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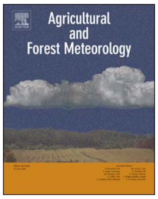

Ecosystem carbon exchange on conversion of Conservation Reserve Program grasslands to annual and perennial cropping systems

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ABSTRACT

Land use changes into and out of agricultural production may substantially influence ecosystem carbon (C) balance for many years. We examined ecosystem C balances for eight years after the conversion of 22 year-old Conservation Reserve Program (CRP) grasslands and formerly tilled agricultural fields (AGR) to annual (continuous no-till corn) and perennial (switchgrass and restored prairie) cropland. An unconverted CRP field (CRP-Ref) was maintained as a historical reference. Ecosystem C balance was assessed using adjusted net ecosystem carbon exchange (NEE_{adj}) calculated by adding C removed in harvested biomass to NEE measured using eddy covariance method. The cumulative NEE_{adj} of the corn and perennial systems on former CRP fields showed that these systems were a net C source to the atmosphere over the 8-year period while on former AGR fields, the perennial systems were net C sinks and the corn system near-neutral. The CRP-Ref was near neutral until a drought year when it became a net source. The corn system on the CRP field will likely reach a new lower soil C equilibrium at least 14 years after conversion but will never regain the C lost upon conversion under current no-till management with residue partially removed. On the other hand, the perennial systems could fully regain in ~14 years the C lost following conversion. The cumulative NEE_{adj} of the corn systems exhibited a higher C emission than did the perennial systems within the same land use histories, reflecting the dominant role of crop type and management in agricultural ecosystem C balance. Results suggest that converting croplands to grasslands results in immediate C gains whereas converting grasslands to croplands results in permanent (no-till corn with partial residue removal) or temporary (perennial herbaceous crops) net C loss to the atmosphere. This has a significant implications for global climate change mitigation where biomass production from annual and perennial crops is promoted to avoid fossil-fuel C emissions (biofuel) or to remove CO_2 from the atmosphere (bioenergy C capture and storage).

1. Introduction

Agricultural cropping systems can act as sinks or sources of atmospheric carbon dioxide (CO_2), depending on the balance between formation of organic carbon (C) and its decomposition. These, in turn, are affected by interactions among land use history, climate, cropping systems, and management practices. Land use conversions from either uncultivated or abandoned lands into agriculture, retirement of agricultural croplands out of production, or a shift in management practices on existing agricultural croplands are common land use changes that may substantially alter ecosystem C balances (Post and Kwon, 2000; Guo and Gifford, 2002; Zenone et al., 2011). Establishment of perennial grasslands on retired agricultural croplands, in particular, builds soil C over many years (Post and Kwon, 2000; Bowman and Anderson, 2002; McLauchlan et al., 2006; Norton et al., 2012; Phillips et al., 2015). For example, in the US, $\sim 15 \times 10^6$ ha of marginal agricultural croplands were retired primarily into perennial grasslands under the USDA Conservation Reserve Program (CRP) between 1985 and 2007 (United States Department of Agriculture Farm Services Agency (USDA-FSA, 2017), accumulating on average $\sim 62\,g\,C\,m^{-2}\,yr^{-1}$ in the top 10 cm of the soil (McLauchlan et al., 2006). Growing perennial grasses over decades on such lands serves to conserve soil, increase C sequestration, improve water quality (Food and Agricultural Policy Research Institute (FAPRI, 2007), and enhance wildlife habitat (Herkert, 2007; Niemuth

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et al., 2007; Riffell et al., 2008).

Increased commodity prices and demand for grain biofuel drove many landowners to discontinue CRP contracts and convert their lands back into agricultural production in the 2000s (Wright and Wimberly, 2013; Lark et al., 2015; Mladenoff et al., 2016). Accordingly, the total land area in the CRP declined by ~5×10^6 ha by 2016 (United States Department of Agriculture Farm Services Agency (USDA-FSA, 2017). In many instances, the C sequestration benefits accrued during CRP tenure were lost upon re-conversion. In particular, conversion back to row crop agriculture emits the greenhouse gases CO_2 and N_2O (Ruan and Robertson, 2013) that create, for bioenergy cropping systems, a large amount of C debt that may take many years to repay (Fargione et al., 2008; Gelfand et al., 2011; Sanderman et al., 2017).

Ecosystem C balances following land use conversions are critical for understanding environmental impacts and developing climate change mitigation strategies. A few studies have investigated ecosystem C balance upon conversion (e.g., Gelfand et al., 2011, Zeri et al., 2011; Zenone et al., 2013), but none for more than three years afterwards. Longer term effects are thus unknown. Here we provide a longer term perspective by following ecosystem C balances over an eight-year post-conversion period using eddy covariance (EC) in no-till continuous corn (maize; *Zea mays*) systems and perennial croplands (monoculture switchgrass [*Panicum virgatum*] and restored native prairie) converted from CRP grasslands and conventionally tilled agricultural croplands. The CRP grasslands were planted in smooth brome grass (*Bromus inermis*) for 22 years prior to conversion while the agricultural sites were conventionally tilled corn-soybean rotations for many decades prior. We hypothesize that: (1) converting CRP grasslands will release previously stored C for many years, perhaps permanently, while converting agricultural croplands to no-till annual and perennial crops will store C; and (2) the perennial croplands will store more C than the corn systems within the same land use history due to less intensive soil disturbance.

2. Materials and methods

2.1. Study sites

The study sites are located within the northeastern part of the US Midwest Corn Belt in southwest Michigan at the Great Lakes Bioenergy Research Center of the W. K. Kellogg Biological Station (KBS) Long-Term Ecological Research (LTER) site (42°24′ N, 85°24′ W, 288 m asl). The area has a humid continental temperate climate with mean annual air temperature of 9.9 °C and mean total annual precipitation of 1027 mm (1981–2010; Michigan State Climatologist's Office, 2013). The mean air temperature and total precipitation during May–-September, roughly representing the growing season, over the past thirty years are 19.7 °C and 523 mm, respectively. Soils at the sites are well-drained sandy loams, Typic Hapludalfs developed on glacial outwash (Thoen, 1990; Robertson and Hamilton et al., 2015).

We used two sets of fields with distinct land use histories. In one set, three fields (11–17 ha) were managed as CRP lands where the dominant vegetation was smooth brome grass (*Bromus inermis* Leyss)—a cool season C_3 grass of Eurasian origin—for 22 years before conversion (Fig. 1, Table 1). The grass was cut every three years but not harvested. Another set of three fields (11–14 ha) was in conventionally tilled corn-soybean rotation agricultural (AGR) croplands for several decades prior to this study. One CRP field (9 ha, CRP-Ref) was maintained as smooth brome grass during the study (Fig. 1). At the outset of conversion, former CRP fields had significantly higher soil organic C and nitrogen (N) concentrations than the former AGR fields in the top 0.25 m of soil (Table 1; Zenone et al., 2011; Abraha et al., 2016).

All fields except CRP-Ref were treated with glyphosate at a concentration of 2.9 kg ha^{-1} (*N*-(phosphonomethyl) glycine; Syngenta, Greensboro, NC, USA) on day of year (DOY) 125 in 2009 to kill extant vegetation. The killed vegetation was left in place. All treated fields were then planted to no-till glyphosate-tolerant soybean (*Glycine max*) with a seed drill on DOY 160/161. Glyphosate was again applied on DOY 184 on former CRP fields and on DOY 205 on former AGR fields to suppress weeds. Soybeans were planted to allow multiple herbicide applications to fully suppress brome grass and prepare the fields for subsequent continuous corn or perennial crops.

Each of three former CRP and three former AGR fields were planted to either no-till continuous corn, to switchgrass, or to restored prairie (a mixture of 19 species; see Abraha et al., 2016) in 2010. Corn was planted with a seed drill in early May and harvested in early November each year. Corn stover was left in place in all years but on average ~35% of the stover was removed in 2015 and 2016 at harvest. Lime (~5 Mg ha^{-1}) was applied in 2012 and 2015, phosphorus (P_2O_5) and potash (K_2O) fertilizers were applied in early spring before planting, and urea ammonium nitrate (28% liquid N: ~180 kg N ha^{-1} yr^{-1}) was applied by split application at planting and by side dressing in June each year to the corn fields. Fertilizer applications were based on Michigan State University Extension recommendations. Herbicide mix was applied a few days following planting and later in the season as needed to suppress weeds.

Switchgrass was planted at the end of April 2010. Urea ammonium nitrate (28% liquid N: ~56 kg N ha^{-1} yr^{-1}) was applied each year in early spring except in 2014. Native prairie species were planted in early June 2010. The restored prairie sites did not receive any added N. Oats were planted with the switchgrass and native prairie species in 2010 to serve as an over-winter nurse crop. Both switchgrass and restored prairie were harvested, except during the planting year in 2010, around early November each year.

2.2. Eddy covariance (EC) and meteorological measurements

Eight years of EC and meteorological measurements (2009–2016) were used in this study. The EC system included a LI-7500 open-path infrared gas analyzer (IRGA, LI-COR Biosciences, Lincoln, NE) for CO_2 and H_2O concentration measurements and a CSAT3 three-dimensional sonic anemometer (Campbell Scientific Inc. CSI, Logan, UT) for wind speed and direction measurements. The EC instruments were mounted 1.5–2 m above the average canopy height and measurements were conducted and logged at 10 Hz using a Campbell CR5000 datalogger. The LI-7500s were calibrated every four to six months. Half-hourly meteorological measurements of incoming and outgoing radiation (CNR1, Kipp & Zonen, Delft, The Netherlands) and air temperature and relative humidity (HMP45C, CSI) were also logged at each site. Additionally, soil temperature (CS107, CSI) at 0.02, 0.05 and 0.1 m and soil heat flux density (HFT3, CSI) at 0.02 m were also measured at each site. Precipitation (TE525WL-S: Texas Electronics, Dallas, TX) and photosynthetically active radiation (PAR) (LI-190, LI-COR) were obtained from a nearby weather station (http://lter.kbs.msu.edu/datatables, accessed March 2017). More information about instrumentation and measurements can be found in Zenone et al. (2011) and Abraha et al. (2015).

The raw EC data were processed offline using EdiRe software (University of Edinburgh, v 1.5.0.32, 2012) to determine 30-min net ecosystem carbon exchange (NEE). Out-of-range values, spikes, and time lags between scalars and vertical velocity were removed from the raw data (McMillen, 1988). The three velocity components were rotated into the mean streamline coordinate system using the planar fit coordinate rotation (Wilczak et al., 2001). The sonic temperature was corrected for pressure and humidity (Schotanus et al., 1983), the CO_2 and H_2O fluxes for frequency response (Moore, 1986) and for air density fluctuations (Webb et al., 1980), including surface heating of the LI-7500 (Burba et al., 2008). Stationarity, flux-variance similarity, and friction velocity thresholds of the 30-min fluxes were also used to remove periods with poorly developed turbulent mixing (Foken and Wichura, 1996).

On average ~72% of the daytime and ~45% of the nighttime NEE data passed these quality checks and controls and the rest were filled by

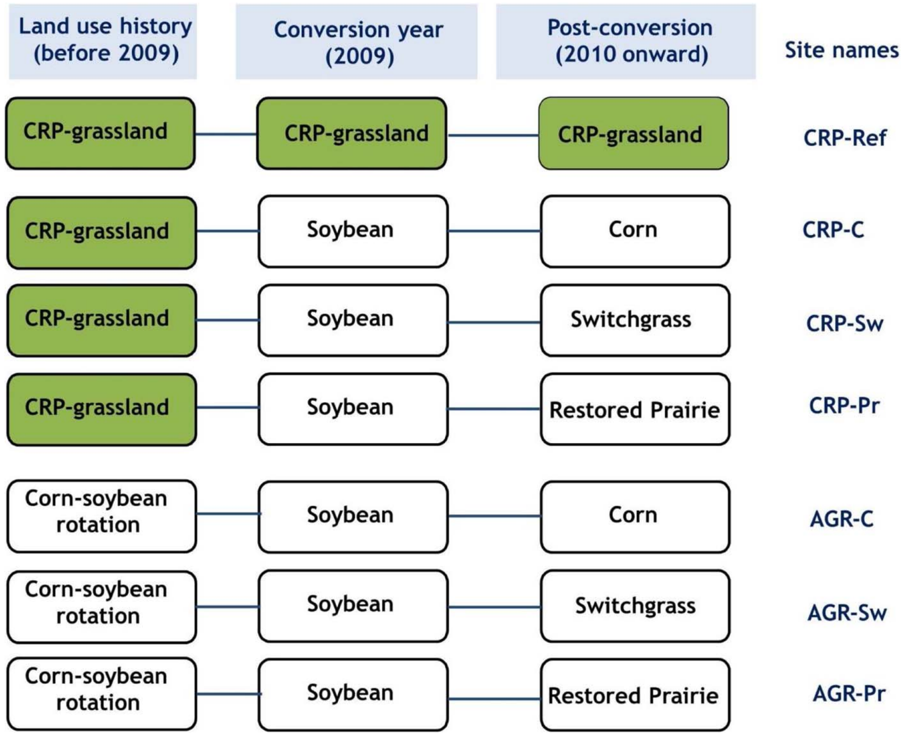

Fig. 1. Land use and conversion history of study sites. The Conservation Reserve Program (CRP) grasslands had been established in 1987 and the conventionally tilled corn-soybean rotation agricultural (AGR) fields had been in row crops since at least 1950. Fields were first converted to no-till soybean in 2009, then the post-conversion treatments (C = no-till corn, Sw = switchgrass, and Pr = restored prairie) were maintained from 2010 onward except for CRP-Ref, which remained in CRP grassland.

Table 1
Soil physical and chemical properties for the top 0.25 m of soil at each study site in 2009 before land use conversion: sites were planted to corn, switchgrass, and restored prairie, converted from either Conservation Reserve Program (CRP) grassland or conventionally tilled corn-soybean agricultural croplands (AGR). The CRP-Ref site was not converted. See Fig. 1 for land use and site name information. Means followed by same letter are not significantly different by *t*-test ($p < 0.05$).
Source: http://lter.kbs.msu.edu/datatables/372, Abraha et al. (2016).

Site	Area (ha)	Soil pH	Bulk Density ($g\,cm^{-3}$)	Nitrogen ($g\,kg^{-1}$ soil)	Carbon ($g\,kg^{-1}$ soil)
CRP-C	17	6.1^{a}	1.58^{b}	2.0^{d}	21.2^{c}
CRP-Sw	13	5.9^{a}	1.66^{b}	1.6^{c}	18.5^{c}
CRP-Pr	11	6.2^{a}	1.59^{b}	1.7^{c}	19.5^{c}
AGR-C	11	6.4^{a}	1.54^{a}	1.2^{a}	12.2^{b}
AGR-Sw	14	6.4^{a}	1.79^{c}	1.1^{a}	10.8^{a}
AGR-Pr	13	5.8^{a}	1.69^{b}	1.4^{b}	13.5^{b}
CRP-Ref	9	6.2^{a}	1.56^{b}	1.9^{d}	20.9^{c}

a standardized gap-filling algorithm (Reichstein et al., 2005) (http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/, accessed March 2017). Detailed information regarding data quality, processing and gap-filling is provided in Abraha et al. (2015).

2.3. Grain yield, stover and biomass C

Soybean (2009) and corn (2010 onward) grain yields, and corn stover (when harvested), switchgrass and restored prairie biomass yields were weighed from entire fields following harvest. Biomass C was calculated based on the C fraction of soybean and corn grains (0.50 and 0.42, respectively), of corn stover (0.44), of switchgrass (0.46), and of restored prairie (0.45) obtained from a nearby site (http://lter.kbs.msu.edu/datatables/470, accessed March 2017).

2.4. Adjusted net ecosystem exchange

Adjusted net ecosystem exchange (NEE_{adj}, $g\,C\,m^{-2}$) was computed by adding C harvested in grain, stover and biomass (C_{bio}) to NEE ($g\,C\,m^{-2}$) measured by EC. We assumed here that most or all of the exported C in harvest will eventually be released to the atmosphere (e.g., Verma et al., 2005).

$$NEE_{adj} = NEE + C_{bio}$$

$$C_{bio} = f_c \times Y$$

where f_c is C fraction of Y, the harvested dry mass ($g\,C\,m^{-2}$). NEE directed towards the land surface is indicated by negative C (i.e., uptake from the atmosphere) and away from the surface by positive C (emission) values. Since NEE and C in harvest are by far the largest components of the C balance in our systems, we will refer to the resulting NEE_{adj} as net C gain (uptake) or loss (emission) throughout (Chapin et al., 2006).

2.5. Statistics

Student's *t*-test was used to analyze soil C, N, pH and bulk density. Means were considered significant at $p < 0.05$. Uncertainties associated with gap filling techniques, friction velocity threshold selection criteria, and Monte Carlo simulations (95% confidence intervals) of the 30-min NEE were propagated into annual NEE uncertainties (e.g., Goulden et al., 1996; Moncrieff et al., 1996; Abraha et al., 2015) to facilitate across site and within crop comparisons. Statistical variances for exported C in harvest were derived from dry mass of aboveground net primary productivity (ANPP; $n = 10$) harvested at peak biomass in July or August for each year and field. We assumed that the ratio of the standard error (SE) of ANPP to ANPP is equal to the ratio of the SE of exported C in harvest to exported C in harvest. The NEE uncertainty and the SE of exported C in harvest were propagated into NEE_{adj} uncertainty. The NEE, exported C in harvest and NEE_{adj} uncertainties (as SE) were used to create lower and upper bounds, and significant differences were determined based on whether the ranges overlapped. All data reported here are openly available on Dryad (Abraha et al., 2018).

3. Results

Precipitation during May–September at our study sites, roughly representing the growing season, varied between 227 and 726 mm from

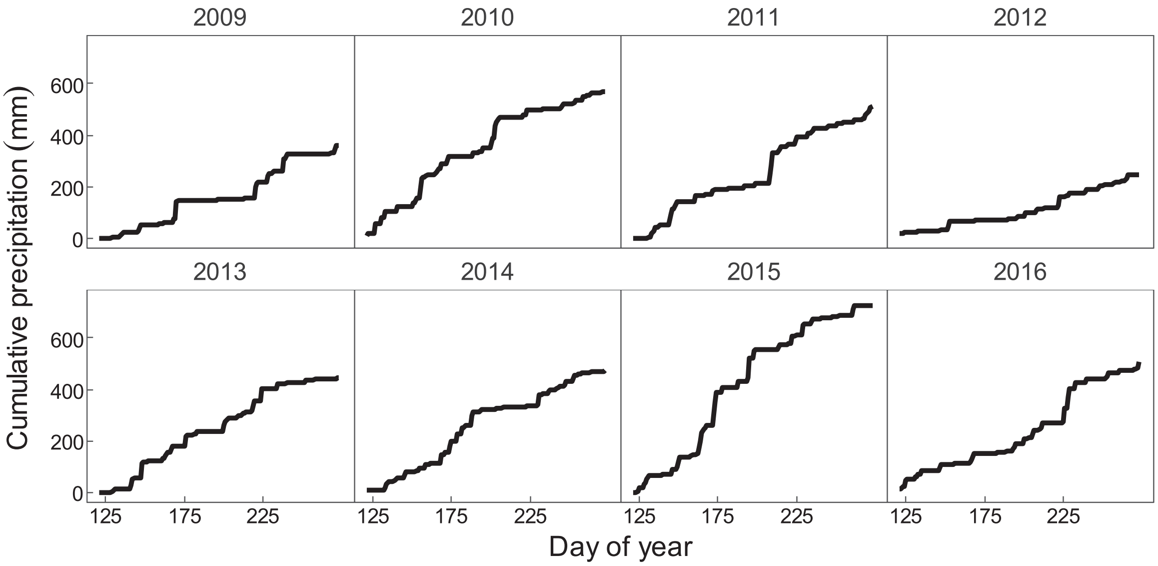

Fig. 2. Cumulative precipitation during May to September growing season (DOY 121–274) from 2009 through 2016.

Table 2
Growing season (May–September) and annual (October–September) daily average air temperature (T_{air}), total precipitation and daily average photosynthetically active radiation (PAR) from 2009 through 2016.
Source: http://lter.kbs.msu.edu/datatables.

Year	T_{air} (°C)		Precipitation (mm)		PAR (μmol m^{-2} s^{-1})	
	May–Sept	Annual	May–Sept	Annual	May–Sept	Annual
2009	18.0	8.4	358	875	359	258
2010	19.8	10.0	568	936	355	251
2011	19.2	9.0	510	975	333	241
2012	20.1	11.3	227	796	364	251
2013	18.9	9.1	446	1139	335	224
2014	18.1	7.5	473	971	343	241
2015	18.9	8.4	726	1173	310	220
2016	19.8	10.7	500	948	316	211
1981–2010 average	19.7	9.9	523	1027	–	–

2009 through 2016 (Fig. 2, Table 2). The growing season precipitation totals in 2012 and 2015 were much lower and higher, respectively, than the 30-year average (1981–2010) for May–September (523 mm). The precipitation in 2009 was also lower than the long-term average. The growing season mean air temperature in 2014 (18.1 °C) was notably lower than the long-term mean (19.7 °C, Table 2).

3.1. Annual net ecosystem C exchange (NEE)

The annual net C uptake (NEE) was greater for crops established on former AGR than that on former CRP fields. However, the difference in a given year diminished with time for the perennial crops while it remained more or less constant for the corn systems (Fig. 3). The NEE of the CRP-Ref field fluctuated around neutral apart from a relatively large net emission during the drought year of 2012 (127 ± 23 g C m^{-2}).

In the 2009 conversion year when soybean was planted on all but the reference field, there was a large net C emission from former CRP fields (Fig. 3). On the former AGR fields, where there was no land use conversion other than a change from till to no-till, on other hand, there was a near-neutral emission on one field, a net C uptake on the second, and a small net C emission on the third field. In the following year, the corn systems in both land use histories showed a net C uptake (−349 ± 31 g C m^{-2} at AGR-C and −163 ± 40 g C m^{-2} at CRP-C). In the same year, upon conversion to perennial croplands, the former CRP fields still showed a net C emission (166 ± 33 g C m^{-2} at CRP-Sw and 166 ± 21 g C m^{-2} at CRP-Pr), while the former AGR fields showed a net C uptake (−84 ± 44 g C m^{-2} at AGR-Sw and −120 ± 26 g C m^{-2} at AGR-Pr).

The corn systems showed a net C uptake on the former AGR (−80 ± 21 g C m^{-2}) and emission on the former CRP (66 ± 24 g C m^{-2}) fields in 2012 when precipitation was low (Fig. 3). The NEE of the corn systems in the other years—with precipitation close to the long-term average—exhibited net C uptake, except for a near-neutral emission on former CRP in 2015, that varied depending on precipitation distribution during the growing season (Fig. 2). On the other hand, the annual NEE of the perennial systems showed progressive increases in net C uptake over the study period, except in 2011 (restored prairie on former AGR field) and in 2012 (switchgrass on both former AGR and CRP fields) when water was severely limiting for a large part of the growing season (Fig. 2).

3.2. Yields

Yields of corn and switchgrass were always greater on former CRP than on former AGR fields whereas for restored prairie yields the pattern was less consistent (Fig. 4). Corn grain yield at both land use histories was lowest during the drought year in 2012 compared to the other years (Figs. 2 and 4, Table 2). The yields of perennial crops, which were not harvested during the planting year in 2010, increased each year until they stabilized by 2013 for most fields (by 2015 for CRP-Pr field). There was little change in yield during the 2012 drought compared to previous years. The CRP-Ref field was not harvested or mowed

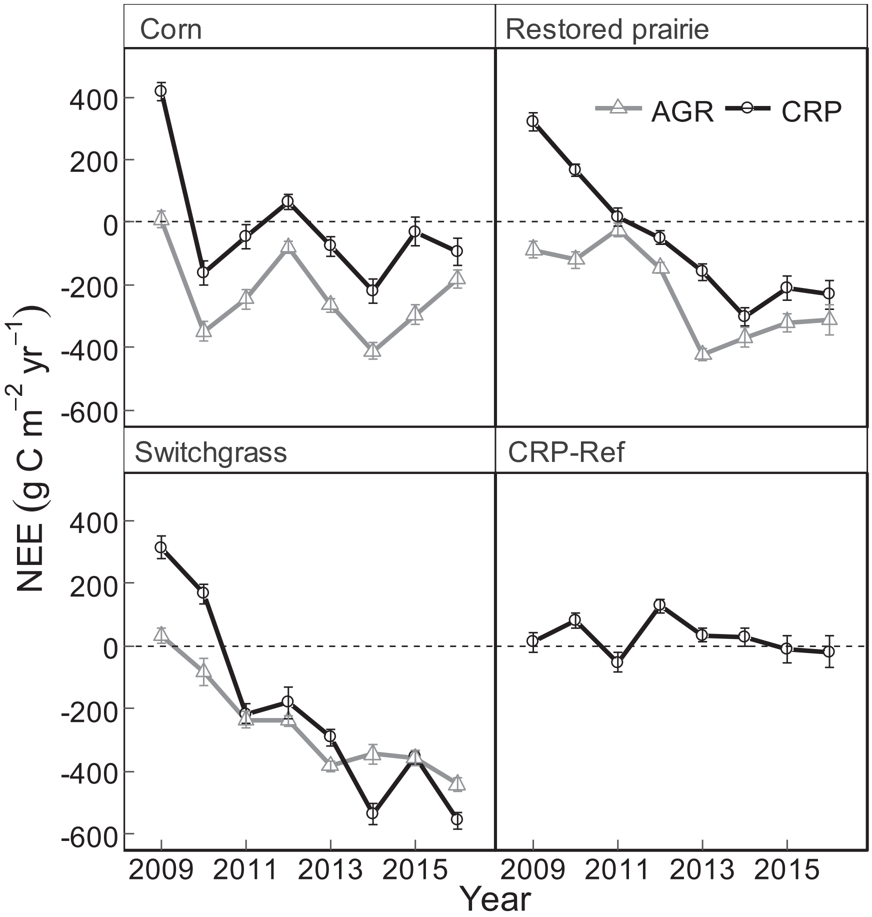

Fig. 3. Annual net ecosystem C exchange (NEE) from 2009 through 2016 at all fields. With the exception of the CRP-Ref, all fields were planted to soybean in 2009. The broken horizontal line indicates neutral C emission, below the line indicates net C uptake from the atmosphere while above the line is net carbon emission to the atmosphere. NEE does not include harvested C (See Figs. 4 and 5).

during the study period.

3.3. NEE adjusted for crop yields

The annual adjusted NEE (NEE_{adj}) showed a higher C emission for crops established on former CRP than on former AGR fields (Fig. 5a). The annual NEE_{adj} values for soybean in 2009 on former AGR and CRP fields indicated net C emission to the atmosphere, except for a near-neutral emission from the AGR-Pr field. The CRP-C remained a C source in all years while all other fields became C sinks in at least several years during the study. On average, ~35% of corn stover was harvested for the last two years of the study, contributing a large amount of C source in both corn systems. The annual NEE_{adj} of the former AGR fields appeared to have stabilized with little change over time while that of the former CRP fields were decreasing (becoming more of a C sink) over time, especially in the perennial croplands. Accordingly, the difference in annual NEE_{adj} between the former AGR and CRP fields for the same crop in the perennials diminished over time.

The cumulative NEE_{adj} over the eight-year study period showed a distinct net C emission for crops established on former CRP fields (means ± SE: 2454 ± 118 g C m^{-2} for CRP-C, 482 ± 107 g C m^{-2} for CRP-Sw, and 468 ± 95 g C m^{-2} for CRP-Pr) and net uptake for crops established on former AGR fields (-478 ± 101 g C m^{-2} for AGR-Sw, −735 ± 88 g C m^{-2} for AGR-Pr) except for corn (AGR-C, 82 ± 100 g C m^{-2}) with near-neutral emission (Fig. 5b). The cumulative NEE_{adj} of the CRP-Ref field showed net C emission to the atmosphere (196 ± 94 g C m^{-2}) but much less than the other crops on former CRP fields (Fig. 5b). For all cropping systems within their respective land use history, the cumulative NEE_{adj} of the perennial croplands showed greater net C uptake than did the corn system. For the corn system established on former AGR field, the cumulative NEE_{adj} was near-neutral for most of the years, including 2015 and 2016 when corn stover was partially harvested and exported off-site. In contrast, the perennial croplands on former AGR fields became net C sinks from the second (restored prairie) and third (switchgrass) year onwards following land use conversion.

4. Discussion

We found that the C sink/source strength of our cropping systems was strongly influenced by the combination of legacies of land use history and whether the crop established was annual or perennial. Consistent with our hypotheses, after eight years the crops established on former CRP fields exhibited higher C emission to the atmosphere than those established on former AGR fields; and the perennial croplands showed higher C uptake than the corn systems within a given land use history after accounting for exported biomass over the study period.

4.1. Annual net ecosystem C exchange

There was a net C emission to the atmosphere in 2009 upon conversion to soybean for all former CRP fields and on the AGR-Sw field; a near-neutral emission on AGR-C (9 ± 25 g C m^{-2}); and a net uptake on the AGR-Pr field (−87 ± 26 g C m^{-2}) (Fig. 3). The magnitude of the emission was by far greater on former CRP than on former AGR fields. This is presumably because accumulated C in the soil and vegetation during the preceding 22 years under the CRP became available for microbial decomposition upon conversion. This suggests that land use conversions that cause soil and vegetation disturbances will result in a large net C emission to the atmosphere (Fargione et al., 2008; Zenone et al., 2011; Gelfand et al., 2011). Carbon emissions similar to those observed in our AGR fields were also reported elsewhere from no-till

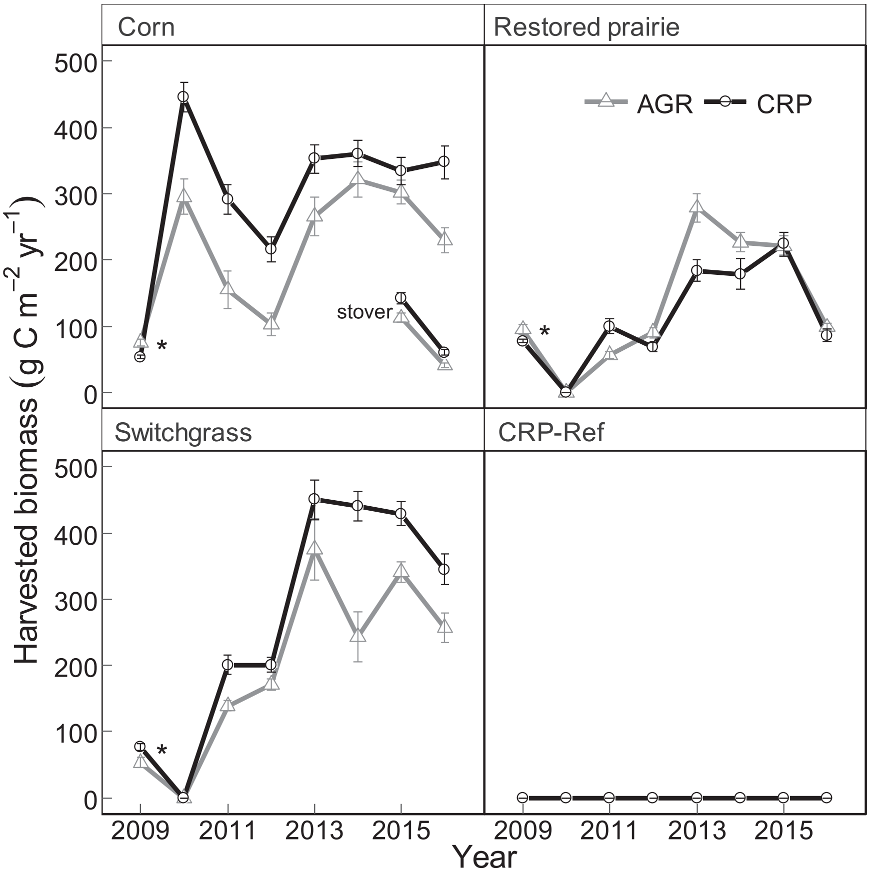

Fig. 4. Harvested biomass C from 2009 through 2016 at all fields. With the exception of the CRP-Ref, all fields were planted to soybean in 2009 (*) only. Corn stover was partially harvested in 2015 and 2016 (bottom right in the Corn panel).

soybean fields in corn-soybean rotation (e.g., Hollinger et al., 2006; Suyker and Verma, 2012).

Net C emissions from the corn systems were always higher on former CRP than on former AGR fields (Fig. 3). This is likely due to lower available soil C on the former AGR vs. CRP fields (Table 1), arising from land use legacy. Hollinger et al. (2006) and Suyker and Verma (2012) reported C emissions similar to those observed in our AGR-C field from no-till corn fields in corn-soybean rotation.

In the perennial croplands, a net C emission on the former CRP fields but a net C uptake on the former AGR fields was observed by 2010, reflecting the strong land use legacy effect of the former CRP fields. In 2011, the net C balance was similar within the respective

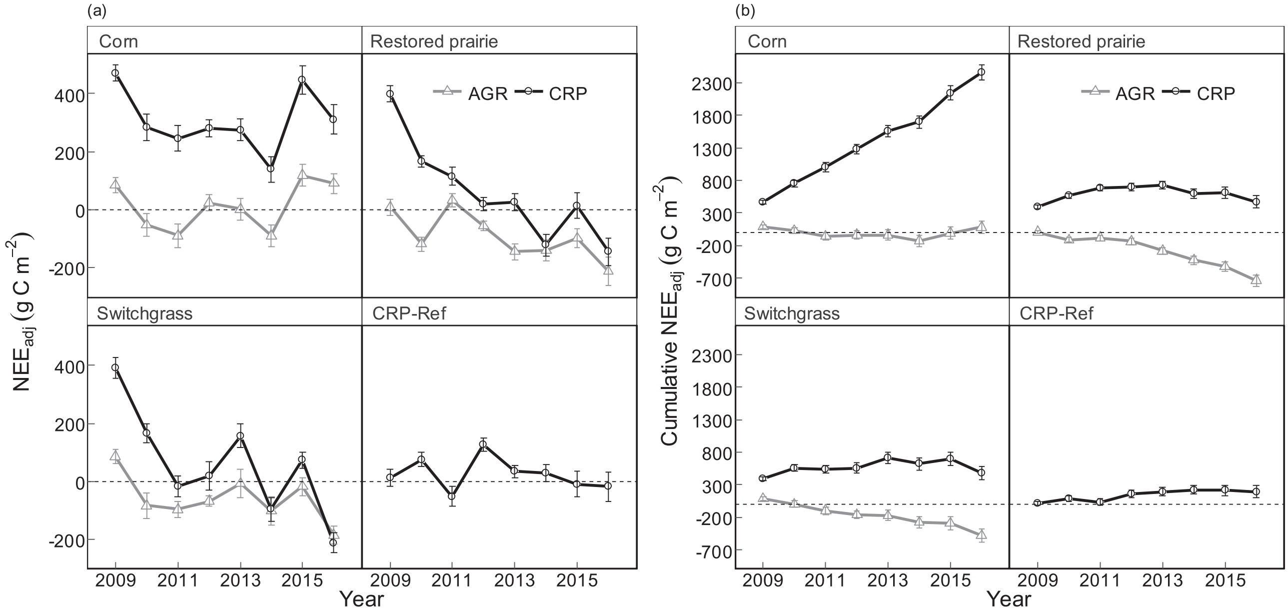

Fig. 5. Annual (a) and cumulative (b) NEE$_{adj}$ (NEE adjusted for C in harvest) for all fields. The broken horizontal line indicates neutral C emission, below the line indicates net C uptake from the atmosphere while above the line is net carbon emission to the atmosphere. NEE$_{adj}$ includes harvested C.

perennial croplands for both land use histories, with C uptake at the switchgrass and near-neutral C balances at the restored prairie fields. This was likely due to decomposition of the grasses (including the initial oat nurse crop) that were not harvested in the previous year. During the dry year of 2012, the NEE of the restored prairie fields showed increased C uptake while that of the switchgrass fields showed a stable or decreased C uptake compared to the previous year. The perennial croplands on former AGR fields achieved peak annual NEE by 2013 after which NEE stabilized, while those on former CRP fields achieved peak NEE by 2014.

The net C balance in the early years suggests that NEE in the perennial croplands is affected not only by land use conversion and interannual climate variability but also establishment of the crops following planting. Generally, it takes a few years for perennial grasslands to realize their full potential productivity (Fig. 4; Parrish and Fike, 2005; Zeri et al., 2011; Wagle and Kakani, 2014; Eichelmann et al., 2016b). In central Illinois, Zeri et al. (2011) showed a similar NEE trend for perennial grasslands (switchgrass and restored prairie) during three years of establishment. Skinner and Adler (2010) also reported NEEs of -31, -118, -248 and $-189\,\mathrm{g\,C\,m^{-2}}$ for switchgrass during four years following planting in the northeastern US. In southern Ontario, Canada, with a similar climate to ours, Eichelmann et al. (2016a,b) reported similar NEE values during the 2012–2014 growing seasons (-380 ± 25, -430 ± 30 and $-336 \pm 40\,\mathrm{g\,C\,m^{-2}}$, respectively) for a mature switchgrass stand that was converted from conventional agriculture in 2006. All three studies support the conclusion that perennial croplands exhibit higher C uptake following planting until full establishment when uptake rates stabilize.

The perennial croplands, in general, showed less net C uptake than that of the corn systems in the first two years following planting (except for CRP-Sw in 2011) but greater net C uptake for the rest of the study years (except 2014 on former AGR fields) within the respective land use history. This reflects the establishment and post-establishment phases of the perennial croplands during which the net C uptake increases.

4.2. Yields

The higher yields of corn and switchgrass on former CRP compared to former AGR fields indicate a land use legacy effect on yield. However, there was no clear trend for yields of the restored prairie other than higher yields on former AGR than on former CRP fields following the 2012 drought, likely due to shift in species composition (Abraha et al., 2016).

The annual corn yields from both land use histories fluctuated similarly to annual NEE, both reflecting the inter-annual climatic variability (Table 2, Figs. 2 and 4). The perennial crop yields were lower during the establishment period but kept increasing each year, except in 2012 on the former CRP fields, until a peak was reached by 2013 for most fields (by 2015 for the CRP-Pr field) (Fig. 4). This is consistent with previous studies conducted on young stands of perennial herbaceous crops (e.g., Skinner and Adler, 2010; Zeri et al., 2011, 2013; Wagle and Kakani, 2014). The yield of the perennial crops fluctuated in response to inter-annual climate variability following full establishment.

4.3. Adjusted NEE

The annual adjusted NEE ($\mathrm{NEE_{adj}}$) of crops established on former CRP fields showed more C emission to the atmosphere than did the same crops established on former AGR fields (Fig. 5a). The annual $\mathrm{NEE_{adj}}$ on the CRP-C field was always higher than that on the AGR-C field because of its higher exported yield coupled with the higher annual NEE (lower net C uptake due to high soil C emissions). The C emission from the perennials on former CRP fields was high immediately following conversion but diminished with time, resulting in annual $\mathrm{NEE_{adj}}$ values similar to those of perennials on former AGR fields (Fig. 5a). The annual $\mathrm{NEE_{adj}}$ of soybean in 2009 was a C source on both the former AGR and CRP fields, except for a near-neutral C emission from the AGR-Pr field. Suyker and Verma (2012) found the annual $\mathrm{NEE_{adj}}$ of a no-till corn-soybean rotation to be a C source, but slowly moving towards near-neutral C balances over eight years in Mead, NE, USA.

The annual $\mathrm{NEE_{adj}}$ of corn also showed more net C emission than did the perennial croplands within a given land use history in all years, except in 2011 on the former AGR fields when AGR-Pr emitted more than AGR-C (Fig. 5a). This general trend was mainly due to the larger exported harvest, including stover in 2015 and 2016, in the corn systems compared to the perennial croplands during the establishment phase for switchgrass, and in all years for restored prairie. Also, the corn stover left on the ground (2010–2014) was slowly decomposing, and contributing to C emissions, while relatively little biomass was left behind in the perennial crops following harvest and thus that residue had less influence on C balances. In addition, C uptake in the fully established perennial crops was higher, likely due to a large live root biomass in the perennials compared to the corn systems where roots die at the end of growing season and eventually decompose, contributing C emissions.

The cumulative $\mathrm{NEE_{adj}}$ of the annual and perennial croplands established on former CRP fields exhibited a net C emission to the atmosphere during this eight-year study, while those established on former AGR fields showed a net C uptake except for a near-neutral C balance at the corn field (Fig. 5b). These results suggest that converting existing perennial grasslands into annual crop production results in C emissions that persist for many years after conversion, whereas converting into perennial crop production results in high C emission for 2–3 years and lower or negative emissions thereafter (Fig. 5a,b). The cumulative $\mathrm{NEE_{adj}}$ at the CRP-C field, in particular, was still increasing by the end of the eighth year and will likely keep increasing until the soil C is depleted to the level of that of AGR-C—which has lost most of its pre-conversion soil C during decades of agricultural row crop production (Table 1).

The C emission upon conversion was partly due to pre-existing plants (above and belowground) and surface litter in which the C was fixed prior to the EC measurement. Gelfand et al. (2011) estimated $\sim 360\,\mathrm{g\,C\,m^{-2}}$ would be released from pre-existing plants and $\sim 80\,\mathrm{g\,C\,m^{-2}}$ from surface litter (https://data.sustainability.glbrc.org/datatables/225, accessed March 2017) upon conversion at our former CRP fields. After accounting for these C losses, the $\mathrm{NEE_{adj}}$ of the CRP-C field suggests that about a quarter of the initial soil C was lost during the eight years following conversion. This is ~60% of the soil C that accumulated during the 22 CRP years at the CRP-C field, assuming the CRP-C and AGR-C fields had the same soil C content in 1987 when the CRP lands were established and that the AGR-C soil C did not change until 2009 when soil C was sampled at all fields (Table 1). At the average annual $\mathrm{NEE_{adj}}$ rate of the CRP-C field (2010–2016), it will likely take another six+ years for the soil C of the CRP-C to be depleted to the level of that of the AGR-C. At that time, the C emissions from the CRP-C field will likely reach a new equilibrium similar to that shown by AGR-C (Fig. 5b). However, the soil C emitted until equilibrium is reached may never be regained under the same crop and management. It should be noted that this assumes a linear soil C decomposition rate which, in reality, may slow down with time as the system approaches a new steady state. Therefore, the time it takes for the CRP-C field to reach a new lower soil C equilibrium may be longer than ~14 years. This needs to be confirmed by soil C stock sampling in future years. A meta-analysis for temperate grassland to cropland conversion suggests that for many temperate grassland soils it takes about 17 years to reach a new lower soil C equilibrium with an estimated soil C loss of 36 ± 5% (Poeplau et al., 2011).

In contrast, the annual $\mathrm{NEE_{adj}}$ values of the perennials on former CRP fields decreased over time (Fig. 5a), implying a C uptake rate similar to those on former AGR fields towards the last three years of the study. This indicates that the perennial croplands on former CRP fields will likely become net C sinks in the near future. At the annual NEE_{adj} rate of post-establishment (2014–2016), it would take ~4 years more for the CRP-Pr and CRP-Sw to produce C emissions similar to or less than that of the CRP-Ref field, respectively, and another two years to become C sinks. The cumulative NEE_{adj} values of perennial croplands reported elsewhere show an increasing trend of C uptake following planting, which is similar to our perennials on former AGR fields (e.g., Skinner and Adler 2010; Zeri et al., 2011).

Cumulative NEE_{adj} for the corn systems showed a higher C emission than for the perennial (switchgrass and restored prairie) croplands on both the former AGR and CRP fields (Fig. 5b). This is not surprising as the trend of the cumulative NEE_{adj} follows that of the annual NEE_{adj} (Fig. 5a). The CO_2 emission arising from liming of the corn system cannot be discerned by EC, but the fate of C in lime has been studied on nearby soils and appears to be about equally balanced between conversion to CO_2 and dissolution by the bicarbonate weathering pathway, which sequesters CO_2, and thus the net effect of liming on C balance is nil (Hamilton et al., 2007).

The low to nil NEE_{adj} of the AGR-C field implies no soil C change on conversion of till to no-till in our study, as has been found for some other short-term studies (e.g., Ogle et al., 2005; Verma et al., 2005). While it is possible that our soils will not accumulate C under no-till management, especially with partial residue removal, prior work at a nearby site (Senthilkumar et al., 2009; Syswerda et al., 2011) suggests otherwise, as do most but not all long-term pairwise comparisons (e.g., West and Post, 2002; Ogle et al., 2005). However, Verma et al. (2005) also found near-neutral NEE_{adj} three years after conversion to no-till for irrigated continuous corn, and for irrigated and rain-fed corn-soybean rotations in Nebraska. Confidence in our finding of no soil C change upon no-till conversion awaits confirmation of gravimetric soil sampling, not reliable in these and most Midwest US soils until > 10 years post-conversion (Necpálová et al., 2014).

The stover removal in the last two years at the AGR-C field also affected the NEE_{adj}. With the stover left in place, the NEE_{adj} would still have remained near-neutral. However, continuous stover removal will have a negative effect on soil C in the long run as it deprives the soil of C inputs. Declines in soil C were reported with increasing removal of stover elsewhere (e.g., Villamil and Nafziger, 2015). Modeling studies on stover removal also point in the same direction (e.g., Anderson-Teixeira et al., 2009; Jones et al., 2018). The decline in soil C at our site after eight years of no-till with stover partially removed in the last two years was minimal (~0.02%) but the loss may accumulate over time if the same stover removal management were adopted.

The cumulative NEE_{adj} of the CRP-Ref field indicates net C emission to the atmosphere. This was largely due to C emission in the 2012 drought. Because the CRP-Ref field is approximately C neutral in most non-drought years, as the gradual decomposition of the unharvested vegetation offsets the C uptake at the field, it may take several years for the cumulative NEE_{adj} of the CRP-Ref field to return to neutral following a natural disturbance like drought. There may also be little capacity for additional soil C sequestration at this field after being set-aside in grassland for 30 years.

5. Implications

The ecosystem C balances of different cropping systems developed on contrasting land use history have important implications for climate change mitigation. The potential for C sequestration by ecosystems is contingent on the history of the land, the climatic conditions, the crop type, and associated management. In our study, initial conversion of former CRP grasslands to perennial cropland emitted a large amount of C to the atmosphere that has persisted to date (Fig. 5b) and will likely continue to persist for a total period of ~14 years before the systems shift back to being net C sinks. Conversion to an annual crop emitted even larger on-going amounts of C to the atmosphere (Fig. 5b), creating a C source that will likely persist until a new lower soil C equilibrium is reached at least 14 years post-conversion. This C may never be regained under the no-till management practice with partial stover removal adopted here.

The increase in land use conversion from perennial grasslands to annual grain crops by $\sim 5 \times 10^6$ ha between 2007 and 2016 in the US (United States Department of Agriculture Farm Services Agency (USDA-FSA, 2017), driven mostly by higher demand for corn to produce grain ethanol (Wright and Wimberly, 2013; Lark et al., 2015), has almost certainly been accompanied by enhanced C emissions to the atmosphere. This subverts one of the main reasons for producing grain ethanol – to mitigate greenhouse gas emissions, particularly if the fossil fuel C offset, not considered here, is insufficient to offset the land-based C debt. On the other hand, converting former croplands to perennial croplands exhibits a large direct C benefit through C uptake from the atmosphere, contributing directly to climate change mitigation even in the absence of a fossil fuel C credit. Growing perennial crops for biofuel on abandoned or marginal croplands has the added benefits of avoiding competition with food production (Robertson et al., 2017); increased biodiversity (Werling et al., 2014); and improved soil conservation and water quality (Food and Agricultural Policy Research Institute (FAPRI, 2007). Although C debt is created when converting CRP grasslands to perennial biomass cropping systems, that these systems likely become a C sink within ~14 years further enhances the greenhouse gas mitigation provided by the fossil fuel offset when biomass is converted to cellulosic ethanol, which itself can repay the debt within several years of conversion (Gelfand et al., 2011).

6. Conclusions

The major conclusions from this study are:

(1) Converting Conservation Reserve Program (CRP) grasslands to either no-till corn or perennial croplands emitted a large amount of C that had accumulated in the soil and vegetation during the CRP years, whereas converting conventionally tilled agricultural (AGR) fields to the same crops resulted in immediate C uptake from the atmosphere for the perennial systems and no significant change for the corn system;
(2) The net C emission to the atmosphere following conversion of CRP grassland to no-till continuous corn is on-going and will likely continue to increase until a new lower soil C equilibrium is reached (perhaps ~14 years after conversion), and the C emitted during this time may never be regained by the system. After conversion to perennial croplands, however, the system appears likely to become a C sink ~14 years following conversion;
(3) Conversion of conventionally tilled AGR fields to perennial croplands showed a large C sink with progressive increases in net C uptake over the years, while conversion to no-till continuous corn was near-neutral;
(4) The net C uptake following conversion was higher for perennial systems than for annual corn systems within a given land use history; and
(5) During a drought year a 25-year-old C-neutral CRP grassland (CRP-Ref) became a net C source and five years post-drought the C lost had still not been recaptured.

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