Impact of Management Practices on Carbon and Water Fluxes in Corn–Soybean Rotations

C. Dold,* J. L. Hatfield, J. H. Prueger, T. J. Sauer, T. B. Moorman, and K. M. Wacha

Core Ideas
• Soil management affects carbon and water dynamics.
• Net ecosystem production was higher in reduced till systems.
• Ecosystem respiration was higher in tillage systems.
• Residue management most likely to affect net ecosystem production and ecosystem respiration.

ABSTRACT
Corn \([Zea mays \text{ L.}]\) and soybean \([Glycine max \text{ (L.) Merr.}]\) are important US crops, and soil management typically comprises tillage activities, yet improvements in management practices may have substantial impact on C and water dynamics. This study's aim was to determine management impact on C and water fluxes. Four eddy covariance stations monitored evapotranspiration (ET) and net ecosystem production (NEP) in 2016–2017 in two corn–soybean–rotation systems—a conventional and a transitional system to reduced till with cover crop (i.e., aspirational). Net biome production (NBP), gross primary production (GPP), ecosystem respiration (RE), and inherent water use efficiency (IWUE*) were calculated. Aspirational NEP was higher than the conventional site with 565 vs. 421 g C m\(^{-2}\) in corn, and 108 vs. 64 g C m\(^{-2}\) in soybean. The aspirational RE was lower than under conventional management for both corn and soybean. Aspirational corn GPP was lower than conventional with 1285 and 1405 g C m\(^{-2}\), and no difference in soybean with 750 and 742 g C m\(^{-2}\). Linear regression \((p < 0.05)\) showed higher NEP regression slopes in spring in the conventional compared with the aspirational system, with \(-0.016\) and \(-0.004\) in soybean, and \(-0.012\) and \(-0.005\) in corn. The soybean-years were a C source in both management systems. Although annual ET was similar among crops and management with 589 to 610 mm, the growing season IWUE* was higher under conventional management. Reduced tillage substantially improved C dynamics in corn and soybean, whereas ET was less affected.

Abbreviations: \(r_c\), carbon dioxide density; \(r_w\), water vapor density; DOR, day of rotation; EC, eddy-covariance; ET, evapotranspiration; \(F_c\), carbon dioxide flux; \(F_{c\text{ day}}\), daytime CO2 flux; \(F_{c\text{ night}}\), nighttime CO2 flux; GPP, gross primary production; H, sensible heat flux; HI, Harvest Index; IQR, interquartile range; IRGA, infrared gas analyzer; IWUE*, inherent water use efficiency; LE, latent heat flux; LTAR, Long-Term Agroecosystem Research Network; NBP, net biome production; NEP, net ecosystem production; \(R_d\), daytime respiration; RE, ecosystem respiration; RUSLE, Revised Universal Soil Loss Equation; SOC, soil organic carbon; STIR, Soil Tillage Intensity Rating; \(T_s\), sonic temperature; UAN, urea ammonium nitrate; \(w'\), instantaneous vertical wind velocity; \(z_m\), measurement height.

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This is an open access article distributed under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)
emissions. Kern and Johnson (1993), as well as West and Marland (2002), estimated a substantial US-wide reduction of soil organic carbon (SOC) loss by reducing tillage activities or shifting to no-till management. These changes in tillage would not result in a yield penalty since there is no substantial difference on yield among tillage systems in the midwestern United States (Daigh et al., 2018).

Despite these promising results, the effect of tillage on soil C and water dynamics is still not fully understood. It has been assumed that soil respiration increases substantially, owing to an initial CO₂ flush occurring shortly after tillage (Reicosky et al., 1997). Reduced tillage practices can reportedly reduce soil respiration and soil water evaporation rates and have higher soil moisture content when compared with conventional tillage (Phillips et al., 1980; Lal et al., 2007; Schwen et al., 2015; Chi et al., 2016). Soil organic C increases with decreasing intensity of tillage (Olson et al., 2013) due to the reduction in soil erosion and soil respiration (Lal et al., 2007; Papanicolaou et al., 2015). Tillage enriches the soil with oxygen, incorporates crop residues, and mechanically breaks soil aggregates, which increases aerobic microbial degradation, hence, soil CO₂ respiration (Schlesinger and Andrews, 2000; Mehra et al., 2018). Hollinger et al. (2005) found that mature no-till corn–soybean systems are a C sink, whereas conventional systems are a C source, at least in soybean-years (Dold et al., 2017). Yet, different studies found adverse effects of reduced tillage. Soil respiration in no-till systems was reportedly greater than in conventional tillage systems (Hendrix et al., 1988; Franzluebbers et al., 1995; West and Madland, 2002), and there was no net C gain in soils and C fluxes attributable to reduced tillage (Baker et al., 2007). A continuous corn long-term study showed that the increase in SOC under no-till was limited to the top 5 cm of soil (Ismail et al., 1994).

Few studies focused on the impact of cover crops on C and water fluxes. In recent years, the use of cereal rye (Secale cereale L.) and other cover crops during the spring–fall off-season in corn–soybean rotations had been investigated to ameliorate C dynamics (e.g., Martinez-Feria et al., 2016). Moore et al. (2014) found increased topsoil SOC in corn–soybean–rye rotations. However, previous studies suggest that the C sequestered by cover crops is quickly mineralized, resulting in higher respiration (Baker and Griffiths, 2005; Bavin et al., 2009).

Since most of the agricultural land in Iowa is grown with corn and soybean, a small but widespread change in management practices may substantially increase or decrease C and water fluxes. In this study, we present C and water flux data of annual corn–soybean rotation systems under conventional tillage and under transition to a cover crop reduced tillage system, measured with four EC stations. The period of interest was from 2016 harvest to the end of 2017 to evaluate the impact of 2016 crop residues on 2017 C and water fluxes. The aim of the study was to quantify net ecosystem production (NEP), gross primary production (GPP), ecosystem respiration (RE), evapotranspiration (ET), and inherent water use efficiency (IWUE*) of corn and soybean, and compare these variables between the conventional and transitional production systems.

**MATERIAL AND METHODS**

**Study Sites**

The study was conducted in central Iowa on two sites, each with two adjacent farmer-managed fields with each phase of the corn–soybean rotation present during the study, which began after the 2016 crop harvest (i.e., day of rotation [DOR] 299) and continued to the end of 2017 (DOR 731) (total of 440 d) (see also Appendix A). The first site (41.975°N, -93.692°W, 313 m asl) has been under conventional soil management for >20 yr with spring tillage using a field cultivator prior to planting and fall tillage after corn harvest using a chisel plow to incorporate corn residues. The soils are disturbed during fertilizer application. Anhydrous NH₃ at a rate of 168 kg N ha⁻¹ is injected into the soil prior to corn planting, and P and K fertilizer is incorporated with a field cultivator after soybean harvest. The two fields have a size of 31.5 and 25.8 ha and will thereafter be referred to as “conventional corn” and “conventional soybean,” according to the 2017 crop. On conventional soybean, corn was harvested in 2016 on DOR 298, and soybean was planted and harvested in 2017 at DOR 503 and 663, respectively. On conventional corn, soybean was harvested in 2016 on DOR 290, and corn was planted and harvested in 2017 on DOR 483 and 683, respectively. The planting rate of corn and soybean in 2017 was approximately 83,500 and 345,000 plants ha⁻¹. Soils belong to the Clarion–Nicollet–Webster (fine-loamy, mixed, superactive, mesic Typic Hapludolls; fine-loamy, mixed, superactive, mesic Aquic Hapludolls; fine-loamy, mixed, superactive, mesic Typic Endoaquolls) association with loam–clay loam soil texture (USDA-NRCS, 2018). Average (±SD) SOC concentration in surface 30 cm in 2016 was 2.6 ± 0.8% and 2.5 ± 0.6% on soybean and corn, respectively.

The second site (42.485°N, -93.523°W, 355 m asl) is part of the Upper Mississippi River Basin Long-Term Agroecosystem Network Research (LTAR) of USDA-ARS, where “aspirational” crop management strategies are investigated under field conditions compared with conventional management (Spiegal et al., 2018). The crop management was converted from conventional management to a reduced tillage system with cover crops following the 2016 growing season. Soil disturbance was limited to one spring tillage using a field cultivator on the corn site in 2016, and strip tillage in fall after soybean harvest with P and K application. In fall 2017, the soil of the headlands was loosened with a subsoiler. The application of NH₃, and UAN applied in corn in spring 2016 and the growing season 2017 was at a rate of 157 kg N ha⁻¹. Note that the 2016 corn residues were not incorporated into the soil prior to soybean planting in 2017. In addition, cereal rye was planted as a cover crop after soybean harvest (DOR 284 and 664) and during the growing season in corn (DOR 277 and 606). The cover crop was terminated shortly before corn and soybean planting. It should be noted that cover crops did not grow well in 2016 and 2017 with poor germination, reduced growth, and an approximate total height of 10 cm. The two fields on the second site have a size of 47.5 and 60.8 ha and are referred to as “aspirational corn” and “aspirational soybean,” according to the 2017 crop. Planting rate and time of planting and harvest were similar to the first site: Soybean was harvested in 2016 on DOR 273, and corn was planted and harvested in 2017 on DOR 481 and 655, respectively. Corn was harvested in 2016 on DOR 282, and soybean was planted and harvested in 2017 on DOR 501 and 658, respectively. The planting rate of corn and soybean in 2017 was approximately 83,200 and 310,000 plants ha⁻¹. Soils belong to the Clarion–Nicollet–Webster association with loam–clay loam soil texture (USDA-NRCS, 2018). Average (±SD) and SOC in the surface 30 cm in 2016 was 2.4 ± 0.8% and 2.3 ± 0.8% for soybean and corn, respectively.
rain gauges, and rainfall data averaged for each site. The EC sampling was performed for rain gauges and included relative humidity. Precipitation was recorded using tipping bucket gauges. An air temperature sensor was placed away from the flux tower to avoid any interference of the incoming– outgoing shortwave and longwave radiation. An air temperature and humidity sensor was placed on the aspirational site, whereas on the conventional site there was a temperature and humidity sensor (Al-Kaisi et al., 2005). There was also a 3-D sonic anemometer that measured wind speed, wind direction, and air density based on the Webb–Pearman–Leuning algorithm (Webb et al., 1980).

Eddy Covariance Systems

Turbulent fluxes of latent heat (LE), sensible heat (H), and carbon dioxide (F) at each site were computed using the EC method. Details of the EC approach are well described in the literature (Burba, 2013). Briefly, EC stations were deployed in the center of each field so that the EC footprint covered the crop of interest in a representative portion of the field. Each EC station was equipped with a high-frequency open-path infrared gas analyzer (IRGA, conventional: LI-7500, LICOR Biosciences, Lincoln, NE, USA; aspirational: IRGASON, Campbell Scientific, Logan, UT, USA) that measures water vapor (\(\rho_v\)) and carbon dioxide (\(\rho_c\)) densities. High frequency instantaneous wind speed velocity components (\(u, v, w\) in s\(^{-1}\)) and sonic temperature (\(T_s\)) were measured with a 3-D sonic anemometer (CSAT, Campbell Scientific, Logan, UT, USA). The measurement height (\(z_u\)) of IRGAs and sonic anemometers ranged between 200 and 500 cm, depending on crop height and season. The \(F_c, LE, and H\) fluxes were computed as the covariance between the instantaneous vertical wind velocity (\(w\)) and \(\rho_c, \rho_v,\) and \(T_s\), respectively. The turbulent fluxes were coordinate rotated (Tanner and Thurtell, 1969) and corrected for variations in temperature and air density based on the Webb–Pearman–Leuning algorithm (Webb et al., 1980).

All EC stations were instrumented with a four-component net radiometer (conventional: CNR-1, Kipp & Zonen, Delft, the Netherlands; aspirational: NR-01, Hukseflux, Delft, the Netherlands) positioned over the canopy at a nominal distance away from the flux tower to avoid any interference of the incoming–outgoing shortwave and longwave radiation. An air temperature and relative humidity probe (Vaisala HMP45c, Vaisala, Vantaa, Finland) recorded air temperature, saturation vapor density, and relative humidity. Precipitation was recorded using tipping bucket rain gauges, and rainfall data averaged for each site. The EC sampling rate (high frequency) was 20 Hz, and the remaining slow response instrument was all sampled at 0.1 Hz (10 s) on an averaged 15-min interval. Signals from all EC instrumentation were recorded on data loggers (CR5000, Campbell Scientific, Logan, UT). Total rainfall during the observation period was 808 and 798 mm for the aspirational and conventional site, respectively. Ambient air temperature was similar among both sites (see Appendix A, Fig. A1). Further specifications of the EC systems are listed in Appendix A (Table A2).

Outlier Screening and Interpolation

The datasets were screened for sensor failures and statistical outliers and subsequently interpolated to fill data gaps. All data that violated empirically set upper and lower thresholds were excluded from further analysis. Additional screening included periods of precipitation (Hernandez-Ramirez et al., 2011), possible water condensation on the instruments (Baker and Griffis, 2005), low wind turbulence, wind direction opposite to the sensor head direction (Hernandez-Ramirez et al., 2010), and when flagged by the manufacturer’s internal IRGA and CSAT warning systems (e.g., during storm events). We also used the water vapor saturation measurement from the humidity probe to screen LE, since the humidity sensor is not affected by dust or rainfall events (Schmidt et al., 2012). The \(F_c\) was separately checked for daytime and nighttime (\(F_c\text{ day}, F_c\text{ night}\)). Data were also screened using the interquartile range (IQR) procedure, where outliers were defined as first/third Quartile ± 1.5 × IQR. The 15-min dataset was interpolated (or gap filled) following an inverse weighted time average procedure (Hernandez-Ramirez et al., 2010). Prior to that, \(F_c\text{ night}\) was gap filled using the relation between air temperature and CO\(_2\) fluxes (Reichstein et al., 2005), whereas \(F_c\text{ day}\) was gap filled using light response curves (Gilmanov et al., 2007). Daily values were calculated as the daily average multiplied by the number of samples per day. Further information on outlier screening and interpolation procedures can be found in Dold et al. (2017). Depending on site and year, 12 to 55% of 15-min \(F_c\) and LE was excluded as outliers, and 4 to 38% was interpolated.

Partitioning of Net Ecosystem Production, Evapotranspiration, and Water Use Efficiency

Daily NEP was calculated as the sum of daily \(F_c\text{ day}\) and \(F_c\text{ night}\). Note that the arithmetic sign convention is negative for \(F_c\) from the surface to the atmosphere, and that NEP can be below zero. The NEP was partitioned into RE and GPP. The GPP was calculated as the difference between NEP and RE. Daily RE was calculated as the sum of daytime respiration (\(R_d\)) and nighttime respiration (\(F_c\text{ night}\)). During the non-growing season, \(R_d\) equals \(F_c\text{ day}\), whereas during the growing season \(R_d\) can be derived from the nonlinear relationship between PAR and \(F_c\text{ day}\) using light response curves, such as the rectangular hyperbola function (Gilmanov et al., 2007):

\[
F_c\text{ day} = \frac{AQY \times PAR \times P_{g \text{max}}}{P_{g \text{max}} + AQY \times PAR} - R_d
\]

where \(F_c\text{ day}\) is daytime CO\(_2\) flux (\(\mu mol m^{-2} s^{-1}\)), \(AQY\) is apparent quantum yield (\(\mu mol CO_2 \mu mol PAR^{-1}\)), \(P_{g \text{max}}\) is maximum gross photosynthesis rate (\(\mu mol CO_2 m^{-2} s^{-1}\)), PAR is photosynthetic active radiation (\(\mu mol m^{-2} s^{-1}\)), and \(R_d\) is mean daytime respiration (\(\mu mol CO_2 m^{-2} s^{-1}\)).
Photosynthetic active radiation was derived from incoming shortwave radiation, assuming that 1 W m\(^{-2}\) equals 4.6 μmol m\(^{-2}\) s\(^{-1}\) (Norman and Campbell, 1998), and that 45% of incoming shortwave radiation is the photosynthetic active radiation (Schmidt et al., 2012). Daily NEP, RE, GPP, and \( R_{\text{y}} \) was screened to empirically derived thresholds and interpolated using an inverse weighted time average procedure. The net biome production (NBP), here defined as amount of field C sequestered/mineralized, was calculated as the difference of NEP and 2017 yield C.

Daily water use efficiency was computed following Beer et al. (2009):

\[
\text{IWUE}^* = \frac{\text{GPP} \times \text{VPD}}{\text{ET}}
\]

where

\[
\text{IWUE}^* = \text{daily inherent water use efficiency (g C \times hPa mm}^{-1} \times \text{m}^{-2}),
\]
\[
\text{GPP} = \text{daily gross primary production (g C m}^{-2}),
\]
\[
\text{VPD} = \text{daily daytime vapor pressure deficit (hPa), and}
\]
\[
\text{ET} = \text{daily evapotranspiration (mm).}
\]

The ET was calculated as the quotient between mean daily LE and the latent heat of vaporization, of which the latter was calculated as a function of air temperature (Allen and Pruitt, 1991). The total NEP, RE, GPP, and ET for the period of interest was calculated as:

\[
X = \sum_{d=1}^{n} x_d \times n
\]

where

\[
X = \text{total NEP, GPP, RE, and ET per crop rotation period,}
\]
\[
x_d = \text{daily NEP, GPP, RE, and ET,}
\]
\[
d = \text{number of measured or gap-filled days, and}
\]
\[
n = \text{number of days per crop rotation period.}
\]

RESULTS AND DISCUSSION

Carbon Fluxes

Corn and soybean followed reported annual C flux patterns at both sites with higher NEP, GPP, and lower RE (i.e., higher respiration) in corn as a C4 plant than soybean as a C3 plant (e.g., Verma et al., 2005; Dold et al., 2017) (Fig. 1 and 2). Considering the total observed period of 440 d, the corn and soybean NEP on the aspirational site was higher with 565 and 119 g C m\(^{-2}\), compared with 421 and –64 g C m\(^{-2}\) on the conventional site, respectively. Thus, conventional soybean was already a C source even before considering C loss by grain removal. The calculated NBP for the aspirational corn and soybean was 118 and –35 g C m\(^{-2}\), indicating that soybean production was a C source and corn production was a C sink. Thus, the overall corn–soybean system was a C sink during the studied transitional period. Verma et al. (2005) found soybean to be a C source before accounting for grain C removal in no-till systems, and that the corn–soybean no-till system is C neutral, with being a C source in soybean-years and a C sink in corn-years. The NBP for conventional corn and soybean was –59 and –187 g C m\(^{-2}\), respectively, i.e., the conventional corn–soybean system is a C source. This is similar to the results of Dold et al. (2017) in a long-term study. It however contrasts the findings of Baker and Griffis (2005), who reported higher NEP and equal NBP in conventional Midwestern corn–soybean compared with reduced till-cover crop systems. Furthermore, the authors demonstrated that both corn and soybean production systems were a C source. Total GPP from the aspirational site was lower in corn and slightly higher in soybean, with 1285 and 750 g C m\(^{-2}\) compared with the conventional site with 1405 and 742 g C m\(^{-2}\), respectively. Similar GPP values were found by Verma et al. (2005) in no-till corn–soybean rotations. The higher GPP resulted from higher RE on the conventional site during both the growing and off-season.

The RE was higher (i.e., lower respiration) during the growing season on the aspirational site with –660 and –499 g C m\(^{-2}\) compared with the conventional site with –851 and –619 g C m\(^{-2}\) for corn and soybean, respectively. The NEP was negative (i.e., C source) at both sites during the main crop off-season, and positive (i.e., C sink) during the main crop growing season. The aspirational site NEP (and RE) during the off-season was higher with –60 and –134 g C m\(^{-2}\), than on the conventional site with –132 and –184 g C m\(^{-2}\) for corn and soybean, respectively. During the growing season, total NEP on the aspirational site was higher with 625 and 234 g C m\(^{-2}\) compared with the conventional site with 553 and 119 g C m\(^{-2}\) for corn and soybean, respectively. Although NEP and RE of aspirational corn agreed with a previous study on a midwestern no-till corn–soybean system, higher RE was observed, leading to negative NEP (C source) (Verma et al., 2005). If C assimilation and respiration of plants is similar among the sites and the sown rye cover crop in corn did not contribute substantially, the increased RE and NEP values on the aspirational site are likely derived from changes in tillage and residue management.

In addition, a faster rate of decreasing daily NEP has been observed on the conventional site compared with aspirational site in both crops in winter–spring 2017 (DOR 367–520). A linear regression was significant (\( p < 0.05 \)) between DOR as independent and daily NEP as dependent variable. The calculated rate of decline was –0.012 and –0.016 g C m\(^{-2}\) d\(^{-1}\) in conventional corn and soybean, whereas it was –0.005 and –0.004 g C m\(^{-2}\) d\(^{-1}\) on the aspirational site, respectively (Fig. 3). The NEP before planting was –105 and –162 g C m\(^{-2}\) on conventional corn and soybean, whereas it was –12 and –33 on aspirational corn and soybean. This means that approximately 143 and 32% of soybean and corn residue C input (see “Study Sites” above) had been respired under conventional crop management between 2016 harvest and 2017 planting, whereas under aspirational management it was only 14 and 7%, respectively. Although spring tillage appeared to substantially increase RE and reduce NEP, Baker and Griffis (2005) noted a higher impact of reduced fall tillage on NEP.

These trends of higher GPP, NEP, and RE on the aspirational site could be related to the reduced tillage activity, or the increased C assimilation by cover crops. Further, the incorporation of the 2016 corn residues into the soil at the conventional site might have reduced NEP. It is difficult to state the contribution of each management practice to these changes in C dynamics without further measurements. As indicated above, it is more likely that the cover crops played a minor role owing to their stunted and sparse growth (see “Study Sites” above). Baker and Griffis (2005) and Bavin et al. (2009) investigated similar midwestern corn–cover crop–soybean systems with reduced tillage and found higher RE/lower NEP than in conventional systems due to cover crop mineralization after termination. This was not visible in this study, an indicator that the impact of the cover crop was minimal in these first 2 yr of plant production. In addition, Martinez-Feria et al. (2016) noted a wide
Fig. 1. Daily GPP, RE, NEP (all in g C m⁻²), and ET (mm) of conventional (A–D) and aspirational com (E–H) system in 2016–2017 rotation period. The crop management is shown in panel D and H with bricked area for the soybean season, dotted area for the corn season, crossed hatched area for cereal rye season, dots and crosses for tillage and fertilizer events, respectively.

Fig. 2. Daily GPP, RE, NEP (all in g C m⁻²), and ET (mm) of conventional (A–D) and aspirational (E–H) soybean system in from 2016 to 2017. The crop management is shown in panel D and H with bricked area for the soybean season, dotted area for the corn season, crossed hatched area for cereal rye season, dots and crosses for tillage and fertilizer events, respectively.
range of rye aboveground biomass in corn–soybean rotations of 0.12 to 2.50 Mg ha$^{-1}$, weather-dependent, with an average C concentration of 39.5%, which makes up an additional 5 to 99 g C m$^{-2}$ of cover crop input. Thus, rye inputs might only have substantial impact on the C balance under optimal growth conditions, where it reaches residue C comparable to soybean (see “Study Sites” above). Note that these results are not indicative for long-term effects on C fluxes, as the aspirational site is still in transition to reduced and eventually no-till system. Similar to the results of this study, Hollinger et al. (2005) found in a 5-yr-study that no-till corn–soybean systems are C sinks in corn-years and C source in soybean-years.

**Evapotranspiration and Water Use Efficiency**

Previous authors have noted a reduction in evaporation from no-till systems (Phillips et al., 1980; Lal et al., 2007; Schwen et al., 2015; Chi et al., 2016), an effect that was not observed in this study. Total ET on the aspirational and conventional corn-sites was 592 and 610 mm, and on the soybean-sites it was 596 and 589 mm, respectively. Hence, there was also no crop-specific difference in ET (Fig. 1D, 1H; Fig. 2D, 2H). The aspirational soybean ET was lower in spring with 142 mm than in conventional soybean with 183 mm. This ET reduction of 41 mm could be due to the 2016 corn residues in spring with 142 mm than in conventional soybean with 183 mm. This ET reduction of 41 mm could be due to the 2016 corn residues. The impact of the rye cover crop was probably low. Baker and Griffis (2009) stated that rye cover crop could reduce available soil water, which could delay planting date and germination. The average IWUE* during the main crop growing season was higher in corn than soybean, which is a typical pattern for C4 to C3 crops and is connected to higher GPP in C4 crops (Dold et al., 2017). The seasonal averaged IWUE* on the aspirational site was slightly lower for corn and soybean with 30.7 and 18.2 g C × hPa mm$^{-1}$ m$^{-2}$ compared with the conventional site with 32.6 and 21.3 g C × hPa mm$^{-1}$ m$^{-2}$ (Fig. 4). This increase in IWUE* results from increased GPP on the conventional site, whereas ET and VPD (1.0–1.1 kPa) did not change substantially among sites. The anticipated effect of increased water use efficiency owing to reduced tillage, and hence, ET was not observed in this short-term study (Hatfield et al., 2001).

**CONCLUSION**

The impact of tillage and cover crops on C and water dynamics in corn–soybean rotation systems was investigated between the 2016 harvest and the end of 2017 (440 d). The impact of cover crops was probably low, as growth was stunted during the observed period. The NEP and GPP in a transitional reduced till and cover crop system was higher compared with the conventional system, already after the second year of the transition period. The RE was also lower, probably owing to reduced soil disturbance and leaving crop residues on the soil surface. The NEP decreased more rapidly under conventional production in winter/spring 2017, which substantially reduced the C inputs of the 2016 harvest residues. The ET was similar among crops and sites; however, lower ET in spring under reduced till indicated wetter soils, which could delay planting date and germination. The IWUE* was lower under reduced till with cover crops, as GPP was higher in conventional systems. This suggests that the water use efficiency was not improved under reduced tillage. The NBP was negative in soybean-years in both systems, indicating that soybean production acts as a C source even under improved soil management. The corn NBP was negative in conventional and positive in aspirational production, showing an improvement in the C balance by these management changes. The corn–soybean production system was a C source in conventional and a C sink in the aspirational system. These findings partly contrast with the few available studies comparing soil management practices using EC, which suggests that long-term continuous monitoring is needed to further investigate C and water dynamics.

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APPENDIX A: Site Comparison

Table A1. Average STIR (Soil Tillage Intensity Rating) values for the crop rotation 2016–2017 on conventional and aspirational corn and soybean, respectively. STIR values according to RUSLE2 software, here summarized for pest management, planting and harvest, fertilizer application, and tillage activities.

<table>
<thead>
<tr>
<th>Management practice</th>
<th>Conventional</th>
<th>Aspirational</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Corn</td>
<td>Soybean</td>
</tr>
<tr>
<td>Pest management</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Planting and harvest</td>
<td>7.6</td>
<td>7.6</td>
</tr>
<tr>
<td>Fertilizer application</td>
<td>31.0</td>
<td>31.0</td>
</tr>
<tr>
<td>Spring and fall tillage</td>
<td>119.3</td>
<td>119.3</td>
</tr>
<tr>
<td>No. years per rotation</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Average rotation STIR</td>
<td>79.3</td>
<td>79.3</td>
</tr>
</tbody>
</table>

Table A2: Specification of the EC (eddy-covariance) stations: Temperature and humidity probe, 3-D sonic anemometer and infrared gas analyzer, and radiation sensor model, measurement height, and azimuth from north of the sonic.

<table>
<thead>
<tr>
<th>Management practice†</th>
<th>Conventional</th>
<th>Aspirational</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Corn</td>
<td>Soybean</td>
</tr>
<tr>
<td>Sonic/IRGA model</td>
<td>CSAT-3 and LI-7500</td>
<td>IRGASON</td>
</tr>
<tr>
<td>$z_m$, cm</td>
<td>225–500</td>
<td>225–240</td>
</tr>
<tr>
<td>Azimuth from north</td>
<td>270°</td>
<td></td>
</tr>
<tr>
<td>Radiation sensor model</td>
<td>CNR-1</td>
<td></td>
</tr>
<tr>
<td>Temp./humidity sensor</td>
<td>Vaisala HMP</td>
<td></td>
</tr>
</tbody>
</table>

† Sonic, 3-D sonic anemometer; IRGA, infrared gas analyzer; $z_m$, measurement height.

Fig. A1. Daily average air temperature (dotted line) and rainfall (black bars) ($n = 2$ EC stations) at the reduced till and till site.

Fig. 4. Daily IWUE* (g C × hPa mm$^{-1}$ m$^{-2}$) of soybean under tillage (A) and low-till (B) and corn under tillage (C) and low-till (D) system in 2016–2017. The crop management is shown in panel D and H with bricked area for the soybean season, dotted area for the corn season, crossed hatched area for cereal rye season, dots and crosses for tillage and fertilizer events, respectively.