evaporation between corn or soybean rows.

3.5. Estimated evapotranspiration

Patterns of cumulative ETe were similar across systems within a corn growing season and ranged from 200 to 250 mm depending on the year (Fig. 4). These values are within the range reported for no-till corn ET in Mid-Atlantic Coastal Plain soils (Roygard et al., 2002). Differences in cumulative ETe among the systems were limited (Table 7). Significant interactions between CumGDD and System were present for 2017, 2018 and 2019 indicating intermittent differences in cumulative ETe among the systems (Table 7) that can be seen in Fig. 4 as divergence of the plotted values. The trends suggest periodically lower cumulative ETe during the growing season for CC systems (Systems 5 and 6) compared to NC systems (Systems 3 and 4). This difference was most apparent in 2018 and 2019. Differences based on contrast statements among the systems at specific corn development stages were significant only in 2018 (Table 8). When directly comparing NC and CC systems, significant differences were only found in 2018 (Table 9) when lower ETe in CC systems was primarily a result of the lower ETe in System 5 (Table 8). Surprisingly, we found no differences among systems at V6 for any year even though we expected evaporation to be reduced in CC compared to NC systems due to soil surface cover as has been previously reported (Balwinder-Singh et al., 2011; Bond and Willis, 1969; Unger and Parker, 1976; Yang et al., 2020). While the trends in the data in other years indicate lower cumulative ETe for the CC systems (Table 9), the differences were not large enough to reach the level of significance. Choosing to investigate differences at specific corn development stages limited our ability to identify other times in the growing season where differences between NC and CC systems might have been significant.

Similar to our results, few differences in estimated ET are reported in field studies assessing the effects of CC residues and surface mulches across a range of soils, climates and cropping systems (Alfonso et al., 2020; Balwinder-Singh et al., 2011; Gabriel et al., 2012; Li et al., 2021; Tolk et al., 1999; Yang et al., 2020). Cover crop residues reduced corn crop ET by an average of 6% in 50- and 80-year simulations of a corn-soybean rotation in Mississippi (Li et al., 2021; Yang et al., 2020) and crop ET by 3% in a 40-year simulation of a corn-soybean rotation in Iowa (Qi et al., 2011b). These results are consistent with the small effect of cover cropping on ET in humid regions revealed in a meta-analysis of 117 studies across a range of climates and geographic locations (J. Wang et al., 2021).

3.6. Estimated infiltration

Similar to the results with cumulative ETe, differences in cumulative INFe were primarily related to changes over time with limited differences among systems (Table 7 and Fig. 5). System by date interactions were present in 2019 and 2020. Cumulative INFe was lowest in 2019 (the driest year, Table 2 and Fig. 1) and greatest in 2020 (Fig. 5). The greater INFe in 2020 is surprising since total rainfall was greater in 2018. Rainfall in 2020 was more evenly distributed compared to 2018 (Fig. 1). The intense rainfall events late in 2018 maintained high water contents and probably resulted in drainage below the soil profile which we could not quantify. Also, the greater INFe in 2020 may relate to sufficient soil drying between rainfall events that allowed changes in soil water content to be detected and credited to infiltration. Estimated differences in INFe between NC and CC systems were inconsistent and predominantly nonsignificant (Table 11). Significant differences between NC and CC systems were only observed in 2019 on 1 September where cumulative infiltration was 23 mm greater for CC systems compared to NC systems.

The presence of CC residues has been shown to enhance infiltration in most soils (Unger and Vigil, 1998). Rankoth et al. (2021) found that soil water recharge for Missouri claypan soils was greater in CC compared to NC systems. Cover crop soils maintained 1.7% and 2.8% more water compared with NC soils during corn years at 10- and 20-cm depth, respectively, and 4.2% and 3.1% more water during soybean years, respectively. Similarly, Chalise et al. (2018) reported 80% greater soil water infiltration following a CC compared with NC in a silt loam soil in Brookings, SD. Mitchell et al. (2015, 2017) found 2.8 times greater soil water infiltration in a clay soil following a CC compared with NC in San Joaquin Valley, California.

Variability in infiltration response could be related to off-season changes in porosity and soil structure due to the weak structural stability of coarser textured soils. Steele et al. (2012) observed a pattern of decreased bulk density and increased air penetration, water infiltration and hydraulic conductivity during the season following a rye CC compared to a control soil for two Maryland Coastal Plain soils similar to the soils in our study. They concluded from the temporal variability of soil physical properties that timing of single point-in-time measurements was critical to the conclusions reached. Alvarez et al. (2017) found in a meta-analysis of CC effects on soils and subsequent crops in the Pampas region of Argentina that infiltration was enhanced around 36% by use of CC in 82% of 22 treatment comparisons. In half of the comparisons, the increase in infiltration exceeded 25 mm h^{-1} and were greatest for soils with low infiltration rates. Carreker et al. (1968) reported average infiltration rates for years eight through ten of a continuous corn study on a typical piedmont soil in Georgia. Three-year average infiltration rates were 3.8 and 2.8 cm hr^{-1} in the spring and 8.5 and 5.8 cm hr^{-1} in

Table 7
Mixed models analysis for estimated cumulative evapotranspiration (ETe) and estimated cumulative infiltration (INFe) as influenced by cover crop system, time, and their interaction. For cumulative ETe the time component is cumulative growing degree days (CumGDD C°), and for INFe the time component is date. Bolded values indicate significantly different effects.

Year	2017		2018		2019		2020	
Effect	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F
Cumulative ETe								
System	0.08	0.9700	0.67	0.594	0.32	0.8123	0.12	0.9453
CumGDD	**27.96**	**< .0001**	**25.51**	**< .0001**	**34.04**	**< .0001**	**146.39**	**< .0001**
System*CumGDD	**1.93**	**< .0001**	**1.71**	**< .0001**	**1.3**	**0.0084**	0.7	0.9998
INFe								
System	0.04	0.9886	0.65	0.6046	0.4	0.754	0.44	0.7333
Date	**130.02**	**< .0001**	**121.35**	**< .0001**	**105.68**	**< .0001**	**150.3**	**< .0001**
System*Date	1.09	0.2329	0.84	0.9406	**2.92**	**< .0001**	**1.21**	**0.0209**

Table 8
Estimates of cumulative ETe at specific corn development stages and cumulative growing degree days (CumGDD C°) for the four cropping systems in 2017 through 2020. Cumulative ETe values for each growth stage are estimated from the begining of the growing season as indicated in Table 2.

Corn Developmental Stage	V6		V10		VT		R1	
CumGDD C°	**600**		**840**		**1235**		**1400**	
Year / System	Cumulative ETe mm							
2017								
3 NC†	-73.4	a‡	-128.3	a	-175.1	a	-202.4	a
4 NC	-59.0	a	-137.3	a	-187.3	a	-209.6	a
5 CC	-63.8	a	-132.4	a	-170.2	a	-196.0	a
6 CC	-53.6	a	-125.5	a	-163.2	a	-188.2	a
2018								
3 NC	-54.6	a	-134.2	ab	-182.8	ab	-204.5	a
4 NC	-63.2	a	-152.7	a	-187.8	a	-205.6	a
5 CC	-65.5	a	-102.0	c	-161.5	b	-174.0	b
6 CC	-70.6	a	-111.0	bc	-179.5	ab	-200.2	a
2019								
3 NC	-84.5	a	-139.4	a	-218.9	a	-246.0	a
4 NC	-96.3	a	-140.9	a	-217.7	a	-241.7	a
5 CC	-74.4	a	-122.2	a	-204.4	a	-227.4	a
6 CC	-69.4	a	-122.5	a	-222.8	a	-251.7	a
2020								
3 NC	-92.2	a	-157.1	a	-205.3	a	-223.7	a
4 NC	-89.6	a	-163.9	a	-222.9	a	-242.9	a
5 CC	-82.4	a	-157.0	a	-214.4	a	-234.9	a
6 CC	-88.7	a	-163.4	a	-220.9	a	-243.6	a

† System designations are as in Table 1. NC indicates no cover crop prior to corn. CC indicates the presence of cover crops prior to corn.
‡ Letters indicate significant differences among systems within a year and developmental stage at $P < 0.1$.

Table 9
Test for difference in cumulative ETe between NC and CC systems at specific corn development stages (CumGDD) in 2017 through 2020.

Corn Developmental Stage	V6		V10		VT		R1	
CumGDD°C	**600**		**840**		**1235**		**1400**	
Year	Diff mm†	Prob > t	Diff mm	Prob > t	Diff mm	Prob > t	Diff mm	Prob > t
2017	-7.5	0.6858	-3.9	0.8341	-14.4	0.4494	-13.9	0.4652
2018	9.1	0.3341	**-37.0**	**0.0018**	-14.8	0.1309	**-17.7**	**0.0761**
2019	-18.5	0.2887	-17.8	0.3075	-4.8	0.779	-4.3	0.8006
2020	-5.3	0.6184	-0.4	0.9729	3.6	0.7356	5.9	0.5805

† Diff mm is the estimated difference between NC and CC systems and was calculated as (mean Systems 3 and 4) – (mean Systems 5 and 6). Negative values indicate less cumulative ETe and positive values indicate greater cumulative ETe for CC systems compared to NC systems.

the fall with and without a rye CC, respectively. The more favorable responses for infiltration cited above occurred in heavier textured soils where organic matter inputs have been reported to have a greater effect on soil aggregation and soil structure (Bronick and Lal, 2005). Chalise et al. (2018) indicated that the reason for higher infiltration rates with CC in their study was probably due to improved soil structure with more and continuous macro and micro pores, root channels, and less compaction. They cited previous work by Osborne et al. (2014) from the same experimental plots that showed greater stability of soil aggregates and smaller erodible fraction for CC treatments compared with NC treatments.

Using the information on cumulative INFe for September 1 from Table 10 and cumulative rainfall since planting, the fraction of rainfall estimated as INF was 0.36, 0.30, 0.33 and 0.60 for NC systems and 0.42, 0.39, 0.53, and 0.61 for CC systems for 2017, 2018, 2019 and 2020, respectively. The four-year average fraction of rainfall as INFe was 0.40 for NC systems and 0.49 for CC systems. The loam soils at the research site are conducive to rapid infiltration while the minimal slope limits substantial runoff. Our deepest soil water measurements were slightly above the depth of the drain tiles leaving a portion of the soil profile unaccounted for in our SWS estimates. We also had no way to determine losses to drainage. Consequently, unmeasured drainage losses when the soil profile was close to saturation are a likely source of error in our estimates of INFe. This in turn contributed to our low estimates of rainfall capture. Using a daily time step for SWS values may have also contributed to not fully capturing INFe, particularly for small rainfall events. Although a more finite estimation of infiltration may have been obtained from shorter time steps, determination of INFe on a daily basis was useful for illustrating differences among NC and CC systems.

3.7. Corn yields and water use efficiency

Yields averaged 9.48 Mg ha^{-1} across systems in 2018 and were lower ($P = 0.0069$) than in the other three years (2017 =12.0, 2019 =11.8, and 2020 =12.1 Mg ha^{-1}). In 2018, early season drought coupled with late season cloudy conditions resulting from high rainfall likely contributed to lower yields. Though both 2017 and 2018 suffered periods of extended dry conditions early in the growing season, greater cumulative rainfall during the latter part of the growing season in 2018 may have also led to greater N leaching, reduced N availability, and concomitant yield losses relative to 2017. Corn yields averaged across the four years were 10.7, 10.7, 11.8, and 12.3 Mg ha^{-1} for Systems 3, 4, 5, and 6 respectively. Yields were not different between Systems 3 and 4 or between Systems 5 and 6. Corn yields averaged across the four years were lower in NC systems (10.7 Mg ha^{-1}) compared to CC systems (12.1 Mg ha^{-1}) ($P < 0.001$). Comparisons between NC (Systems 3 and 4) and CC (Systems 5 and 6) systems were significant for 2017, 2018, and 2019. Both increased water availability and greater synchrony between N availability and crop uptake probably contributed to the greater yields in the CC systems. Though fertilizer application rates were adjusted for legume N contributions, N mineralization from legume and grass cover crop residues would likely have occurred later in the growing season

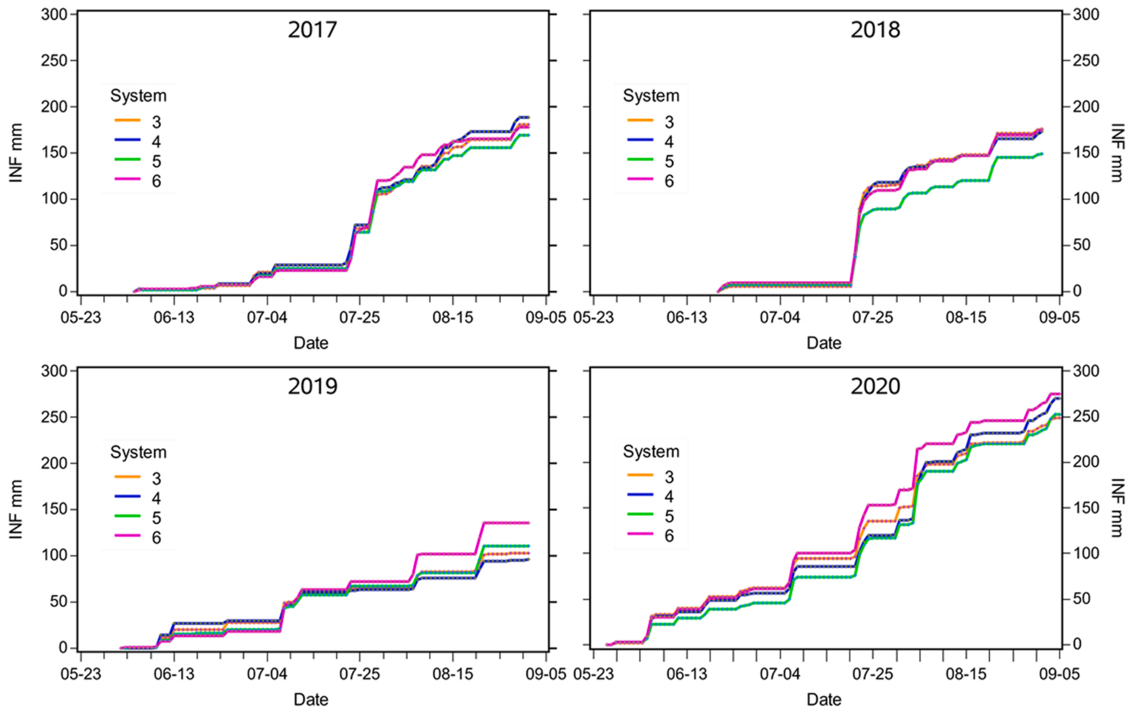

Fig. 5. Estimated cumulative infiltration (INfe) during the corn growing season for the four cropping systems in 2017 through 2020.

Table 10
Estimates of cumulative infiltration estimates (INFe) on July 1, August 1 and September 1 during the corn growing season for four cover crop systems in 2017 through 2020.

Month	July 1		Aug 1		Sep 1	
Year / System	Cumulative INFe mm					
2017						
3 NC†	6.7	a‡	68.1	a	164.0	a
4 NC	7.9	a	72.1	a	173.3	a
5 CC	7.1	a	64.0	a	155.5	a
6 CC	7.7	a	70.0	a	165.8	a
2018						
3 NC	5.2	a	114.5	a	170.9	a
4 NC	8.0	a	117.9	a	165.4	ab
5 CC	6.9	a	88.8	b	145.2	b
6 CC	9.2	a	109.9	ab	169.8	ab
2019						
3 NC	27.4	a	65.0	a	102.5	a
4 NC	29.6	a	62.9	a	95.2	a
5 CC	20.3	a	67.0	a	110.4	a
6 CC	17.6	a	72.2	a	135.4	a
2020						
3 NC	62.6	a	135.1	a	234.5	a
4 NC	56.8	a	120.6	a	246.2	a
5 CC	45.6	a	117.4	a	230.1	a
6 CC	61.6	a	153.8	a	257.7	a

† System designations are as in Table 1. NC indicates no cover crop prior to corn. CC indicates the presence of cover crops prior to corn.
‡ Letters indicate significant differences among systems within a year and date at $P < 0.1$.

when corn N demand was greater. In contrast, the NC systems had fewer biomass N inputs to soil organic matter and had a greater potential for leaching losses of fertilizer N and consequent reduced N availability.

Various researchers have shown increases and decreases in corn yields following CC. In North Carolina, crimson clover depleted soil water in the surface 15 cm of a Norfolk sandy loam soil by 28% and 55% in two years and reduced corn yields 0.5 Mg ha^{-1} and 0.9 Mg ha^{-1} (Ewing et al., 1991). In contrast, Clark et al. (2007) found that spring soil moisture (0–20 cm) following several CC was greater than or equal to the no-cover controls throughout the spring and summer for corn grown on a Mattapex silt loam Coastal Plain soil in Maryland. They observed that corn grain yield was greater following a hairy vetch compared to a vetch-rye mixture or pure rye. The three CC treatments provided N fertilizer equivalence of about 80, 15, and 50 kg N ha^{-1}. Poffenbarger et al. (2015) observed that a rye-hairy vetch mixture provided 136 and 68 kg N ha^{-1} in two years on fields near the site of our study with similar soils. This was ~30–40 kg N ha^{-1} more than with a rye CC alone and ~ 60 kg N ha^{-1} less than following pure hairy vetch. Most studies only account for N contributions from CC above ground biomass. In addition to those contributions, root biomass can contribute additional N of 25% for rye and 10% for vetch (Shipley et al., 1992). These results point to the potential dual benefit of the CC used in our study.

Table 11
Test for differences in cumulative infiltration (INFe) between NC and CC systems during the corn growing season at specific dates in 2017 through 2020.

Month	Jul 1		Aug 1		Sep 1	
Year	Diff mm†	Prob > t	Diff mm	Prob > t	Diff mm	Prob > t
2017	-0.1	0.9935	3.0	0.8372	8.0	0.5941
2018	-1.5	0.885	16.8	0.1203	10.7	0.3107
2019	9.5	0.1229	-5.7	0.3462	**-23.8**	**0.0022**
2020	6.1	0.6664	-7.8	0.5842	-3.5	0.8015

† Diff mm is the estimated difference in cumulative INFe between NC and CC systems and was calculated as (mean Systems 3 and 4) – (mean Systems 5 and 6). Negative values indicate greater cumulative INFe and positive values indicate less cumulative INFe for CC systems compared to NC systems

Corn yields and cumulative ETe at the end of each year were used to estimate water use efficiency (WUE) at the field production scale. Unlike WUE measured at the leaf-level, that are snapshots in time (seconds to minutes), field production based WUE integrates plant responses over a growing season (Dietzel et al., 2016; Hoover et al., 2022). Because soil water measurements did not begin immediately at corn planting due to the time required for sensor installation, these values do not include a portion of the early growing season but do provide a basis for comparison among systems. We acknowledge that the differences in planting dates between NC and CC may have confounded differences in soil water availability at planting with differences in WUE. For example, prior to CC termination both evaporation and transpiration would lead to greater soil water losses in the CC systems relative to the evaporative losses alone in the NC systems. However, the magnitude of these differences was likely moderated by corn water use in the NC systems following emergence. During the same period, CC systems were only subject to evaporative losses following CC termination. Evaporative losses in the CC systems would be lowered by interception of solar radiation and reduction of windspeed by the CC residues relative to the predominately bare soil in the NC systems. Earlier planting and corn development in the NC systems would be expected to result in greater corn biomass and transpiration relative to the CC systems on a given date; however, this effect did not persist through the entire growing season as evidenced by greater black layer corn biomass in the CC systems (data not shown).

Differences in WUE were present due to CC ($P = 0.0059$), but not for years ($P = 0.1461$) or the interaction between year and system ($P = 0.6027$). This is in contrast to long-term modelling results which found that system-level water use efficiency varies across years due to differences in rainfall (Dietzel et al., 2016; Yang et al., 2020). However, the range of annual cumulative rainfall during this study fell within the range classified as 'normal' years by Yang et al. (2020), with the exception of Systems 3 and 4 in 2018. In addition, Dietzel et al. (2016) found that WUE was similar among years with comparable amounts of rainfall to our study site. Optimal corn WUE in Iowa was found to occur at 430 mm of precipitation (Dietzel et al., 2016). Water use efficiency ranged from 4.8 to 6.0 kg m^{-3} across the four years of our study and averaged 4.8, 4.6, 5.6 and 5.5 kg m^{-3} for Systems 3, 4, 5, and 6, respectively. System 5 had greater WUE than Systems 3 and 4, while System 6 was only different from System 4. Cover crop systems averaged 0.86 kg m^{-3} greater WUE compared to the NC systems across the four years. When evaluated for each year, differences between NC and CC systems were significant in each year except 2020. Differences were 1.3, 0.9, 1.1 and 0.13 kg m^{-3} for 2017, 2018, 2019 and 2020, respectively. Cover crop residues can increase WUE of succeeding crops approximately 5% (J. Wang et al., 2021; Yang et al., 2020) but the effect of surface mulching on WUE and yield is variable due to differences in mulch thickness, soil moisture and ET among years (Balwinder-Singh et al., 2011; Tolk et al., 1999).

Greater yields and WUE for systems with CC prior to corn could be the result of a combination of CC effects on soil N and water availability. Researchers have shown that when sufficient fertilizer N is present, yield increases associated with CC are more likely the result of favorable soil moisture, temperature, physical conditions, or other rotation effects (Clark et al., 1995; Smith et al., 1987). Decker et al. (1994) reported that corn grain yields increased 2 Mg ha^{-1} on a Coastal Plain silt loam and 0.5 Mg ha^{-1} on a Piedmont silt loam soil following legume CC when N was not limiting. Similarly, Clark et al. (1995) hypothesize that this yield advantage was largely due to more favorable water availability because of heavier mulch with mid- or late-kill treatments. For example, soil moisture was 14% greater in well fertilized (180 kg ha^{-1}) corn with rye and rye+vetch CC residues relative to NC plots following two weeks with less than 10 mm of rainfall (Clark et al., 2007). The authors note that corn in the NC plots were visibly water stressed during dry periods relative to the cover cropped plots. Following 122 mm of rain, soil moisture increased by 64% in the CC soil compared to only 38% in NC plots. In addition, differences in corn planting dates can result in water stress impacts occurring at different corn growth stages depending on early season rainfall (Clark et al., 1997). For example, over two years with below average early season rainfall early planted corn suffered drought stress during silking while timely rainfall increased soil water availability during silking of later planted corn (Clark et al., 1997). In CC systems there is potential for greater synchrony of N availability because grass cover crops scavenge N from the soil profile and immobilize N released from legumes and soil organic matter. Mineralization of this N from grasses occurs later in the corn growing season when N demand is high (Poffenbarger et al. (2015). The NC systems have less crop biomass inputs (less residues for immobilization of soil mineral N or fertilizer N) and may have greater potential for leaching losses of fertilizer N. Those avenues of N cycling were not measured in this study but could be consider contributing factors to the greater yields in the CC systems.

4. Summary and conclusions

Beyond biomass production, the effects of CC on soil moisture depend on a number of interacting factors including soil physical properties (soil texture, infiltration rate, susceptibility to surface crusting), antecedent soil moisture, rainfall amount and intensity, and topographical factors like slope and aspect. These interacting factors result in variable effects of CC on soil water status from day-to-day, year-to-year and site-to-site. Our research was conducted on Coastal Plain soils with good infiltration, a factor which most likely influenced the magnitude of our results. The cumulative effects of no-till management with or without a CC prior to the corn phase of the rotation resulted in only modest differences in SWS, infiltration, and evapotranspiration that varied each year. We observed small and variable effects of CC on seasonal average summer soil temperatures. Much more definitive differences in SWS were observed with an average 10–20 mm greater season average SWS for CC systems compared to NC systems. This difference could help delay corn water stress by 2.5–5 days during prolonged periods without rainfall. The trends in the data indicated lower cumulative ETe for CC systems, although the differences were often not large enough to reach the level of significance. Similar to the results with cumulative ETe, differences in cumulative INFe were limited among systems. The four-year average fraction of rainfall captured as INFe was 0.40 for NC and 0.49 for CC systems, indicating greater rainfall capture for systems with CC prior to corn. Adding CC prior to corn also increased water use efficiency by nearly 1 kg m^{-3}. More importantly, the yield benefit of interseeding CC prior to corn was an increase in yields (10.6 Mg ha^{-1} vs 12.1 Mg ha^{-1}). Return from this increased yield would more than offset the cost of CC establishment of ~ \$100 ha^{-1} (Myers et al., 2019) given that 1.5 Mg of corn provides ~\$400 based on September 2022 market prices (https://markets.businessinsider.com/commodities/corn-price).

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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