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# Long-term ecosystem carbon losses from silage maize-based forage cropping systems

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ABSTRACT

Intensification of the US dairy industry has driven increased reliance on maize (*Zea mays* L.) silage as a primary forage source in place of perennial forages such as alfalfa (*Medicago sativa* L.). Using 29 site-years of eddy covariance, plant, and manure measurements, we calculated net ecosystem C balances (NECB) for two silage maize-based forage cropping systems and a soybean-maize grain rotation. We found that C losses were over threefold greater from continuous silage maize (-4.9 Mg C ha$^{-1}$ yr$^{-1}$) than from the predominant grain cropping system in the region, the soybean-maize rotation (-1.3 Mg C ha$^{-1}$ yr$^{-1}$). Including alfalfa in rotation reduced C losses by 23% relative to continuous silage maize, but net losses were still observed (-3.8 Mg C ha$^{-1}$ yr$^{-1}$). For every megagram of crop residue C left in-field, net C balances increased by +0.9 Mg C ha$^{-1}$. A winter rye (*Secale cereale* L.) cover crop and applications of liquid dairy manure marginally improved C-balances but were insufficient to offset C losses in respiration and crop harvest. Increasing manure application rates could bring these systems to a net equilibrium C balance but would also result in soil N and P surpluses and unacceptable loss of nutrients to air and water. Since 1980, over 800,000 hectares of alfalfa have been lost across the Upper Midwest US, and C export in harvested maize grain and silage have increased dramatically. This shift implies a substantial reduction in SOC on forage cropped soils in the region.

## 1. Introduction

Intensification of the US dairy industry has driven increased reliance on maize (*Zea mays* L.) silage as a primary forage source in place of perennial forages such as alfalfa (*Medicago sativa* L.). Silage maize has higher yield and energy content, more uniform quality, and fewer required harvests than perennial forages, which has allowed dairy producers to expand herd size and reduce the land area needed for forage production (Martin et al., 2017; Rankin, 2014). However, this shift in forage usage and the resulting changes in cropping patterns have important implications for the carbon (C) balance of agroecosystems in dairy producing regions of the US. Across the Upper Midwest US, alfalfa area has decreased by 840,000 ha (30%) over the past twenty years, while land area in summer annual forages and grains has increased (USDA-NASS, 2019, 2014). Soils that were in perennial living cover are now subject to more frequent tillage and reduced plant residue inputs, which can deplete soil organic matter and negatively impact C balances (Haddaway et al., 2017). Moreover, silage maize yield has increased by 42% since the mid-1980’s (USDA-NASS, 2016), suggesting a comparable increase in C export from forage cropped soils.

Research documenting carbon balances for maize systems in the Midwest US has been mostly focused on grain maize-soybean rotations. These studies show that grain maize typically ranges from being a small source of C to being a small sink, depending on local conditions and management (Baker and Griffis, 2005; Bavin et al., 2009; Dold et al., 2017; Suyker and Verma, 2012; Verma et al., 2005). Studies from across Europe have shown net losses of C from silage maize production (Beziat et al., 2009; Ceschia et al., 2010; Poyda et al., 2019), which is unsurprising given that the majority of aboveground biomass is removed in harvest. Similarly, it has been well documented that maize stover removal for forage or biofuel production negatively impacts SOC stocks (Xu et al., 2019), indicating that such management leaves less than

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adequate crop residue C behind to support the belowground C economy. With such intensive harvest, root biomass accrual and turnover provide critical C inputs for maintaining SOC stocks in forage systems. With perennial forages such as alfalfa, residue contributions to soil can be up to 5-fold higher than for maize due to greater allocation of resources to belowground growth (Angers, 1992). Land application of dairy manure provides additional C inputs that may help offset C export in harvest. However, a variety of cropping systems have shown net losses of C despite high inputs of manure and crop residues (Kutsch et al., 2010).

It's unclear how recent changes in forage production practices may interact to influence the C balance of dairy agroecosystems in the Upper Midwest US. The shift toward greater usage of maize silage has coincided with increased prevalence if liquid manure management on larger dairy farms, and changes in climate are driving increased reliance on irrigation throughout the region (DeLucia et al., 2019; USDA-NASS, 2019). As a result, we initiated a set of production-scale studies at four field sites representing three common forage and grain cropping systems in the Upper Midwest US. This study includes year-round field-scale eddy covariance $CO_2$ flux measurements to calculate the net ecosystem production (NEP, or the net $CO_2$-C flux in each field), gross primary productivity (GPP, or crop $CO_2$-C assimilation), and ecosystem respiration ($R_e$, the sum of autotrophic and heterotrophic respiration $CO_2$-C fluxes), where NEP is equivalent to GPP – $R_e$. We also collected detailed manure, plant, and soil measurements to calculate net ecosystem C balances (NECB), where NECB = NEP + manure C – crop harvest C. The three cropping systems were: (1) irrigated continuous silage maize, (2) irrigated silage maize-alfalfa, and (3), a rain-fed soybean – grain maize rotation. The first two systems were designed for dairy forage production, received applications of liquid dairy manure in most years, and were artificially (tile) drained. A winter rye (*Secale cereal* L.) cover crop was planted following silage harvest in one year of the irrigated silage maize-alfalfa system. The soybean-maize system received only mineral fertilizer, was freely drained, and as the predominant grain cropping system in the region, was included as a benchmark against which the forage cropping systems could be compared. Our objective was to evaluate how modern dairy forage crop, manure, and irrigation management influence interannual variability in NECB. We analyzed at least 8 years of annually integrated C-fluxes for each cropping system and address the following questions: (a) How do the annual GPP, $R_e$, NEP, harvested C, and NECB vary among individual crops and cropping systems? (b) What are the impacts of irrigation, manure application, and winter rye cover cropping on NECB in these systems? (c) How well do eddy covariance- and soil sampling-based estimates of C balance agree for these systems?

## 2. Materials and methods

### 2.1. Measurement sites

The study was conducted on three 65-ha fields on a privately-owned dairy farm in west central Minnesota and a 17-ha field at the University of Minnesota's Rosemount Research and Outreach Center (RROC), approximately 25 km south of St. Paul, MN. The soils at the dairy farm were formed in calcareous loamy glacial till and consist primarily of a somewhat poorly drained Hamerly clay loam (fine-loamy, mixed, superactive, frigid Aeric Calciaquolls), a moderately well-drained Aastad clay loam (fine-loamy, mixed, superactive, frigid Pachic Argiudolls), and a poorly drained Parnell silty clay loam (fine, smectitic, frigid Vertic Argiaquolls; Table S1). The soils at the RROC are a Waukegan silt loam (fine-silty over skeletal mixed, superactive mesic Typic Hapludoll) consisting of a silt loam surface layer 0.5–1.8 m thick overlying a layer of sand and gravel >20 m thick.

### 2.2. Agronomic management

The dairy forage production fields were managed as part of the cooperating dairy, and all management decisions were made by the farm operator. The three fields are extensively tile drained and were managed with irrigation beginning in May 2009. One field was planted to silage maize each year of the study (continuous silage maize, 2008 - 2015; Fig. 1, Table S2), the second field was planted to silage maize for five years and alfalfa for the subsequent three years, with a winter rye cover crop following silage maize over the 2007 to 2008 winter (silage maize-alfalfa 1, 2008 - 2015), and the third field was planted to alfalfa for three years and silage maize for the subsequent two years (silage maize-alfalfa 2, 2011 - 2015).

Liquid dairy manure was applied to the forage systems in most years. In the continuous silage maize system, liquid dairy manure was dragline injected in fall 2008, no manure was applied in 2009, and from 2010 to 2015 manure was fertigated via center-pivot irrigation system during the growing season. In the silage maize-alfalfa systems, liquid dairy manure was injected following maize silage harvest each fall. For alfalfa, no manure was applied in the establishment year, but in mature years manure was applied after the first harvest via subsurface deposition slurry applicator (Aerway SSD, Holland Equipment Ltd.). A winter rye (var. "Rymin") cover crop was established in the silage maize-alfalfa 1 system following silage harvest in 2007 and then terminated in May 2008. Typical management also included tilling the fields to a depth of 23 to 30 cm following fall manure injection in each field. The soybean-maize field at RROC was farmed conventionally, which in this area means fall tillage that consisted of a chisel plow in combination with a tandem disk, and fertility maintained with spring pre-plant chemical fertilizer applications as dictated by soil testing.

### 2.3. Crop, manure, and soil measurements

At each harvest, total wet mass of alfalfa silage was recorded by the farmer by weighing each truckload removed from the field, and five approximately 1.5-kg subsamples were collected for dry matter (DM) determination. Maize silage DM yield was determined by hand harvesting and weighing a 3 m length of row in at least 16 randomly selected locations in each field and collecting a subsample of three plants in each location. Subsamples of maize silage were dried at 65 °C for 48 h for DM determination and ground to pass through a 1 mm sieve for C analysis by dry combustion (Bremner and Mulvaney, 1982) using a Leco TruSpec CHN Analyzer (Leco Corp., St. Joseph, Michigan). Maize grain and soybean yield were recorded each year. The C removed in harvest of maize grain and soybean was calculated using a grain content of 448 and 511 g C $kg^{-1}$, respectively (Hernandez-Ramirez et al., 2011). For alfalfa, the C removed in harvest was calculated using a C content of 432 g C $kg^{-1}$ (Mayland, 1968).

Carbon applied in manure was estimated each year of the study with application rates supplied by the producer. For slurry applied with injection or SSD, grab samples of the manure were obtained from the pump station just prior to or during application. For fertigated dairy slurry, sample containers were placed in the field during fertigation to collect grab samples. Samples were analyzed for DM content by a commercial laboratory (Agvise Labs, Benson, MN). In 2006, manure C was determined via combustion using an Elementar Variomax C/N analyzer. Manure C in remaining years was calculated as a constant fraction of DM content (442.5 g $kg^{-1}$) based on the 2006 analysis.

Soil samples were collected following harvest each fall in the silage maize alfalfa 1 and continuous silage maize fields. Cores were collected at 49 gridded sample locations per field each year and analyzed via dry combustion. Soil organic C was calculated as total C less inorganic C and SOC stocks were calculated via equivalent soil mass methods. Further detail can be found in Gamble et al (2018).

### 2.4. Eddy covariance measurements

Eddy covariance data were collected continuously at each site from 12-Sept. 2007 to 31-Dec. 2015, except for the silage maize - alfalfa 2 site

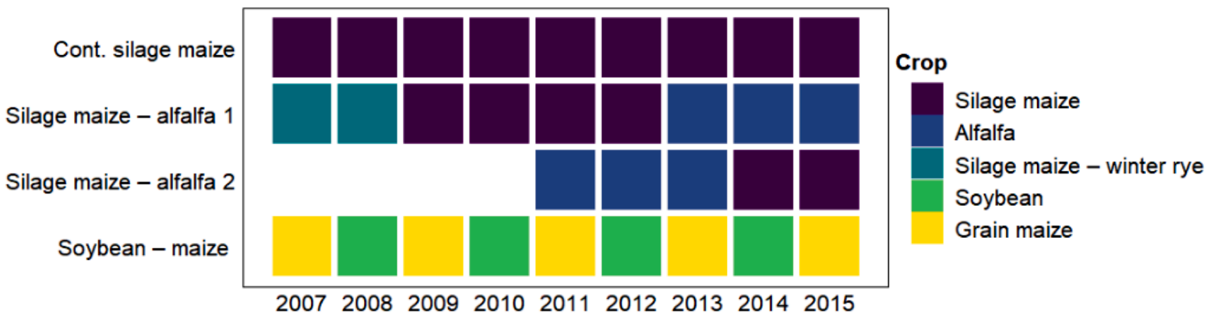


**Fig. 1.** Crop sequence at each research site over the study period. Data collection began in fall 2007 following crop harvest, except for the silage maize – alfalfa 2 site for which data collection began in fall 2010. The total site years analyzed for each crop are $n_{silage\ maize} = 15$, $n_{alfalfa} = 6$, $n_{soybean} = 4$, and $n_{grain\ maize} = 4$. The dairy forage sites (those including alfalfa and silage maize) were located at a Minnesota dairy farm, while the soybean-maize site was at the University of Minnesota Rosemount Research and Outreach Center (RROC).

where data were collected from 3-Aug. 2010 to 31-Dec. 2015. Field scale $CO_2$ fluxes were quantified using an open-path infrared gas analyzer (LI-7500, Licor Inc. Lincoln, Nebraska) and a three-dimensional sonic anemometer (CSAT-3, Campbell Scientific, Logan, UT) positioned on a boom or an irrigator pivot at the center of each field, providing at least 380 m of fetch in all directions at the dairy forage sites and 205 m fetch at the soybean-maize site. The analyzer and anemometer were adjusted relative to crop height throughout each growing season. The eddy covariance instruments were sampled at 10 Hz, with covariances calculated every 30 min using a custom program written in CRBasic (Campbell Scientific, Logan, UT).

Additional meteorological data collected included solar and long-wave radiation with pyranometers and pyrgeometers (Eppley Laboratories, Newport, RI), air temperature and humidity (HMP45C, Vaisala Inc., Woburn, MA), and precipitation was measured using a tipping bucket gauge with a manual rain gauge backup. Frozen precipitation was not measured at the dairy forage sites, so October to April precipitation data were obtained from the University of Minnesota West Central Research and Outreach Center (WCROC), located 16 km away. Any other missing precipitation data throughout the study period were filled with data from the WCROC. Soil heat flux was measured with two heat flux plates (Hukseflux, the Netherlands and REBS, Seattle, WA) installed at 10 cm and corrected calorimetrically, and soil temperature was measured at 2.5-, 5-, and 7.5-cm depths at the center of each field using type E thermocouples potted in epoxy resin. All ancillary data were collected on CR1000 loggers (Campbell Scientific, Logan, Utah) and averaged at 30-min intervals.

Post-processing included two-dimensional coordinate rotation and corrections for sensor separation, frequency attenuation, and density fluctuations caused by changes in temperature and humidity (Webb et al., 1980). Sensor path heat exchange corrections were not applied as they can yield large uncertainties if applied in the absence of a simultaneous reference flux measurement (Deventer et al., 2021). The data were screened to eliminate periods of high relative humidity (>98%), precipitation, and sensor malfunction (Baker and Griffis, 2005) and were despiked using a variation of the method described by Papale et al., (2006) by comparing the double differenced timeseries with the median absolute deviation computed over 13 d (624 records). Additionally, remaining extreme flux values above and below $\pm 50$ $\mu mol\ m^{-2}\ s^{-1}$ were removed from analysis. Gaps in the half-hourly data were filled with the REddyProc R package (Reichstein and Moffat, 2014) which uses an algorithm based on well-established gap-filling procedures (Falge et al., 2001; Reichstein et al., 2005). This algorithm creates a lookup table and replaces values according to the average output under similar meteorological conditions. If the meteorological data required for the look-up table approach are missing, the values are replaced according to the mean diurnal course of adjacent days. REddyProc estimates friction velocity (u*) thresholds by identifying conditions with inadequate wind turbulence and discards half-hourly measured fluxes when u* is below the chosen threshold and marks them as artificial gaps (Papale et al., 2006). Customized "seasons" for u* threshold estimation were specified in REddyProc based upon crop emergence and harvest dates to account for site specific changes in surface roughness with management. The NEP estimates were then partitioned into GPP and $R_e$ according to Reichstein et al., (2005) using the REddyProc R Package. Net primary productivity (NPP) was calculated by first partitioning growing season (GPP > 0.5 g C $m^{-2}$ $d^{-1}$) $R_e$ into heterotrophic ($R_h$) and autotrophic ($R_a$) respiration, then calculating NPP as the difference between GPP and $R_a$. Partitioning of $R_e$ was conducted according to Amiro et al., (2017), whereby daily NEP was regressed on daily GPP, to yield $R_h$ as the intercept and $R_a$/GPP as 1-slope.

To account for the uncertainty introduced by the gap-filling method, both random and bias errors were calculated on a half-hourly basis and propagated over time to estimate annual offsets in NEE. The "FILLALL = T" argument in REeddyProc was used to introduce artificial gaps in the data, one for each half-hourly observation. These artificial gaps were then filled using the same methods used for real gaps. Bias due to gap-filling was then calculated as the difference between observed and predicted half-hourly fluxes, and bias error and annual bias offset were calculated according to Moffat et al., (2007). The random error due to gap-filling was calculated with REddyProc from the standard deviation of half-hourly flux data used for filling each half-hourly gap. The total uncertainty of annual NEP from gap-filling was then calculated using quadrative error propagation (Hurkuck et al., 2016; Richardson and Hollinger, 2007).

$$\sigma_{gap} = \sqrt{\sigma_{bias}{}^2 + \sigma_{random}{}^2} \tag{1}$$

Where $\sigma_{gap}$ is the total error associated with gap-filling, $\sigma_{bias}$ is the bias offset, and $\sigma_{random}$ is the random error. Additional uncertainty is introduced via selection of the u* threshold, as there is a tendency toward higher NEP with lower u* threshold selection. We assessed this uncertainty by estimating the u* thresholds at the 5th and 95th percentiles for 1000 bootstrapped datasets. The difference between the 5th and 95th percentile u* thresholds provides a range of uncertainty ($\sigma_{ustar}$) in NEP fluxes based on the u* filters. Total uncertainty in NEP ($\sigma_{nep}$) was then calculated as the quadrative sum of $\sigma_{gap}$ and $\sigma_{ustar}$.

### 2.5. Calculation of carbon budgets

Half-hourly fluxes were integrated annually on the final crop harvest date of the year, with the start date for the subsequent year occurring the day after harvest. The annual NECB was then calculated as NEP + manure C – crop harvest C. Losses of dissolved organic and inorganic carbon (DOC / DIC) were measured in tile drainage runoff during 2007 and 2008 and found to be no more than 11 kg C $ha^{-1}$ in either field over this period (unpublished data). These fluxes were not measured thereafter and are assumed to be negligible for the sake of NECB calculations here. The total uncertainty in NECB ($\sigma_{necb}$) was calculated as the quadrative sum of $\sigma_{nep}$ and the uncertainty in crop harvest C export ($\sigma_{crop}$). Variance in manure C application was not calculated due to an insufficient number of manure samples. The ecological sign convention is used throughout this manuscript, where positive fluxes indicate $CO_2$ uptake into plants and soil and negative fluxes indicate $CO_2$ loss to the atmosphere.

### 2.6. Statistical analysis

We assessed differences in C balance components (GPP, $R_e$, Harvest C, NEP, NECB) among individual crops and cropping systems using mixed-effects ANOVA, treating crop or cropping system as a fixed effect and year as a random, repeated measure. For the crop analysis, a random effect for year was nested within field to account for variation among fields for the same crop. The silage maize alfalfa 1 and silage maize-alfalfa 2 sites were pooled for the cropping systems analysis. When mixed-effects ANOVA revealed significant effects ($P < 0.05$) of crop or cropping system, Tukey's HSD was used for mean separation. We used simple linear regression to assess relationships between various annual C-balance components and NECB and used mixed-effects ANOVA to evaluate differences among crops in these relationships. Slopes, intercepts, and covariates were considered significant at $P < 0.05$. All statistical analysis was conducted with program R (R Core Team, 2016).

## 3. Results & discussion

### 3.1. Weather conditions & irrigation management

The two study areas differed distinctly in their weather characteristics during the 8-year study period (Fig. 2). The mean air temperature at the dairy forage sites was generally cooler than the soybean-maize site, particularly from October to the following April. When averaged over the whole study period, this amounted to 1.2 °C difference between the sites. However, all sites were slightly warmer than the 1981 – 2010 30-year climatological mean for the nearest weather station. The largest positive temperature anomalies at the dairy forage sites occurred in October to December, and at the soybean-maize site in September to November.

The soybean-maize site received an average of 167 mm more precipitation per year than the dairy forage sites. Most of this difference occurred between April and August. However, center-pivot irrigation at the dairy forage sites provided an additional 46 to 48 mm $yr^{-1}$, (means, with a range of 0 – 130 mm $yr^{-1}$) to meet crop water demands. All sites had lower precipitation than the 30-year climatological mean over the study period. At the dairy forage sites, the months of February, May, June, and October tended toward normal, whereas all other months had 17% lower precipitation than normal, on average. The soybean-maize site had, on average, 20% lower precipitation than normal each month, though the months of April through June tended toward normal.

### 3.2. Effect of crop and cropping system on annual C assimilation and C balances

Cumulative NEP over the 8-year study period was 12.9 ± 4.7, 19.5 ± 4.1, and 14.3 ± 3.3 Mg C $ha^{-1}$ in silage maize-alfalfa 1, continuous silage maize, and soybean-maize, respectively, and was 12.1 ± 2.8 Mg C $ha^{-1}$ over five years in silage maize-alfalfa 2 (Fig 3A, Table 1). This corresponded to average annual NEP (mean ± 95% CI) of 1.6 ± 0.7, 2.4 ± 0.4, 1.8 ± 1.8, and 2.4 ± 0.9 Mg C $ha^{-1}yr^{-1}$ in these systems. Thus, gross C assimilation exceeded respiration for each cropping system over the study period. Cumulative uncertainty due to u* threshold estimation amounted to 4.7% to 5.2% of NEP in silage maize-alfalfa 1, 4.9% to 5.1% in continuous silage maize, 3.6 to 7.6% in soybean-maize, and 1.4% to 1.7% in alfalfa-silage maize 2 (Table S3). Uncertainty due to random and bias error amounted to ± 1.0, 0.7, 0.4, and 0.6 Mg C $ha^{-1}$, or 7.6%, 3.7%, 3.0%, and 4.7% of cumulative NEP in these systems, respectively.

There were notable differences among individual crops in average annual GPP, NEP, harvest C, and NECB (Fig. 4A, Table 2). As expected, GPP was greater for grain maize (13.5 Mg C $ha^{-1}$ $yr^{-1}$) than all other crops except alfalfa (11.5 Mg C $ha^{-1}$ $yr^{-1}$). This is attributable to the C4 photosynthetic pathway of maize and the intensive breeding that has produced hybrids ideally suited to the growing conditions of the Midwestern US. Perennial C3 forage crops like alfalfa cannot match the peak photosynthetic capacity of C4 maize (Fig. 5), but they have a much longer growing season, and thus exhibit similar annual gross primary productivity. The mean annual GPP of silage maize was significantly lower (10.2 Mg C $ha^{-1}$ $yr^{-1}$), for reasons discussed below. The GPP of C3 soybean (7.7 Mg C $ha^{-1}$ $yr^{-1}$) was substantially less than all other crops

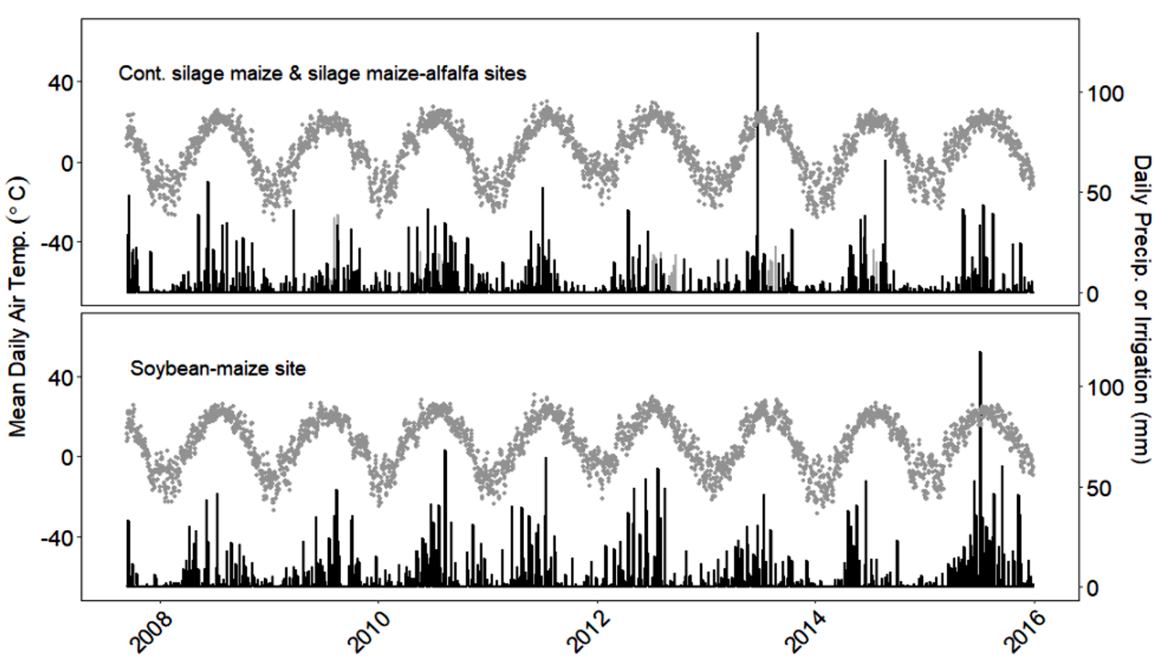


**Fig. 2.** Daily precipitation (black bars), irrigation (gray bars), and mean daily air temperature (gray points) at the study sites from 9-12-2007 to 12-31-2015.

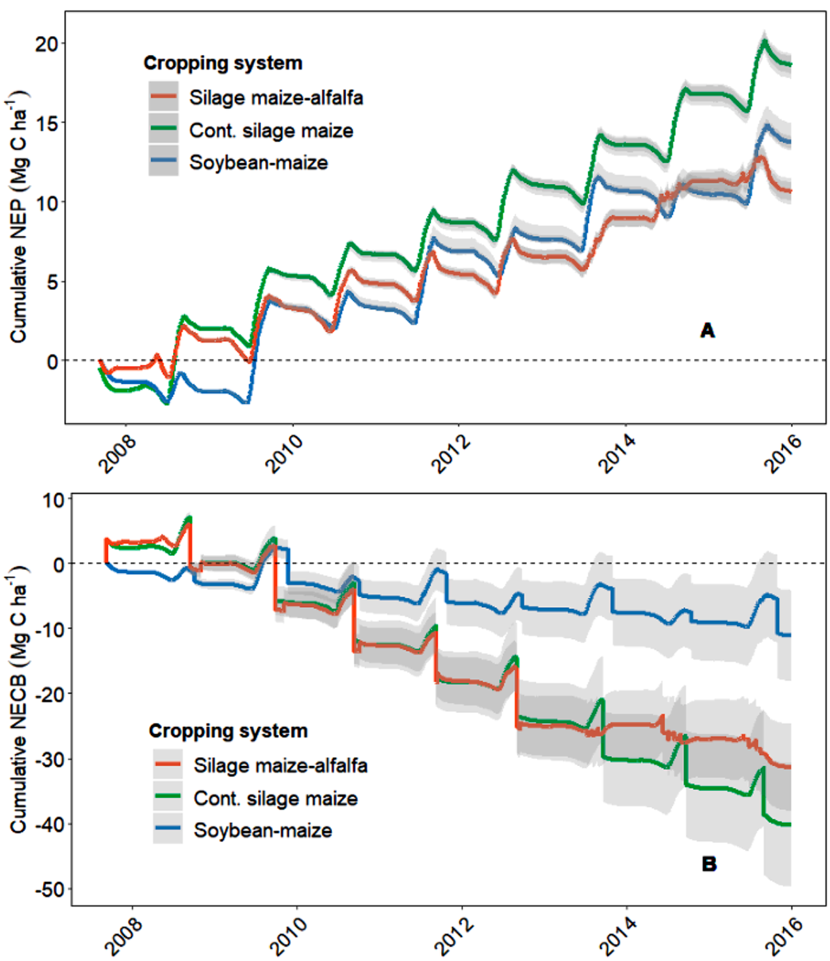


**Fig. 3.** Cumulative net ecosystem production (NEP; panel A) and net ecosystem carbon balance (NECB; panel B) of three cropping systems from 10 Sept. 2007 to 10 Sept. 2015. Gray shading denotes cumulative uncertainty due to u* threshold estimation, bias error, random error, and harvest exports (NECB only). Note that sharp, single-day changes in NECB represent manure additions (C gains) or harvest exports (C losses) from the systems, respectively. The silage maize-alfalfa system consisted of one field with five years of silage maize followed by three years of alfalfa. The continuous maize system was eight years of silage maize. The soy-maize system was eight alternating years of soybean and maize for grain.

**Table 1**
Annual net ecosystem carbon balance components for the four research sites.

| Cropping system | Flux | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Mg C ha$^{-1}$ | | | | |
| Silage maize – alfalfa 1 | GPP | 12.3 | 11.8 | 10.7 | 9.1 | 11.3 | 7.0 | 12.3 | 10.7 | 85.2 |
| | $R_e$ | -10.2 | -9.9 | -9.1 | -8.0 | -10.5 | -6.5 | -9.2 | -8.8 | -72.3 |
| | NEP | 2.1 | 1.9 | 1.6 | 1.2 | 0.8 | 0.4 | 3.1 | 1.9 | 12.9 |
| | Manure C | 3.8 | 1.4 | 1.4 | 1.6 | 1.4 | 0 | 0.9 | 1.1 | 11.5 |
| | Crop C | -6.5 | -9.7 | -9.4 | -7.5 | -9.1 | -2.2 | -5.8 | -4.8 | -55.0 |
| | NECB | *-0.6* | *-6.5* | *-6.4* | *-4.7* | *-6.9* | *-1.8* | *-1.8* | *-1.8* | *-30.5* |
| Continuous silage maize | GPP | 10.7 | 11.2 | 9.7 | 9.8 | 10.3 | 10.2 | 9.9 | 8.7 | 80.6 |
| | $R_e$ | -8.0 | -8.2 | -8.3 | -7.5 | -7.9 | -8.0 | -7.0 | -6.4 | -61.1 |
| | NEP | 2.7 | 3.0 | 1.5 | 2.2 | 2.5 | 2.3 | 2.9 | 2.4 | 19.5 |
| | Manure C | 3.8 | 1.4 | 1.1 | 0.2 | 0.5 | 0.2 | 0.3 | 0 | 7.4 |
| | Crop C | -7.6 | -9.5 | -8.8 | -7.9 | -9.0 | -8.7 | -7.6 | -7.4 | -66.5 |
| | NECB | *-1.1* | *-5.1* | *-6.3* | *-5.5* | *-6.0* | *-6.2* | *-4.4* | *-5.0* | *-39.7* |
| Silage maize – alfalfa 2 | GPP | - | - | - | 11.0 | 13.7 | 14.1 | 8.6 | 9.0 | 56.4 |
| | $R_e$ | - | - | - | -9.2 | -10.8 | -10.9 | -7.1 | -6.3 | -44.3 |
| | NEP | - | - | - | 1.8 | 2.9 | 3.2 | 1.5 | 2.7 | 12.1 |
| | Manure C | - | - | - | 0 | 1.0 | 1.2 | 1.1 | 1.2 | 4.5 |
| | Crop C | - | - | - | -4.2 | -5.0 | -4.1 | -6.9 | -8.1 | -28.3 |
| | NECB | - | - | - | *-2.4* | *-1.1* | *0.3* | *-4.3* | *-4.2* | *-11.6* |
| Soybean – maize | GPP | 6.7 | 14.8 | 9.0 | 13.1 | 8.3 | 13.6 | 6.8 | 12.6 | 84.9 |
| | $R_e$ | -7.7 | -9.9 | -8.8 | -9.3 | -7.7 | -10.6 | -7.2 | -8.9 | -70.2 |
| | NEP | -1.0 | 4.9 | 0.1 | 3.8 | 0.65 | 3.0 | -0.4 | 3.3 | 14.3 |
| | Crop C | -1.3 | -5.1 | -2.2 | -4.4 | -1.8 | -3.6 | -1.3 | -5.3 | -24.9 |
| | NECB | *-2.3* | *-0.3* | *-2.0* | *-0.6* | *-1.2* | *-0.5* | *-1.7* | *-2.0* | *-10.6* |

including alfalfa, another C3 plant, but a perennial with a much longer growing season. Remarkably, there were no significant differences in $R_e$ among crops, perhaps in part due to substantial annual variability, with average annual $R_e$ losses of 9.7 Mg C ha$^{-1}$ yr$^{-1}$ for grain maize, 9.2 Mg C ha$^{-1}$ yr$^{-1}$ for alfalfa, 8.1 Mg C ha$^{-1}$ yr$^{-1}$ for silage maize, and 7.9 Mg C ha$^{-1}$ yr$^{-1}$ for soybean. As a consequence, NEP followed the same trends as GPP, being greatest for grain maize (3.7 Mg C ha$^{-1}$ yr$^{-1}$) and lowest for soybean (-0.2 Mg C ha$^{-1}$ yr$^{-1}$), with intermediate values for silage

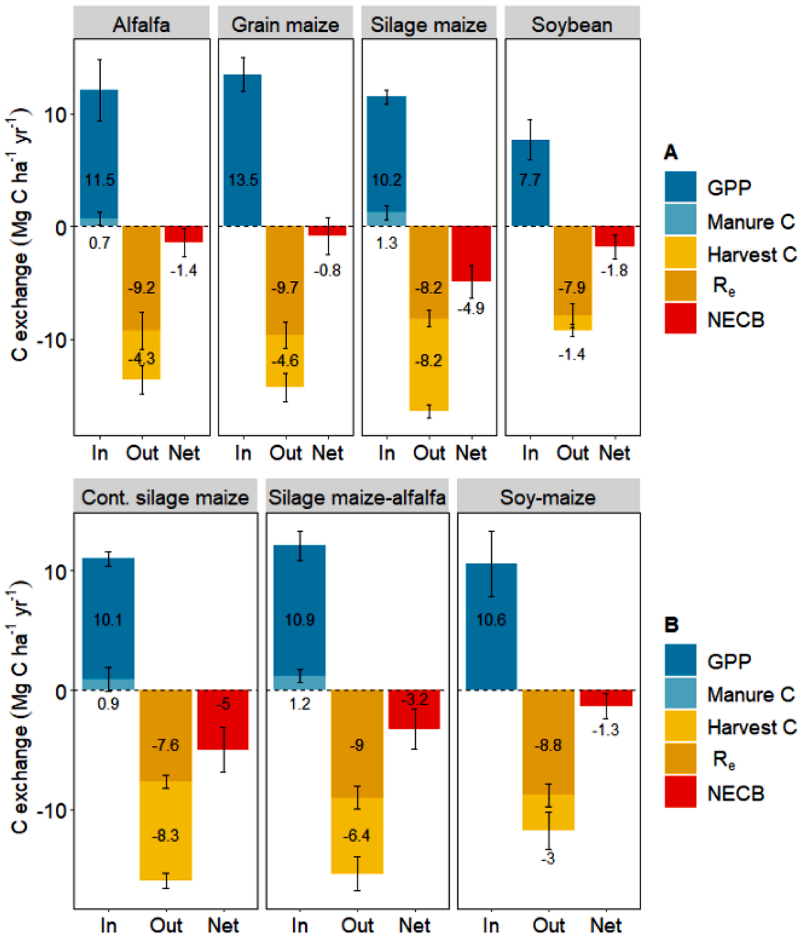


**Fig. 4.** Mean annual components of the NECB for each individual crop (A) and cropping system (B). Error bars denote a 95% confidence interval (CI) for the mean, except for NECB for which they denote the quadrative sum of the 95% CI and $\sigma_{necb}$. The silage maize-alfalfa system consisted of one field with five years of silage maize followed by three years of alfalfa, and a second field with three years of alfalfa followed by two years of silage maize ($n$ = 13). The continuous maize system was eight years of silage maize (n = 8). The soy-maize system was eight alternating years of soybean and maize for grain (n = 8). The total site years analyzed for each crop are $n_{silage\ maize} = 15$, $n_{alfalfa} = 6$, $n_{soybean} = 4$, and $n_{grain\ maize} = 4$.

**Table 2**
Tests of fixed effects on C balance components.

| Effect | Response | *F* | *P* |
|---|---|---|---|
| Crop | GPP | 10.81 | < 0.0001*** |
| | R$_e$ | 2.21 | 0.115 |
| | Harvest C | 66.77 | < 0.0001*** |
| | NEP | 16.96 | < 0.0001*** |
| | NECB | 17.84 | < 0.0001*** |
| Cropping system | GPP | 0.29 | 0.8284 |
| | R$_e$ | 1.95 | 0.1577 |
| | Harvest C | 11.82 | < 0.0001*** |
| | NEP | 0.76 | 0.5307 |
| | NECB | 5.73 | 0.0062** |
| Irrigation[a] | GPP | 1.16 | 0.3855 |
| | R$_e$ | 1.62 | 0.2872 |
| | Harvest C | 4.32 | 0.0814 |
| | NEP | 0.46 | 0.6531 |
| | NECB | 4.56 | 0.0746 |
| Manure method | | | |
| | GPP | 0.21 | 0.6721 |
| | R$_e$ | 1.75 | 0.2429 |
| | Harvest C | 0.16 | 0.7062 |
| | NEP | 0.77 | 0.4203 |
| | NECB | 0.04 | 0.8503 |

[a] Tests for irrigation and manure application method were only possible for silage maize

maize (2.1 Mg C ha$^{-1}$ yr$^{-1}$) and alfalfa (2.2 Mg C ha$^{-1}$ yr$^{-1}$). Thus, gross C assimilation exceeded respiration for each crop except soybean, but it should be noted that in a soybean-maize rotation the soybean year includes respiration of residues remaining from the maize year, and vice-versa.

Estimates of annual NEP in the present study are within ranges reported by others for maize, soybean, and alfalfa grown under similar conditions (Baker and Griffis, 2005; Bavin et al., 2009; Dold et al., 2017; Saliendra et al., 2018; Skinner, 2008), with the notable exception of silage maize which, despite being irrigated in most years, had a 44% lower average annual NEP than maize for grain. We first suspected that this was due to a somewhat shorter growing season, since maize silage is harvested earlier than maize grain, but closer examination revealed that this was not the case. There is little additional photosynthesis during the 4 to 8-week period between the time of silage harvest and the time of grain harvest in the Upper Midwestern US; the primary reason for the time gap is to allow the grain to dry to the point where it can be safely stored. Instead, the reason for lower NEP of silage maize appears to be due to breeding for digestibility. So-called brown mid-rib (BMR) silage maize varieties such as those in this study typically have lower dry matter yield than other silage or grain varieties (Ballard et al., 2001; Sheaffer et al., 2006), but also have lower lignin content and higher digestibility, which can result in superior milk yields relative to conventional varieties. On average, GPP of silage maize was 23% lower than grain maize in this study, which is similar to the 22% maximum yield gap noted by Sheaffer et al. (2006) between BMR and conventional silage varieties at two sites in Minnesota. This difference in productivity, combined with a greater fraction of GPP lost as R$_e$ in silage maize (0.79) versus maize grain (0.71), are the reasons for the substantial difference in NEP between the two crops.

After accounting for harvest C exports and manure C imports, the cumulative NECB over the eight-year study period amounted to -30.5 ± 6.7 Mg C ha$^{-1}$ for silage maize-alfalfa, -39.7 ± 9.5 Mg C ha$^{-1}$ for

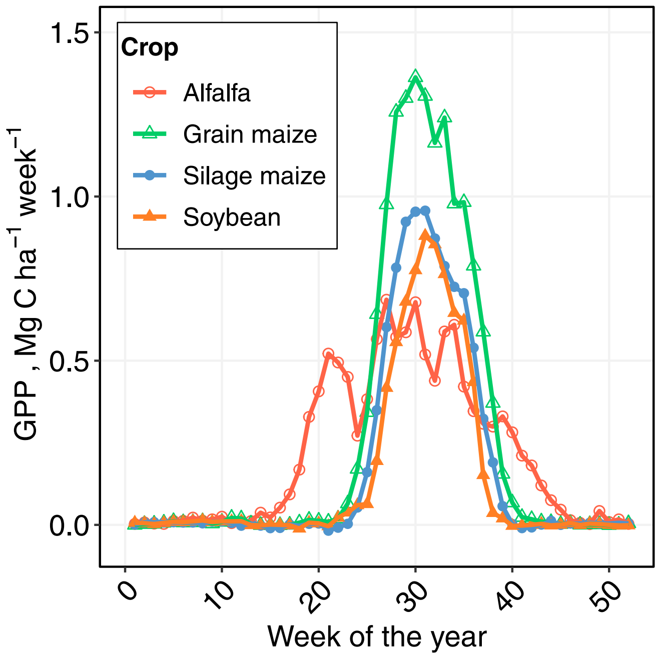


**Fig. 5.** Average weekly gross primary productivity (GPP) of four crops across four study sites from 9-10-2007 to 12-31-2015.

continuous silage maize, and -10.6 ± 7.0 Mg C ha$^{-1}$ for the soybean-maize rotation (Fig 3B). The average annual NECB showed greater C loss for the silage maize-alfalfa systems (-3.2 ± 1.5 Mg C ha$^{-1}$ yr$^{-1}$) and continuous silage maize (-5.0 ± 1.4 Mg C ha$^{-1}$ yr$^{-1}$) than the soybean-maize rotation (-1.3 ± 0.7 Mg C ha$^{-1}$ yr$^{-1}$; Fig 4B). All three cropping systems were significantly different from C-neutral as indicated by the bounds of the 95% confidence intervals. These findings imply a substantial reduction in SOC at the dairy forage sites. The dairy forage systems had substantially greater C losses than the grain system because of the predominant silage maize, which had an NECB of -4.9 ± 1.0 Mg C ha$^{-1}$ yr$^{-1}$. All other crops had a similar NECB; -1.4 ± 1.0 g Mg C ha$^{-1}$ yr$^{-1}$ for alfalfa, -1.8 ± 0.8 Mg C ha$^{-1}$ yr$^{-1}$ for soybean, and -0.9 ± 1.3 Mg C ha$^{-1}$ yr$^{-1}$ for grain maize. Except for grain maize, the NECB for all crops was significantly different from C-neutral (zero) when considering the 95% confidence bounds, which indicates a net loss of C from these crops.

Harvest of grain or forage represents a substantial C export that can profoundly impact the C balance of agricultural systems (Ceschia et al., 2010; Skinner, 2008). The amount of C removed in harvest was greatest for silage maize (-8.3 Mg C ha$^{-1}$ yr$^{-1}$), where all vegetative material above the cutting height of approximately 15 cm is removed, and lowest for soybean (-1.4 Mg C ha$^{-1}$ yr$^{-1}$). Grain maize (-4.7 Mg C ha$^{-1}$ yr$^{-1}$) and alfalfa (-4.3 Mg C ha$^{-1}$ yr$^{-1}$) had similar removal rates. It is notable that, like maize silage, alfalfa is cut close to the ground and all mowed material is removed, yet it had a much lower C removal rate than silage maize despite similar GPP and $R_e$, indicative of substantial allocation of C to the root system. Although the NECB of alfalfa was closer to C-neutral than that of silage maize (a difference of 3.6 Mg C ha$^{-1}$ yr$^{-1}$), this difference was smaller than the yield gap between the two crops, with alfalfa C export being 3.9 Mg C ha$^{-1}$ yr$^{-1}$ lower than that of silage maize. This suggests a potential tradeoff between improving C balances in dairy forage rotations and overall milk production, although the impact of forage quality factors on milk yield must also be considered.

Substantial residue additions from unharvested stover improved the NECB of grain maize relative to other crops. Taking the difference between net primary productivity (NPP) and harvested C as the implied residue additions to soil each year, grain maize had over threefold higher residue C additions than silage maize (5.8 vs. 1.9 Mg C ha$^{-1}$ yr$^{-1}$). Surprisingly, residue additions were similar for alfalfa (4.64 Mg C ha$^{-1}$ yr$^{-1}$) and soybean (4.5 Mg C ha$^{-1}$ yr$^{-1}$). Regressing residue C versus annual NECB revealed that, when averaged across all crops, net C balances increased (C loss was reduced) by 0.9 Mg C ha$^{-1}$ for every Mg of residue C left in-field (Fig 6A). This residue retention coefficient demonstrates the importance of unharvested plant material for positively influencing net C balances and maintaining SOC stocks but is comparatively high relative to other studies. Blanco-Canqui and Lal (2009) observed a long-term residue retention coefficient of 0.64, while Smith et al. (2012) found a mean coefficient of 0.79 using both measured and modelled data. However, in a review of the impacts of cover crops and residue removal on SOC, Ruis and Blanco-Canqui (2017) found that with greater than 50% residue removal, mean SOC stock declines of 0.87 Mg ha$^{-1}$ yr$^{-1}$ were observed. This is comparable to the 0.9 residue retention coefficient observed in the present study, albeit expressed in terms of residue removal rather than retention. Moreover, plant-derived C in manure additions likely increased the perceived residue retention relative to other studies where no organic amendments were added. In a meta-analysis of the impacts of animal manures on SOC, Maillard and Angers (2014) found a 0.12 manure C retention coefficient over many sites and manure types. Thus, additive effects of manure and crop residue are likely responsible for the high residue retention coefficient observed in the present study.

The NECBs calculated here for alfalfa and silage maize are consistent with other research that uses both similar and dissimilar methodologies. In eddy covariance studies alfalfa has been observed to be a source of C over four years in a semiarid environment (-2.3 Mg C ha$^{-1}$ yr$^{-1}$; Saliendra et al., 2018) and over four years in a humid climate (-0.5 Mg C ha$^{-1}$ yr$^{-1}$; Skinner, 2008). In both cases, the authors cite high biomass removal rates as the factor limiting overall C-sequestration in these intensively hayed systems. For maize, a one-year eddy covariance study in Guelph, Ontario, found that stover removal for bioenergy reduced maize NECB to -7.0 Mg C ha$^{-1}$ yr$^{-1}$, from -3.9 Mg C ha$^{-1}$ yr$^{-1}$ with grain-only harvest (Eichelmann et al., 2016). In Germany, 12-site years of eddy covariance data showed an average silage maize NECB of -4.3 Mg C ha$^{-1}$ yr$^{-1}$ (Poyda et al., 2019). Results from a single year in southwest France showed an NECB of -3.7 Mg C ha$^{-1}$ yr$^{-1}$. (Beziat et al., 2009). Similarly, a three-year, small-plot study in Wisconsin found the

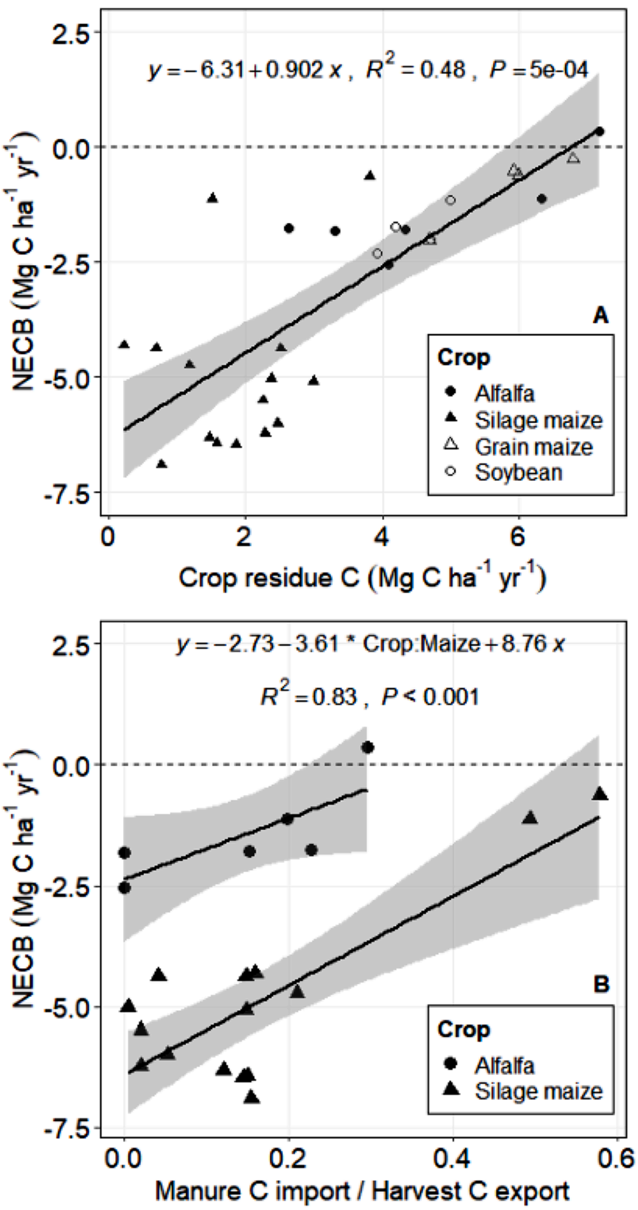


**Fig. 6.** Relationship between annual NECB and (A) crop residue C for all crops and (B) the ratio of manure C applied to crop C harvested for manured forage crops. Crop residue C is calculated as the difference between annual NPP and harvest C.

NECB of silage maize to be -4.3 Mg C ha$^{-1}$ yr$^{-1}$ and grain maize 0.3 Mg C ha$^{-1}$ yr$^{-1}$ (Cates and Jackson, 2018). In contrast, a two-year study in Idaho reported a silage maize NECB of +3.3 Mg C ha$^{-1}$ yr$^{-1}$ (Lentz and Lehrsch, 2014). This system had relatively high solid manure application rates of 3.9 to 5.4 Mg C ha$^{-1}$ yr$^{-1}$ which contributed to the positive C-balance. Furthermore, C losses via soil respiration in their study were, on average, only 30% of those observed in the present study, likely due to lower annual precipitation and other soil and climatic differences in Idaho versus Minnesota. Thus, C-balanced silage maize systems may be possible in dryer climates but not in the humid climate of the Upper Midwest. Collectively, these studies show the potential for substantial C losses under the sustained silage maize production that is common on dairies in the Upper Midwest US.

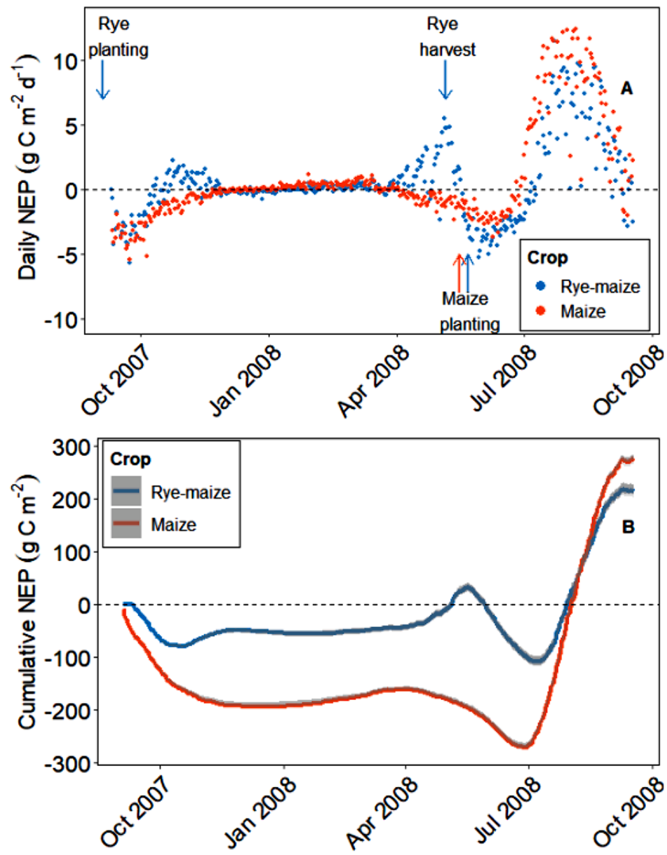


**Fig. 7.** Silage maize daily (A) and cumulative daily (B) net ecosystem production (NEP) with and without a winter rye cover crop from 2007-09-04 to 2008-09-17. Rye was planted on 2007-09-04, eight days prior to the start of NEP measurements.

### *3.3. Effects of cover cropping, irrigation, and manure management on C balances*

In the fall of 2007, maize silage was harvested in both the silage maize-alfalfa 1 and continuous silage maize fields. Management in both fields had been identical to that point in the study, which provided an opportunity to evaluate the impact of the winter rye cover crop on NEP using a paired fields analysis. The winter rye cover crop was seeded into the silage maize-alfalfa 1 field immediately following harvest on 7 Sept., while the adjacent continuous silage maize field was left fallow. The rye germinated quickly and by 24-Oct the crop reached a peak NEP of 2.3 g C m$^{-2}$ d$^{-1}$, while daily NEP in the fallow was dominated by respiration losses and remained below zero throughout the fall (Fig 7A). Rye growth resumed rapidly in the spring, with NEP reaching a peak of 5.2 g C m$^{-2}$ d$^{-1}$, and cumulative NEP since planting reaching a peak of nearly 33 g C m$^{-2}$ (Fig 7B). Cumulative NEP in the winter-fallowed field remained below zero during this period at -200 g C m$^{-2}$. The rye was harvested on 6 May, then terminated with glyphosate. Silage maize was planted in the winter-fallowed field on 16 May and in the rye field on 22 May. After planting, daily NEP was generally lower in the cover-cropped than winter-fallowed silage maize due to $CO_2$ emissions from decomposing rye litter. During the peak growing season months of July and August, daily NEP was greater in the winter-fallowed silage maize than the rye cover-cropped silage maize.

At the end of the 2008 growing season, cumulative NEP since rye planting was 58 g C m$^{-2}$ lower in the rye cover-cropped silage maize (217 g C m$^{-2}$) than the winter-fallowed silage maize (275 g C m$^{-2}$), suggesting that the rye cover crop had a detrimental impact on subsequent maize growth. In fact, yield of the rye cover-cropped silage maize was 650 g C m$^{-2}$ while yield of winter-fallowed silage maize was 762 g C m$^{-2}$, a difference of 112 g C m$^{-2}$. Given the lower NEP and lower C export in harvest, the annual NECB was greater for the rye cover-cropped system (-629 vs -1130 g C m$^{-2}$), suggesting that rye cover cropping may have the potential to improve NECB of silage maize systems, albeit with lower yield. However, our assessment was limited to only a single year due to the producer's hesitance to risk further yield penalties at such a large scale. Recent metanalyses of soil inventory studies suggest that cover crops can increase soil carbon (Jian et al., 2020; Poeplau and Don, 2015), though no such benefit has been observed in a number of carbon balance studies, at least over shorter timescales (Baker and Griffis, 2005; Bavin et al., 2009; Cates and Jackson, 2018; Dold et al., 2019).

Silage maize was irrigated during 13 of the 15 site-years and manure applications included fall manure injection for 10 site-years and fertigation through the irrigators for five site-years. There were no statistically significant differences in GPP, $R_e$, harvest C, NEP, or NECB between irrigated versus rain-fed or manure injected versus manure fertigated silage maize, likely due to the small number of observations of rain-fed and fertigated silage maize. However, the rate of manure application impacted the NECB of forage systems regardless of application method.

Manure application rates ranged from 0 to 3.8 Mg C ha$^{-1}$ yr$^{-1}$ in the forage production fields, with an average rate of 1.4 Mg C ha$^{-1}$ yr$^{-1}$ for years when manure was applied. The annual NECB increased linearly as the proportion of manure C to crop harvested C increased (Fig 6B), with significantly different intercepts for alfalfa and silage maize crops. Solving the regression equation for NECB = 0 for each crop indicated that, on average, manure C rates equivalent to 31% and 73% of the harvest C rates, or 1.4 and 6.0 Mg C ha$^{-1}$ yr$^{-1}$, were required to maintain a net equilibrium C balance for alfalfa and silage maize, respectively. However, increasing manure rates to these levels would result in substantial field N and P surpluses and subsequent environmental losses, including nitrate and phosphorus losses in drainage, and both ammonia and nitrous oxide losses to the atmosphere. Past research in these fields has shown substantial losses of $NO_3$-N and soluble reactive P in tile drainage (Feyereisen et al., 2015;Gamble et al., 2018; Krueger et al., 2013). In 2008 for example, the manure C rate was equivalent to 49% of harvested C in the continuous silage maize system and $NO_3$-N losses in tile drainage were 100 kg N ha$^{-1}$ (Gamble et al., 2018). To reduce $NO_3$-N losses, the producer lowered manure rates in subsequent years. This resulted in loss of only 45.0 kg N ha$^{-1}$ in 2014, but with a manure C rate equivalent to only 4% of harvested C. This apparent tradeoff between soil organic matter maintenance and nutrient loss potentially limits the role of manure management in improving NECB in silage maize-based forage cropping systems in the Upper Midwest, at least with currently available crop and manure management technologies.

The composition of the liquid dairy manure was also an important influence on the NECB of these systems. Manure at the cooperating dairy was anaerobically digested prior to application starting in 2009 but was applied raw in previous years. Depending on the type of manure, anaerobic digestion transforms 20% to 95% of the C in manure into biogas, mostly methane and carbon dioxide (Möller, 2015). After digestion began in 2009, manure slurry DM content was reduced by 55% compared to raw manure in previous years, from 76 g kg$^{-1}$ to 34 g kg$^{-1}$. This suggests that anaerobic digestion was diverting manure C to produce biogas that would have otherwise contributed to soil organic matter maintenance. Thomsen et al., (2013) suggest the retention of plant-derived C in soil is little affected by pretreatments such as passage through a ruminant or anaerobic digestion, since digestion preferentially reduces the easily degradable C in the slurry and leaves behind more recalcitrant C compounds (Holly et al., 2017). Thus, they argue, C losses during digestion are compensated by lower C emissions after field application (Möller, 2015).

However, as is common practice for dairies handling liquid manure, the slurry was also screened to remove some solids prior to application. Solid-liquid separation can reduce total C content by 30% (Holly et al., 2017), removing mostly cellulose and hemicellulose (Rico et al., 2007). Lignin, the most recalcitrant C fraction, is mostly retained in the liquid slurry and is therefore returned to the field upon application (Rico et al., 2007). At the cooperating farm, the screened solids are used for animal bedding at a rate of 7 kg cow$^{-1}$ d$^{-1}$, which corresponds to an additional 940 kg C ha$^{-1}$ yr$^{-1}$ that could potentially be diverted back to the soil. Instead, the bedding solids are scraped from the free-stall barns along with the solid and liquid animal waste and pumped to manure lagoons where they are again subject to solid-liquid separation and subsequent digestion. The fate of the cellulose and hemicellulose in this endless loop is unclear, though presumably some of this material degrades with each cycle and finds its way into the liquid slurry bound for the digester. If so, 50 to 65% of the cellulose and > 80% of the hemicellulose in this mixture are likely lost to anaerobic digestion (Molinuevo-Salces et al., 2013; Möller, 2015) rather than being applied to soil where they can contribute to the belowground C economy. Diverting these fractions decouples the C-cycle between the field and animal and represents a de facto conversion of soil carbon into biogas in this dairy production system.

### 3.4. Changes in soil organic carbon

The NECBs observed here suggest annual SOC losses of 2.1% in the silage maize alfalfa system and 2.5% in the continuous silage maize system, when considering the SOC stock to 90 cm -depth (179 and 198 Mg C ha$^{-1}$, respectively). According to the farm operator, silage maize cropping began in these fields in 2005 following a history of grain maize – soybean rotation, with wheat (*Triticum aestivum* L.) also occasionally planted. Previous research on SOC dynamics under land-use change suggests that gains or losses in SOC following disturbance are rapid, with the rate of change decreasing over time as the soil approaches a new equilibrium (Aref and Wander, 1998; Guo and Gifford, 2002; Kopittke et al., 2017; Murty et al., 2002; Tiessen et al., 1994). For example, Murty et al., (2002) found that SOC loss decayed exponentially following conversion of forests to cultivated land-use, with average losses of 22% by year 10 and stabilizing thereafter. Similarly, if we extend our estimates of C loss to the unsampled years 2005 to 2007, we calculate that in the 10 years since initiation of silage maize cropping, roughly 19% and 22% of the SOC stock has been lost at the silage maize alfalfa 1 and continuous silage maize fields, respectively. Thus, we might expect C loss in the fields to slow in coming years and for soil C to reach a new steady-state equilibrium.

However, previous research at the cooperating dairy showed no statistically significant change in SOC to 90-cm depth over the 8-year study period for the silage maize-alfalfa 1 rotation, and a loss of 5.8 Mg C ha$^{-1}$ in the continuous silage maize system (Gamble et al., 2017; Gamble et al., 2018). This represents a discrepancy between the annual C budgets estimated via soil sampling versus the NECB derived here. However, there was substantial variability in the annual estimates of SOC mass in these fields (average CV = 24%). Consequently, the annual estimates of NECB fall within the standard error for the difference in SOC for all soil-sampled years in the silage maize-alfalfa 1 rotation and half of the sampled years for the continuous silage maize. (Fig. S2).

Another possible factor in this discrepancy is the potential impact of $CO_2$ fluxes associated with carbonate dissolution and precipitation, especially after irrigation began. Soils in these fields are calcareous, with 17 to 19 g kg$^{-1}$ of inorganic C to 90-cm soil depth. The organic vs inorganic C depth distributions are mirror images, with SOC greatest at the surface and decreasing with depth, while SIC is greatest at depth and minimal near the surface. There was no detectable change in total profile SIC over the study period (data not shown), which perhaps suggests that any $CO_2$ fluxes associated with carbonate dissolution or precipitation were negligible, or at least comparable in magnitude such that they offset. However, as with SOC, interannual variability in SIC estimates was large, so the possible influence of carbonate-derived $CO_2$ fluxes cannot be dismissed based on SIC estimates alone.

Examination of the possible role of irrigation provides further evidence that non-biological fluxes of $CO_2$ were negligible. The irrigation water at these sites is rich in carbonates, with 399 Mg $HCO_3^-$ $L^{-1}$ found in a 2006 sampling of the well from which the water is drawn. Given this, we estimate an average annual loss of about 0.04 Mg C $ha^{-1}$ $yr^{-1}$ (range of 0.01 – 0.09 Mg C $ha^{-1}$ $yr^{-1}$) from carbonate precipitation following irrigation events, which is similar to the 0.08 Mg C $ha^{-1}$ $yr^{-1}$ calculated by Schlesinger (1999). However, this does not account for losses of $CO_2$ that may have been dissolved in the irrigation water. In Nebraska, Verma et al. (2005) found that irrigation water with 256 Mg $HCO_3^-$ $L^{-1}$ resulted in a release of 0.26 to 0.49 Mg C $ha^{-1}$ $yr^{-1}$ from both carbonate precipitation and release of dissolved $CO_2$ in irrigation water. Losses of this magnitude do not seem likely for our site; close examination of the flux data following irrigation events and during periods when soil temperatures were $< 0$ °C suggests that non-biological fluxes of $CO_2$ were negligible. Whether present or not, fluxes of this magnitude would not meaningfully change the conclusions of this study.

## 4. Conclusions

The intensification of the US dairy industry has resulted in dramatic increases in productivity over the past four decades. This has been facilitated in part by an increased reliance on maize silage as a primary forage source. The NECBs calculated here show that modern dairy forage production systems were net sources of C over an 8-year period, with greater losses than the predominant grain cropping system in the region, the soybean-maize rotation. Including alfalfa in the rotation improved long-term C-balances, but net C losses were still observed. Cropping system NECB was strongly linked to the amount of plant-derived C returned to the soil in both manure and crop residue, though rye cover cropping and land application of liquid dairy manure at current rates provided insufficient C to reach equilibrium.

Increased reliance on maize silage has negatively impacted the C balance of dairy forage production systems, which implies that for these systems, gains in productivity have come at the expense of soil carbon. There is an acute need for management strategies that retain more plant-derived C in forage-cropped soils. Increasing the frequency of alfalfa or other perennial or cover crops in the rotation, leaving more standing maize stover, and field-applying a greater fraction of the manure solids could all help accomplish this goal to a degree. However, if silage maize remains a major component of the cropping system, these strategies are not likely to improve net ecosystem C balances to the point of C-neutrality. We suggest that greater management changes will be needed to sustain SOC levels and maintain productivity in fields supplying feed to confined dairy operations.

## 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.

### *Author contributions*

JB, GF, and CW conceived the experiment. JB and GF designed the experiment. JB, GF, and CW performed the experiments. JG analyzed the data and wrote the manuscript in consultation with GF, TG, JB, and CW.

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