

# From set-aside grassland to annual and perennial cellulosic biofuel crops: Effects of land use change on carbon balance



Terenzio Zenone<sup>a,b,\*,1</sup>, Ilya Gelfand<sup>b,c</sup>, Jiquan Chen<sup>a,b</sup>,  
Stephen K. Hamilton<sup>b,c,d</sup>, G. Philip Robertson<sup>b,c,e</sup>

<sup>a</sup> Department of Environmental Sciences, University of Toledo, Toledo, OH 43606, USA

<sup>b</sup> Great Lakes Bioenergy Research Center, Michigan State University, East Lansing, MI 48824, USA

<sup>c</sup> W.K. Kellogg Biological Station, Michigan State University, Hickory Corners, MI 49060, USA

<sup>d</sup> Department of Zoology, Michigan State University, East Lansing, MI 48824, USA

<sup>e</sup> Department of Plant, Soil, and Microbial Sciences, Michigan State University, East Lansing, MI 48824, USA

## ARTICLE INFO

### Article history:

Received 29 October 2012

Received in revised form 23 July 2013

Accepted 30 July 2013

### Keywords:

Land use change

Conservation Reserve Program

Switchgrass

Restored prairie

Corn

Soil carbon

## ABSTRACT

Increasing demand for agricultural commodities such as grain for feed and feedstocks for biofuels are driving rapid land use change. We studied the effect of agricultural land-use change on two historical land use types for three different cropping systems using eddy covariance and ecosystem carbon balance approaches. We quantified the consequences of establishing corn, switchgrass, and mixed prairie species on cropland under a recent corn–soybean rotation and on set-aside land planted for 20 years to smooth brome grass (*Bromus inermis* Leyss) enrolled in the USDA Conservation Reserve Program (CRP). We converted three CRP and three cropland fields to no-till soybeans in 2009 (conversion year) and then established fields of corn, switchgrass, and mixed prairie species in fields formerly cropland or CRP. In addition, one CRP perennial grassland site was kept undisturbed as a reference. We measured the harvestable biomass during the conversion and over the two following years. To account for C removed in harvestable biomass we calculated adjusted Net Ecosystem Production ( $NEP_{adj}$ ;  $g\ C\ m^{-2}\ yr^{-1}$ ) as  $NEP$  measured by eddy covariance plus harvested biomass. During the conversion year, fields converted from historical CRP grassland exhibited net C emissions between 261 and 340  $g\ C\ m^{-2}\ yr^{-1}$ . The sites established on recent cropland emitted 37–42  $g\ C\ m^{-2}\ yr^{-1}$ . The undisturbed reference site sequestered (rather than emitted) 35  $g\ C\ m^{-2}\ yr^{-1}$ . Cumulative  $NEP_{adj}$  over the entire 3-year period at the sites converted from CRP grasslands was 170, 740, and 885  $g\ C\ m^{-2}$  for switchgrass, corn, and mixed prairie systems, respectively. At the former cropland sites, cumulative  $NEP_{adj}$  was 214, 364, and 446  $g\ C\ m^{-2}$  for mixed prairie, corn, and switchgrass systems, respectively. Over this period the reference site had an  $NEP$  of  $-260 \pm 30\ g\ C\ m^{-2}$ . Land use change to biofuel crops thus induced large C emissions, even when renewable energy production was included as a fossil fuel carbon offset. The most productive perennial systems had lowest overall C losses. Accounting for fossil fuel offset credits generated from harvested biomass completely attenuated  $CO_2$  emissions in the CRP site converted to switchgrass and partially attenuated emissions in all other converted sites. These results can be readily incorporated into management recommendations for future establishment of biofuels feedstock and row agriculture systems with different management intensities.

© 2013 Elsevier B.V. All rights reserved.

## 1. Introduction

Ensuring the environmental sustainability of future bioenergy systems is among the emerging challenges to both the scientific

and policy-making communities. It is a topic of intensive scientific and political debates worldwide due to increasing societal needs for renewable energy. Sustainable bioenergy systems must be ecologically, economically, and socially sustainable (Robertson et al., 2008). Ecosystem carbon (C) and energy balance as well as greenhouse gas (GHG) emissions are key indicators of environmental sustainability when bioenergy systems are implemented at large scales. Nevertheless, the effects of initial land use change upon establishment of biofuel crop production systems on carbon balances and GHG emissions remain poorly understood but are likely to be substantial (Fargione et al., 2008; Gelfand et al., 2011).

\* Corresponding author at: University of Antwerp, Department of Biology, Research group of Plant and Vegetation Ecology, 2610 Antwerp, Belgium.

Tel.: +32 32652831.

E-mail addresses: [Terenzio.Zenone@ua.ac.be](mailto:Terenzio.Zenone@ua.ac.be), [zenone@msu.edu](mailto:zenone@msu.edu) (T. Zenone).

<sup>1</sup> Present address: Department of Biology, Research group of Plant and Vegetation Ecology, University of Antwerp, 2610 Wilrijk, Belgium.

**Table 1**  
Treatment type, area, land use history (since 1987) and soil physical–chemical properties of the seven GLBRC study sites in “southwest” Michigan, US. The seven fields are denoted as pre–post land use: CRP–Corn (CRP–C), CRP–Prairie (CRP–P), CRP–Switchgrass (CRP–S), Agriculture–Corn (AGR–C), Agriculture–Switchgrass (AGR–S), Agriculture–Prairie (AGR–P), and CRP–reference (CRP–R). CRP sites were grasslands in the Conservation Reserve Program and AGR sites were in corn/soybean rotations. CEC is cation exchange capacity. Soil sampled to depth of 0–25 cm in April 2009.

Site	Area (ha)	Historical land use	Textural class	Sand (g kg <sup>-1</sup> soil)	Silt (g kg <sup>-1</sup> soil)	Clay (g kg <sup>-1</sup> soil)	Soil pH	Bulk density (g cm <sup>-3</sup> )	N (g kg <sup>-1</sup> soil)	C (g kg <sup>-1</sup> soil)
AGR–C	11.2	Corn/soyb	Sandy loam	577 ± 26 <sup>b</sup>	337 ± 23 <sup>b</sup>	86 ± 12 <sup>b</sup>	6.0 ± 0.1 <sup>a</sup>	1.54 <sup>a</sup>	1.2 <sup>a</sup>	12.2 <sup>a</sup>
AGR–S	14.1	Corn/soyb	Sandy loam	651 ± 31 <sup>a</sup>	271 ± 24 <sup>a</sup>	79 ± 12 <sup>ab</sup>	6.1 ± 0.1 <sup>a</sup>	1.79 <sup>b</sup>	1.1 <sup>a</sup>	10.8 <sup>b</sup>
AGR–P	23.0	Corn/soyb	Sandy clay loam	495 ± 32 <sup>c</sup>	360 ± 31 <sup>b</sup>	146 ± 10 <sup>c</sup>	5.8 ± 0.1 <sup>a</sup>	1.69 <sup>c</sup>	1.4 <sup>b</sup>	13.5 <sup>a</sup>
CRP–C	19.5	Grassland	Sandy loam	664 ± 29 <sup>a</sup>	257 ± 24 <sup>a</sup>	80 ± 8 <sup>b</sup>	6.0 ± 0.1 <sup>a</sup>	1.58 <sup>a</sup>	2.0 <sup>c</sup>	21.2 <sup>c</sup>
CRP–S	17.9	Grassland	Sandy loam	688 ± 25 <sup>a</sup>	265 ± 23 <sup>a</sup>	48 ± 6 <sup>a</sup>	5.7 ± 0.1 <sup>a</sup>	1.66 <sup>c</sup>	1.6 <sup>d</sup>	18.5 <sup>c</sup>
CRP–P	13.1	Grassland	Sandy loam	697 ± 53 <sup>a</sup>	245 ± 42 <sup>a</sup>	58 ± 12 <sup>a</sup>	6.3 ± 0.2 <sup>a</sup>	1.59 <sup>a</sup>	1.7 <sup>d</sup>	19.5 <sup>c</sup>
CRP–R	9.1	Grassland	Sandy loam	583 ± 28 <sup>b</sup>	342 ± 25 <sup>b</sup>	75 ± 8 <sup>ab</sup>	6.2 ± 0.1 <sup>a</sup>	1.56 <sup>a</sup>	1.9 <sup>c</sup>	20.9 <sup>c</sup>

Note: Means followed by same letters are not significantly different by *t*-test ( $p < 0.05$ ).

Land use change associated with agriculture has direct, significant effects on the global carbon cycle by changing the rates of soil carbon accumulation and turnover, soil erosion, and plant productivity (Richter et al., 1999; Lal, 2002; Zhang et al., 2010a). In the past two centuries, conversion of natural ecosystems to farming has led to a net loss of carbon to the atmosphere, which remains a significant source of atmospheric carbon dioxide (CO<sub>2</sub>) increases. (Zhang et al., 2010a; Houghton and Hackler, 1999). A large portion of the world's vegetated land surface (~50%) has been affected by agriculture (e.g., Foley et al., 2005). Carbon, water, and nutrient cycles at the global level are affected by agricultural activities that can also play a considerable role in the regulation of the surface energy balance (Bondeau et al., 2007; Feddema et al., 2005a; Foley et al., 2005).

Considering the importance of land use change for biofuel production and the paucity of studies on C balances change we established a field experiment in which we deployed eddy-covariance towers to observe how conversion of perennial grassland and traditional grain crops to bioenergy cropping systems affects ecosystem C balances. Our objectives were to quantify the magnitude and changes in: (i) C assimilation through gross primary production (GPP), (ii) C loss due to ecosystem respiration ( $R_{eco}$ ), and (iii) net C gain through net ecosystem production (NEP) during the conversion of conventional corn–soybean croplands and CRP grasslands (USDA Conservation Reserve Program, 2008) to three types of biofuel production systems: switchgrass, mixed prairie species, and no-till corn.

In an earlier paper (Zenone et al., 2011), we reported how large C imbalances were created in the conversion year and how long-term gains in soil C under CRP management can quickly be lost. Here, we report the cumulative C balance measured during the following two years. We then evaluate the impact of the crop choices and yields together with biomass end-use to show the relative effects of these factors on the C balance of the converted ecosystems.

## 2. Materials and methods

### 2.1. Experimental sites

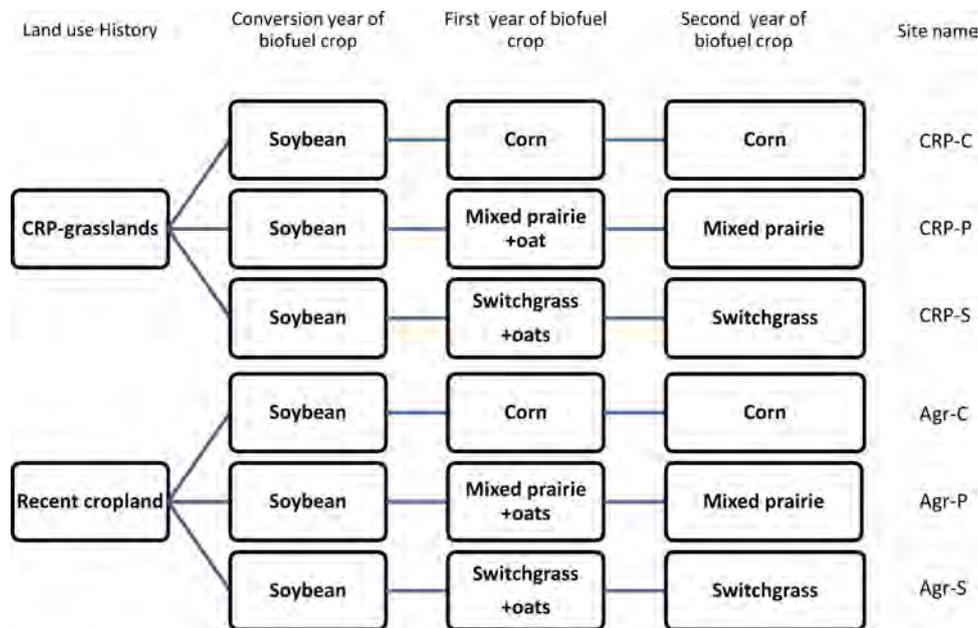
Our experiment is part of the research conducted at the Great Lakes Bioenergy Research Center (<http://glbrc.org/>) located at the Kellogg Biological Station (KBS) Long-Term Ecological Research (LTER) site (42°24'N, 85°24'W, 288 m asl), Michigan, USA. Detailed information on topography and soil physical and chemical properties of the studied sites was described in Bhardwaj et al., 2011 and Zenone et al., 2011. Briefly, the climate is temperate and humid, with a mean annual air temperature of 9.7°C and an annual precipitation of 920 mm. The soil textural class of all sites is sandy loam with a pH range from 5.7 to 6.3. Soil C and N contents were significantly higher in the grassland sites compared to the

agricultural sites (Table 1). Four of the seven fields, hereby denoted as CRP–Corn, CRP–Prairie, CRP–Switchgrass, and CRP–Reference prior to conversion were monoculture grasslands characterized by the dominant presence of smooth brome grass (*Bromus inermis* Leyss) which had been planted as a CRP cover crop in 1987 and cut (but not harvested) every three years. Historical records and aerial photographs obtained from the Michigan State University Aerial Imagery Archive ([www.rsgis.msu.edu](http://www.rsgis.msu.edu)) confirm that prior to conversion the CRP grassland sites were in agricultural row crops. The other three sites designated here as Agriculture–Corn (AGR–C), Agriculture–Switchgrass (AGR–S), and Agriculture–Prairie (AGR–P) were in cropland immediately prior to conversion and cultivated conventionally as corn–soybean rotations for at least the preceding ten years and probably for decades before that. Historical photographs showed no signs of animal grazing on any of the three fields. In spring 2009 (conversion year), all sites except the reference CRP grassland site were converted to no-till soybean cultivation (see Zenone et al., 2011 and Gelfand et al., 2011 for details) (Fig. 1). Converting to glyphosate-resistant no-till soybeans prior to planting biofuel crops allows the existing grasses to be killed by sequential glyphosate applications without having to use tillage. This represents a preferred technique for grassland conversion as described in Wright and Wimberly, 2013; Follett et al., 2009

The agricultural sites were planted with no-till soybeans in 2009 as well (Gelfand et al., 2011).

The CRP–C and AGR–C sites were planted in spring 2010 (first year post conversion) to no-till corn (*Zea mays*, Dekalb DK-52) on DOY 119 (CRP–C) and DOY 120 (AGR–C). An herbicide mix [*Lumax* (5.9 L ha<sup>-1</sup>), *Atrazine 4L* (0.78 L ha<sup>-1</sup>), *Honcho Plus* (2.4 L ha<sup>-1</sup>), and (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> (0.92 kg ha<sup>-1</sup>)] was applied using a pull-type sprayer (Demco Dethmers MFG Company, Boyden, IA, USA). Phosphorus and potassium fertilizer (P<sub>2</sub>O<sub>5</sub> + K<sub>2</sub>O, 168.5 kg ha<sup>-1</sup>) were applied to AGR–C prior to planting (DOY 95) to ameliorate the reduced soil nutrient availability at this site (Bhardwaj et al., 2011). Nitrogen fertilizer (28% liquid nitrogen as urea ammonium nitrate, 112 kg N ha<sup>-1</sup>) was applied to both AGR–C and CRP–C by side-dressing at AGR–C on DOY 165 and at CRP–C on DOY 160. In spring 2011, AGR–C and CRP–C were planted on DOY 125 and DOY 132, respectively, with no-till corn. Similar to 2010, the AGR–C field received phosphorus and potassium fertilization in 2011 at a rate of 294 kg ha<sup>-1</sup> (DOY 104) and both systems received 168 kg N ha<sup>-1</sup> of 28% liquid N fertilizer (urea ammonium nitrate), with 34 kg N applied at planting and the remainder side-dressed on DOY 172. Herbicide application was similar to 2010.

The CRP–S and AGR–S sites were planted in 2010 with switchgrass (*Panicum virgatum*) with oats (*Avena sativa*) as a first-year nurse crop on DOY 119 (CRP–S) and DOY 120 (AGR–S). Both switchgrass sites were fertilized with 55 kg N ha<sup>-1</sup> in May 2010. No other management practices occurred at either site until the above-ground biomass was harvested and baled in October 2011.



**Fig. 1.** Experimental design of the six bioenergy systems, including conversion of lands from Conservation Reserve Program (CRP) and recent cropland to establish the three bioenergy crop production systems (continuous corn, switchgrass, and mixed prairie). A seventh CRP grassland site (not shown) was left unchanged as a reference site.

The AGR-P and CRP-P sites were planted in 2010 on DOY 155 and 156, respectively, to a mix of native prairie species (mainly *Elymus canadensis*, *Schizachyrium scoparium*, *Sorghastrum nutans*, *Rudbeckia hirta*, and *Rubekia triloba*) with oats as a first-year nurse crop. Like the switchgrass treatments, aboveground biomass was harvested in October 2011. Unlike the switchgrass treatment, no N fertilizer was applied at either site. The CRP-R site was left unmanaged to serve as a reference.

## 2.2. Eddy-covariance and micrometeorological measures

Open-path eddy-covariance (EC) systems were installed during the summer of 2008 in each of the seven sites. The turbulent exchange of CO<sub>2</sub> between the canopy and atmosphere was measured throughout 2009–2011 following the same methodologies of Zenone et al. (2011). Briefly, each EC system consisted of a Li-7500 open-path infrared gas absorption analyzer (IRGA, Li-Cor Biosciences, Lincoln NE, USA), a CSAT3 three-dimensional sonic anemometer (Campbell Scientific, Inc. (CSI), Logan, UT, USA), and a CR5000 datalogger (CSI).

During the first year (soybean and grassland reference sites), the height of the EC systems was set to 3 m above the ground (Zenone et al., 2011). After conversion in 2010 the height of the EC systems was set to 5 m in the corn sites and 4 m in the switchgrass mixed prairie and reference sites.

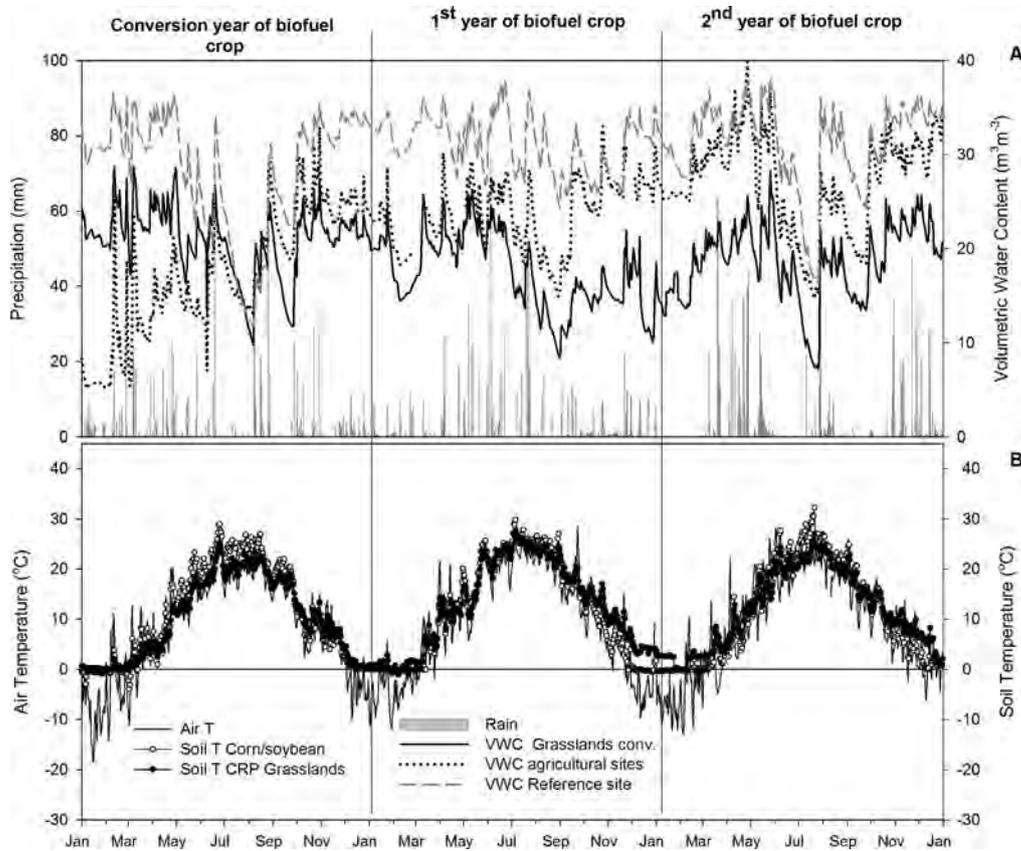
The 30-min mean flux of CO<sub>2</sub> was computed as the covariance of vertical wind speed and the concentration of CO<sub>2</sub>. Quality control measures before the mean calculation included (i) the removal of spikes >6 standard deviations from the 30-min mean through block averaging, (ii) humidity and pressure correction of the sonic temperature (Schotanus et al., 1983), and (iii) correction of the coordinate system by the planar fit method (Leuning, 2004; Wilczak et al., 2001), based on the entire year's mean wind data in all sites investigated using the EC processor software (Noormets et al., 2008; <http://research.eeescience.utoledo.edu/lees/ECP/ECP.html>). The 30-min mean fluxes were corrected for fluctuations in air density using the Webb–Pearman–Leuning expression (Webb et al., 1980), including the term for the warming of the IRGA above air

temperature (Grelle and Burba, 2007). In order to avoid the possible underestimation of fluxes during stable (non-turbulent) conditions at night, data with friction velocity ( $u^*$ ) threshold was derived separately for each year and each site and ranged from 0.17 to 0.10 m s<sup>-1</sup>. The  $u^*$  threshold was estimated using the procedure described in Reichstein et al. (2005). The amount of data removed through this screening procedure was 33% in 2009, 40% in 2011 and 36% in 2011.

For the estimation of the 30-min values of ecosystem respiration ( $R_{eco}$ ) and gross primary production (GPP), we used the marginal distribution sampling (MDS) method (Reichstein et al., 2005), implemented in [www.bgc-jena.mpg.de/~MDIwork/eddyproc/](http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/), (2013 version). This method was adopted by FLUXNET for standardized gap-filling and flux-partitioning techniques (Moffat et al., 2007; Papale et al., 2006). The CO<sub>2</sub> fluxes were gap-filled to calculate the cumulative NEP in 2009, 2010 and 2011, with the error propagated from the half-hourly averaged data into the annual uncertainties.

To assess the consistency of the EC measurements, we examined energy closure by the relationship between latent heat (LE) + sensible heat ( $H$ ) and net radiation ( $R_n$ ) – soil heat flux ( $G$ ) using all of the available half-hour measurements. Because the importance of canopy heat storage is expected to be relatively small in short canopies (Wilson et al., 2002; McCaughey, 1985; Moore and Fisch, 1986), this term was not included in the energy balance analysis.

The following micrometeorological variables were also measured above the canopy: air temperature ( $T_a$ ; °C) and relative humidity (RH; %) using temperature and relative humidity probes (CSI Model HMP45C), photosynthetically active radiation (PAR;  $\mu\text{mol quanta m}^{-2} \text{s}^{-1}$ ) using a LI-190SB light sensor (Li-Cor Biosciences), incoming and reflected solar radiation ( $\text{W m}^{-2}$ ) using four-way net radiometers (Model CNRI; Kipp & Zonen Bohemia NY USA), and precipitation ( $P$ ; mm) using tipping bucket rain gauges (model TE525WS-L; Texas Electronics, Dallas, TX, USA). The 30-min mean soil temperature ( $T_s$ ; °C) was measured at three different depths (2, 5, and 10 cm) using CS107 temperature probes (CSI USA). Soil volumetric water content (VWC; %) in the top 30 cm was



**Fig. 2.** Variation in precipitation, air temperature, soil temperature, and volumetric soil water content (VWC) averaged for the three sites in each land use type for 2009–2011. (A) Daily average precipitation (mm) and VWC ( $\text{m}^3 \text{m}^{-3}$ ); (B) Daily mean air and soil temperatures ( $^{\circ}\text{C}$ ). See Fig. 1 legend for crops grown during each phase.

measured using a vertically inserted Model CS616 Time Domain Reflectometer probe (CSI USA). Soil heat flux ( $G$ ;  $\text{W m}^{-2}$ ) was measured in three different positions using HFT3 flux plates (CSI USA).

### 2.3. Flux terminology

We adopted the flux terminology reported in Chapin et al. (2006). Briefly, net ecosystem exchange (NEE) is defined as the  $\text{CO}_2$  exchange with the atmosphere—the vertical and lateral  $\text{CO}_2$  flux between the ecosystem and the atmosphere integrated over a time-step of 30 min according to the eddy-covariance technique (Baldocchi, 2003). GPP represents the sum of gross carbon fixation by autotrophic organisms per unit of area and time. Ecosystem respiration ( $R_{\text{eco}}$ ) is the respiration of all organisms summed per unit of area and time. Net ecosystem production (NEP) is defined as the difference between GPP and  $R_{\text{eco}}$ , calculated from the cumulative NEE over time (e.g., months or years). In contrast to Chapin et al. (2006), however we assign a positive sign to net C emissions to the atmosphere and negative sign to the net C uptake from the atmosphere, following the atmospheric science convention.

To account for C removed in harvestable biomass we adjusted the NEP ( $\text{NEP}_{\text{adj}}$ ;  $\text{g C m}^{-2} \text{yr}^{-1}$ ) from measured NEP ( $\text{g C m}^{-2} \text{yr}^{-1}$ ) by adding the C content of biomass harvested by farming machinery ( $C_{\text{bio}}$ ;  $\text{g C m}^{-2} \text{yr}^{-1}$ ):

$$\text{NEP}_{\text{adj}} = \text{NEP} + C_{\text{bio}} \quad (1)$$

Carbon in the grain or grass biomass, representing organic C removed from the field in soybean, corn, and grasses by harvest, was calculated as:

$$C_{\text{bio}} = f_c \times Y \quad (2)$$

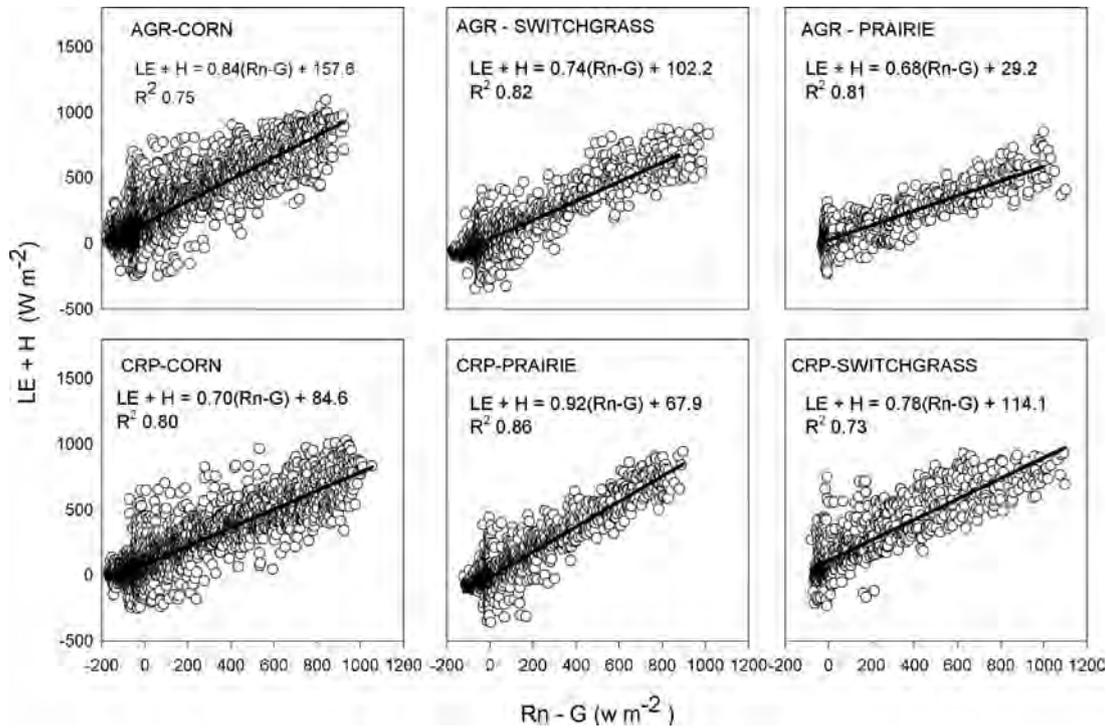
where  $f_c$  is measured C fraction in harvested biomass (either grain or harvestable cellulosic biomass) and  $Y$  is harvested biomass of either soybeans, corn, or grasses ( $\text{Table 3}$ ;  $\text{g m}^{-2} \text{yr}^{-1}$ ). Carbon fractions in the annual crop systems were  $0.53 \pm 0.05 \text{ g C g}^{-1}$  dry mass for soybean and  $0.44 \pm 0.02 \text{ g C g}^{-1}$  dry mass for corn. In the CRP-P and AGR-P systems, we used  $0.44 \pm 0.01 \text{ g C g}^{-1}$  dry mass the average C content of dominant plant species (*Rubekia hirta*, *S. nutans*, and *R. triloba*). In the CRP-S and AGR-S systems we used  $0.46 \text{ g C g}^{-1}$  dry mass of switchgrass (Lemus and Lal, 2005).

### 2.4. ANPP, harvested carbon, and soil properties

Aboveground net primary productivity (ANPP) was estimated by collection of the herbaceous biomass in ten  $1 \text{ m}^2$  subplots randomly distributed in each field at peak biomass in August (for protocols see: <http://lter.kbs.msu.edu/protocols/111>).

Plant components were dried in a forced-air oven at  $65^{\circ}\text{C}$  for at least four days to constant dry mass. Harvested carbon removed from the field was calculated from yield monitor data collected on the farm machinery.

The C content of harvested biomass (i.e., the C component of ANPP) and litter were measured from bulk plant samples that were weighed into tin foil cups in triplicate and analyzed for C and N using a Costech Model ECS 4010 CHNSO Analyzer (Costech Analytical Tech Inc., CA, USA). The carbon dioxide equivalents ( $\text{CO}_2\text{e}$ ) of fossil fuel offsets were calculated according to Gelfand et al. (2011), assuming  $32.7 \text{ g CO}_2\text{e MJ}^{-1}$  for corn grain ethanol,  $89.7 \text{ g CO}_2\text{e MJ}^{-1}$  for cellulosic biomass, and  $226.9 \text{ g CO}_2\text{e MJ}^{-1}$  for soybean-based biodiesel. For the calculation of C balances fossil fuel offsets were converted to  $\text{g C m}^{-2} \text{yr}^{-1}$ .



**Fig. 3.** Energy closure based on the relationships between latent energy + sensible heat flux (LE + H) and net radiation–soil heat flux ( $R_n - G$ ) during the 2010 growing season using the 30-min integrated measurements of each variable at the six biofuel crop sites.

Soil sampling was performed in May 2009 before soybean planting at ten georeferenced positions in each site. At each position, samples were collected from 0 to 25 cm depth with a root auger of 7.5 cm diameter (Eijkelkamp Agrisearch Equipment BV, Giesbeek, Netherlands). A total of 70 samples were collected. All samples were sieved (4 mm) to remove plant residues and stones and then oven dried to constant mass at 65 °C for at least a week. The samples were ground using a shatterbox (Shatterbox Model 8530, SPEX CertiPrep Metuchen, NJ USA) to pass through a 250- $\mu$ m sieve. Total C and N contents were measured as above.

**2.5. Statistical analysis**

All productivity parameters, soil properties, and microclimate conditions were tested using a one-way analysis of variance (ANOVA) and separation of means was subjected to Student’s *t* test using statistical software IBM SPSS Statistics 20. Statistical significance was defined as  $\alpha = 0.05$ .

**3. Results and discussion**

**3.1. Microclimate and energy balance**

Annual precipitation measured at the CRP-R site was 901 mm in 2009, 879 mm in 2010, and 1100 mm in 2011, with an average ( $\pm$ SD) of  $961 \pm 124 \text{ mm yr}^{-1}$  for the three years. Daily average precipitation (considering the days when the rain occurred) showed no significant difference ( $p = 0.47$ ) among years over the three years of data collection.

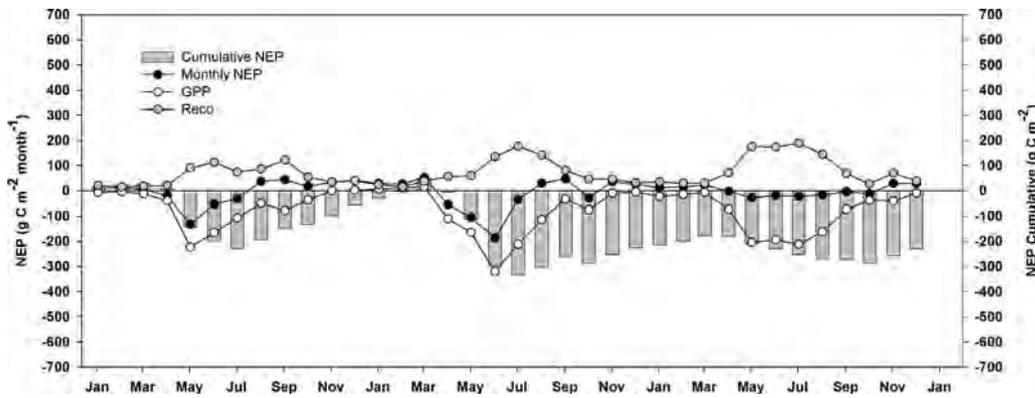
Prior to land conversion, the volumetric soil water content (SWC) of the top 30 cm was, on average, two times higher at the CRP sites than at the recently cropped (AGR) fields ( $0.23 \pm 0.02\%$  and  $0.11 \pm 0.05\%$  for the CRP and AGR sites, respectively) (Fig. 2A). After the conversion SWC was significantly higher ( $p < 0.001$ ) at the reference site compared to all other sites.

Mean annual air temperature of the CRP-R site was 8.6 °C in 2009, 10.0 °C in 2010, and 9.3 °C in 2011; soil temperature at 2.5 cm had patterns similar to air temperature (Fig. 2B).

**Table 2**  
Net ecosystem production (NEP), harvested biomass ( $C_{removed}$ ), and  $NEP_{adj}$  of the seven ecosystems over the three-year study period.

System	NEP			$C_{removed}^{\#}$			$NEP_{adj}$			Cumulative $NEP_{adj}^{\#}$
	2009 <sup>†</sup>	2010	2011	2009	2010	2011	2009	2010	2011	
	$\text{g C m}^{-2} \text{ yr}^{-1}$									
AGR-C	$-38 \pm 5$	$-280 \pm 18$	$135 \pm 22$	80	307	161	$42 \pm 5$	$27 \pm 18$	$296 \pm 22$	$364 \pm 29$
AGR-S	$-8 \pm 23$	$245 \pm 16$	$14 \pm 12$	56	–	139	$48 \pm 23$	$245 \pm 16$	$153 \pm 12$	$446 \pm 30$
AGR-P	$-63 \pm 28$	$141 \pm 24$	$-13 \pm 31$	100	–	55	$37 \pm 28$	$154 \pm 24$	$23 \pm 31$	$214 \pm 48$
CRP-C	$205 \pm 22$	$-261 \pm 28$	$-75 \pm 26$	56	462	303	$261 \pm 22$	$201 \pm 28$	$228 \pm 26$	$690 \pm 44$
CRP-S	$262 \pm 28$	$-130 \pm 29$	$-244 \pm 31$	81	–	201	$343 \pm 28$	$-130 \pm 29$	$-43 \pm 31$	$170 \pm 51$
CRP-P	$258 \pm 31$	$283 \pm 18$	$164 \pm 30$	82	–	98	$340 \pm 31$	$283 \pm 18$	$262 \pm 30$	$885 \pm 47$
CRP-R	$-35 \pm 8$	$-168 \pm 27$	$-3 \pm 9$	–	–	–	$-35 \pm 8$	$-168 \pm 27$	$-3 \pm 9$	$-206 \pm 30$

<sup>\*</sup> Cumulative  $NEP_{adj}$  was calculated as the sum of  $NEP_{adj}$  for years 2009–2011.  
<sup>#</sup>  $C_{removed}$  was calculated from machinery harvest and therefore has no replicates, i.e., represent total yield from an agricultural field measured according to standard agricultural practice by truck weighing.  
<sup>†</sup> 2009–Soybean year, 2010 and 2011 Corn, Switchgrass, and Prairie years, respectively. In 2010 oats were planted as a nurse crop into Switchgrass and Prairie fields.



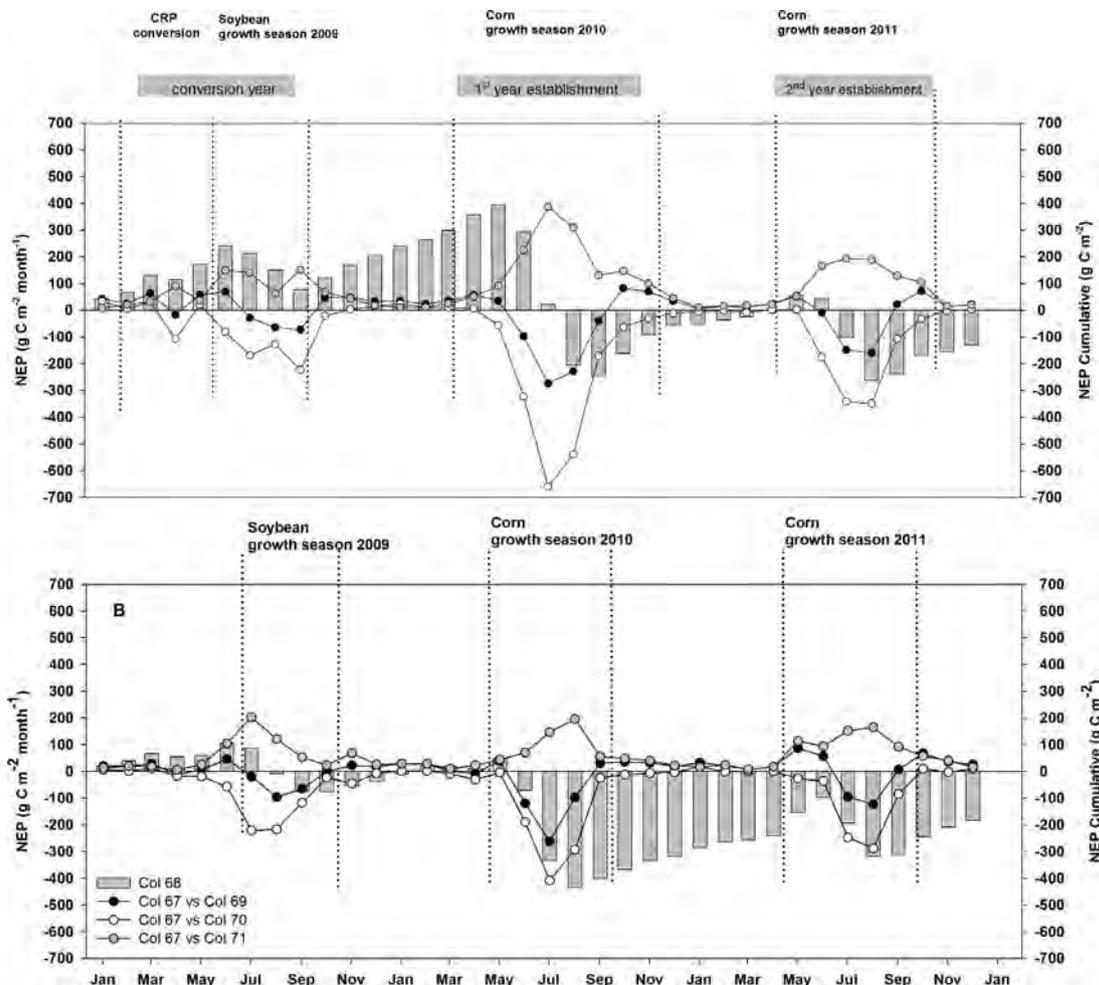
**Fig. 4.** Changes in monthly carbon uptake (GPP), ecosystem respiration ( $R_{eco}$ ), monthly net ecosystem production (NEP), and cumulative NEP at the CRP reference site during the three-year study period (2009–2011).

Energy closure, as indicated by the slope of these relationships in Fig. 3, varies from 0.68 to 0.92 among the crop systems. This range of values is close to that reported by Chen et al. (2009) for a similar low-stature grassland ecosystem in northern China and by Cava et al. (2008) for short-stature vegetation in southern Italy (0.75–0.89). The energy closure of conventional corn and soybean rotations in the Midwestern US ranged from 0.61 to 0.81 in soybean and from 0.68 to 0.78 in corn in a study by Ramirez et al. (2010), suggesting that our energy closures are comparable or better than

those reported for similar ecosystems studied within the FLUXNET community (Wilson et al., 2002).

### 3.2. C balances at the CRP reference site

The annual NEP at the CRP-R site was  $-35 \pm 8 \text{ g C m}^{-2} \text{ yr}^{-1}$  in 2009,  $-168 \pm 27 \text{ g C m}^{-2} \text{ yr}^{-1}$  in 2010, and  $-3 \pm 9 \text{ g C m}^{-2} \text{ yr}^{-1}$  in 2011, with net C uptake from April through July (Table 2, Fig. 4). The maximum monthly NEP was found in May for 2009



**Fig. 5.** Changes in monthly NEP, GPP,  $R_{eco}$ , and the cumulative NEP of the corn bioenergy systems over the three-year study period (2009–2011). (A) Site converted from CRP grasslands; (B) site converted from recently cropped fields.

**Table 3**  
Annual aboveground net primary productivity (ANPP), yield, litter stocks, fossil fuel offset credits, and net ecosystem C balances for the seven bioenergy systems over the three-year study period.

System	ANPP g dry mass (m <sup>-2</sup> yr <sup>-1</sup> )		Harvested yield of crops <sup>§</sup> g biomass (m <sup>-2</sup> yr <sup>-1</sup> )		Surface litter <sup>†</sup> g dry mass (m <sup>-2</sup> yr <sup>-1</sup> )		Fossil fuel offset credits <sup>‡</sup> (gC m <sup>-2</sup> yr <sup>-1</sup> )		Net C balance <sup>*</sup>	
	2009	2010	2009	2010	2009	2010	2009	2010	2009	2010
AGR-C	516 (36)	1802 ± 159	173	833	223 ± 15	437	76	36 ± 5	76	30
AGR-S	366 (50)	155 ± 14	126	–	121 ± 24	302	53	68 ± 8	53	59
AGR-P	514 (46)	280 ± 28	218	–	158 ± 14	124	95	51 ± 4	95	24
CRP-C	561 (32)	2368 ± 118	123	1256	418 ± 29	822	54	156 ± 25	54	86
CRP-S	543 (36)	407 ± 23	177	–	551 ± 25	437	77	82 ± 18	77	86
CRP-P	563 (24)	403 ± 35	179	–	450 ± 23	221	78	75 ± 15	78	43
CRP-R	386 (13)	556 ± 44	–	–	178 ± 17	–	–	219 ± 49	–	–

\* Net balance is calculated as sum of the Cumulative NEP<sub>adj</sub> (Table 2) and sum of the Fossil fuel offset credits for years 2009–2011.

† Surface litter in 2009 at sites converted from CRP was predominantly bromegrass killed during conversion, 2010 was grass and soybean stover, and 2011 was grass, soybean stover, and 2010 was corn stover. Surface litter at sites converted from agriculture was similar, except for the absence of killed grass biomass.

‡ Fields were not harvested during 2010.

§ Agronomic yields are given at standard moisture, 15.5% and 13% for corn and soybean, respectively; the cellulosic crops yields are given as dry mass. The agronomic yields were harvested by farm machinery on per field basis and weighed in a truck according to standard agricultural practice.

<sup>a</sup> Fossil fuel offset credits represent C sequestration from the atmosphere, i.e., with a negative sign.

(–132 gC m<sup>-2</sup> month<sup>-1</sup>), June for 2010 (–186 gC m<sup>-2</sup> month<sup>-1</sup>), and May for 2011 (–28 gC m<sup>-2</sup> month<sup>-1</sup>). During the 2009 growing season (defined as months with net C uptake), from April to July) ecosystem respiration,  $R_{eco}$ , ranged from 20 gC m<sup>-2</sup> month<sup>-1</sup> in April to 74 gC m<sup>-2</sup> month<sup>-1</sup> in July, while it went from 55 and 176 gC m<sup>-2</sup> month<sup>-1</sup> in April and July in 2010 and 70 to 188 gC m<sup>-2</sup> month<sup>-1</sup> in April and July 2011. GPP for the same periods varied from –40 to –106 gC m<sup>-2</sup> month<sup>-1</sup> in 2009, –110 to –212 gC m<sup>-2</sup> month<sup>-1</sup> in 2010, and –73 to –211 gC m<sup>-2</sup> month<sup>-1</sup> in 2011 (Fig. 4).

The NEP of this grassland ecosystem exhibited large variability over time, primarily due to the intra-annual variability of water availability during the growing season; analysis of variance indicates a significant difference ( $F=7.374$   $p<0.001$ ) in the growing-season rainfall among the three years. The growing season rainfall was 358 mm in 2009, 568 mm in 2010, and 276 mm in 2011.

Regression analysis indicated that monthly growing season precipitation explained 41% of the variability ( $p=0.035$ ). Inter-annual variability of water availability often affects inter-annual variability in C sequestration in temperate regions (Zhang et al., 2010b).

Large inter-annual variability in NEP is common in grassland ecosystems, (e.g., Gilmanov et al., 2010; Meyers, 2001; Flanagan et al., 2002; Ma et al., 2007; Nagy et al., 2007; Aires et al., 2008). Overall, grasslands tend to be C sinks during years with favorable precipitation and C sources in dry years (Zhang et al., 2010b). Our measurements show that the CRP-R grassland was still sequestering carbon, most likely into the soil C pool, since aboveground vegetation is recycled yearly. However, the rates of soil C sequestration are already exhibiting signs of equilibration (Gelfand et al., 2011). It can be expected that once soil C equilibrium is reached in the future, the C dynamics will be dominated by growing season precipitation and other environmental factors and not soil C accumulation

### 3.3. The corn biofuel system

The conversion of the CRP grassland into no-till soybean cropland (CRP-C) induced a large C emission resulting in a cumulative NEP of 205 ± 22 gC m<sup>-2</sup> yr<sup>-1</sup> in the conversion year (2009) exclusive of harvest losses (Table 2, Fig. 5A). The annual NEP in 2010, following conversion to no-till corn was –261 ± 26 gC m<sup>-2</sup> yr<sup>-1</sup> exclusive of harvest losses and despite high ANPP (2.4 kg dry matter m<sup>-2</sup> yr<sup>-1</sup>, Table 3), with a peak C uptake of –274 gC m<sup>-2</sup> month<sup>-1</sup> in August (Fig. 5A, first year establishment). During 2011, the annual NEP was further reduced to –75 ± 26 gC m<sup>-2</sup> yr<sup>-1</sup>, which was almost three times lower than in 2010 (Table 2). Large reductions of annual NEP during 2011 was not associated with large reduction in ANPP, which was only 30% lower than that in 2010 (1.6 kg dry matter m<sup>-2</sup> yr<sup>-1</sup>, Table 3). During the second year after conversion (2011), the peak C uptake rate of –159 gC m<sup>-2</sup> month<sup>-1</sup> was observed in August, as it was in 2010 (Fig. 5A).

Large discrepancies between C uptake into ANPP and annual NEP during 2010 and 2011 were potentially driven by changes in the C loads into the ecosystem. During the conversion year (2009) annual NEP was dominated by C flux from the decomposition of grass biomass killed during conversion (Zenone et al., 2011; Gelfand et al., 2011). While the C flux from grass decomposition declined gradually in the two subsequent years, high net productivity in 2010 (ANPP, Table 3) increased the amount of stover left in the field and subject to decomposition during the following year (stover biomass was ~50% of total corn ANPP). Most likely the decomposition of this stover biomass contributed to the reduction in annual NEP in 2011 by masking high C uptake (i.e., high ANPP and low NEP).

The NEP of the AGR-C site was lower than for the CRP-C site, varying between  $-38 \pm 5$ ,  $-280 \pm 18$ , and  $135 \pm 22 \text{ g C m}^{-2} \text{ yr}^{-1}$  in 2009, 2010, and 2011, respectively. AGR-C had a 2010 peak of C uptake in July of  $-262 \text{ g C m}^{-2} \text{ month}^{-1}$  and a 2011 peak in August of  $-123 \text{ g C m}^{-2} \text{ month}^{-1}$ . The cumulative NEP over the three years was  $-183 \pm 29 \text{ g C m}^{-2}$  (Fig. 5B).

In the AGR-C system the NEP drivers were similar to those in the CRP-C system, except for the lack of C fluxes associated with killed grasses. In 2009 the NEP of the AGR-C system was driven by soybean C balance. In 2010, similar to the CRP-C system, the NEP of the AGR-C system was driven mostly by corn ANPP.

In 2011, the increase in total ecosystem C load due to the change in rotation from corn–soybean to continuous corn, caused a subsequent increase in ecosystem C load due to higher corn than soybean productivity in 2010 that likely enhanced the decomposition flux, which, together with lower 2010 productivity, caused a large positive NEP of  $135 \pm 22 \text{ g C m}^{-2} \text{ yr}^{-1}$  (Tables 2 and 3).

In addition to the large NEP differences, the two corn sites with different land use histories showed significant difference in  $R_{\text{eco}}$  mean daily values for  $R_{\text{eco}}$  were 5.1 and  $2.7 \text{ g C m}^{-2}$  at CRP-C in 2010 and 2011, respectively. Meanwhile, the AGR-C site exhibited an almost three fold lower  $R_{\text{eco}}$  of  $1.9 \text{ g C m}^{-2}$  in 2010 and a slightly lower  $R_{\text{eco}}$  of  $2.2 \text{ g C m}^{-2}$  in 2011 ( $F=4.70$ ,  $p=0.030$ ). The overall differences in  $R_{\text{eco}}$  resulted in an almost two-fold larger accumulated soil C flux during the growing seasons across 2010 and 2011 in the CRP-C system:  $2129$  vs.  $1229 \text{ g C m}^{-2}$  for CRP-C and AGR-C, respectively. The two sites also exhibited slight differences in timing of peak soil C fluxes whereas at the CRP-C site peak fluxes were measured in July of both years and the peak soil C fluxes of AGR-C system were measured during August (Fig. 5A and B). The greater  $R_{\text{eco}}$  of the CRP-C site was likely due to its larger soil organic matter content as well as its land use history (Tables 1 and 3). The CRP-C site also showed a larger GPP during the growing season:  $-1812$  and  $-1002 \text{ g C m}^{-2}$  for 2010 and 2011, respectively, compared to the  $-935$  and  $-676 \text{ g C m}^{-2}$  in 2010 and 2011 of the AGR-C site (Fig. 5).

The comparison between GPP obtained with the EC (30-min intervals) and with the LI-cor 6400 confirmed this difference ( $R^2 0.92$   $p < 0.0001$ ) data not shown.

While cumulative NEP measured over the three years (2009–2011) exhibited a net C uptake of  $-131 \pm 44 \text{ g C m}^{-2}$  and  $-183 \pm 29 \text{ g C m}^{-2}$  for CRP-C and AGR-C, respectively, in order to calculate C balances over the three-year period the off-site respiration or combustion of harvested biomass and grain needs to be considered (Zeeman et al., 2010; Gelfand et al., 2011). Both systems were harvested for soybean or corn grain at the end of the growing seasons, i.e., C incorporated into harvested grain would be converted to  $\text{CO}_2$  offsite (Gelfand et al., 2011) and thus the C balance of ecosystems must be adjusted for harvested C ( $C_{\text{removed}}$ , Table 2). After this adjustment, both the AGR-C and CRP-C systems exhibited large net emissions of  $364 \pm 29$  and  $690 \pm 44 \text{ g C m}^{-2}$ , respectively (cumulative NEP<sub>adj</sub>, Table 2). These large emissions over the course of their first three conversion years resulted from both high  $R_{\text{eco}}$  and the biomass harvested and transported out of the field.

If harvested biomass were to be used for fuel rather than food, the carbon balance should also be credited for displacing atmospheric  $\text{CO}_2$  that would have otherwise been released from the equivalent fossil fuel use. Using published values of  $32.7 \text{ g CO}_2 \text{ e MJ}^{-1}$  for the fossil fuel offset credit associated with production of corn ethanol (Gelfand et al., 2011) and corn grain yields of the CRP-C site (total harvested corn grain of 2078 g m over two corn years; Table 3), we calculate the total offsets due to corn-ethanol production as  $142 \text{ g C m}^{-2}$  which together with fossil fuel offset credits generated by first-year biodiesel production from the soybean harvest ( $54 \text{ g C m}^{-2}$ ; Table 3) would reduce the total C emissions to  $494 \pm 44 \text{ g C m}^{-2}$  for the first three years after

conversion of these fields from CRP to the current crop rotations. Similarly, inclusion of fossil fuel carbon offsets into the C balance of the AGR-C system would decrease the three-year balance from  $364 \pm 29 \text{ g C m}^{-2}$  to  $201 \pm 29 \text{ g C m}^{-2}$  (Tables 2 and 3).

Land-use history thus appears to have played a significant role in the magnitude of ANPP which, in turn, contributes differences in  $R_{\text{eco}}$  and ultimately NEP. ANPP at the CRP-C was greater than that at AGR-C (Table 2) most likely due higher soil fertility (i.e., higher soil organic matter) of the CRP-C site (Table 1; Zenone et al., 2011).

### 3.4. The switchgrass biofuel system

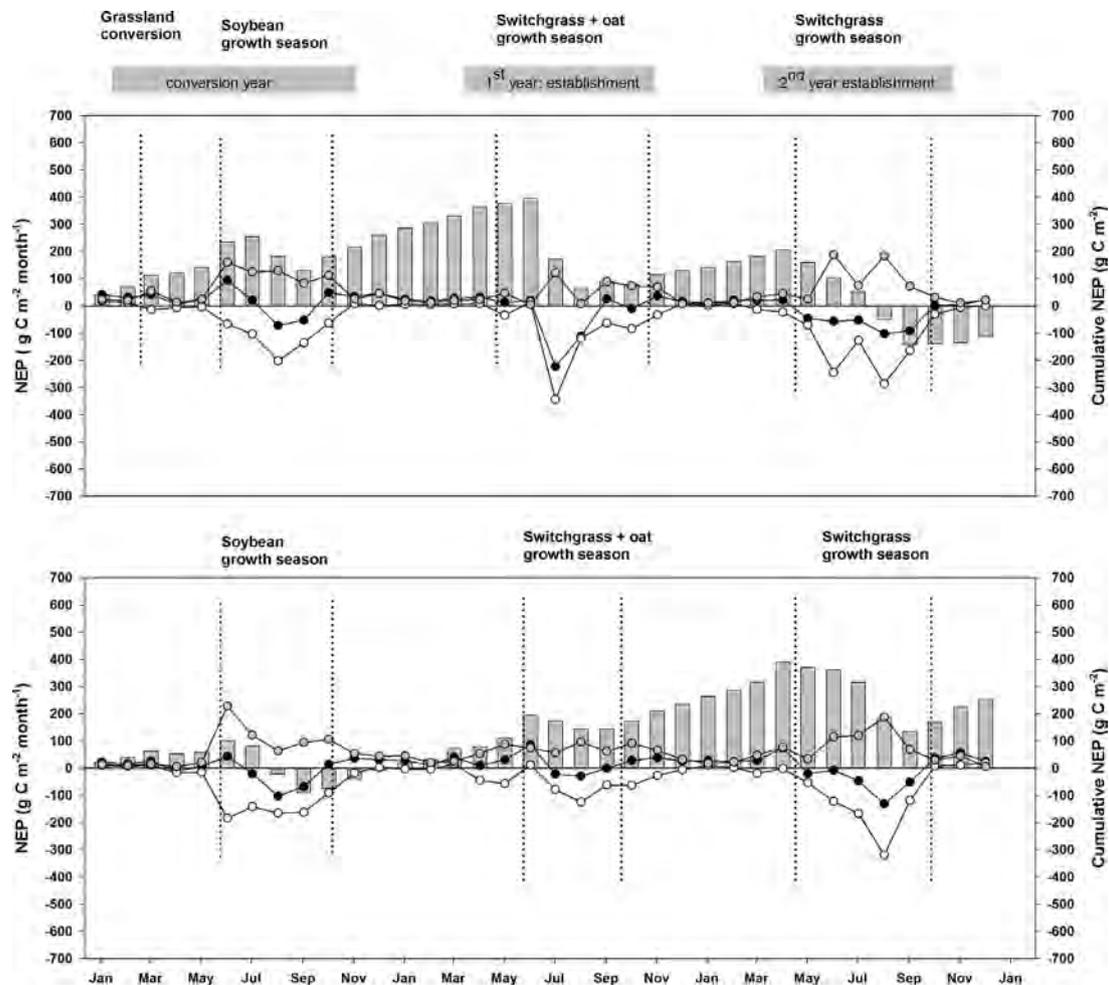
Conversion of the CRP grassland into no-till soybean resulted in a large C emission during the conversion year in 2009 (Fig. 6A). In the CRP sites, the establishment of CRP-S in 2010 resulted in an annual NEP of  $-130 \pm 29 \text{ g C m}^{-2} \text{ yr}^{-1}$  with a peak C uptake of  $-223 \text{ g C m}^{-2} \text{ month}^{-1}$  in July. During the second year (2011), the annual NEP was  $-244 \pm 31 \text{ g C m}^{-2} \text{ yr}^{-1}$ . Net C uptake was  $-45 \text{ g C m}^{-2}$  in May and  $-91 \text{ g C m}^{-2}$  in September with a peak of  $-102 \text{ g C m}^{-2}$  in August 2011. The Cumulative NEP for the CRP-S site over the three-year study was  $-112 \pm 51 \text{ g C m}^{-2}$ . Considering the increase in ANPP over the course of the establishment of switchgrass on the site (Table 3), the relatively low total NEP is likely explained by the land-use history and soil C of the site, similar to the corn biofuel systems. Temporal changes of GPP showed a peak of  $-343 \text{ g C m}^{-2} \text{ month}^{-1}$  in July 2010 and  $-286 \text{ g C m}^{-2} \text{ month}^{-1}$  in August 2011. The cumulative GPP was  $-627 \text{ g C m}^{-2} \text{ yr}^{-1}$  and  $-955 \text{ g C m}^{-2} \text{ yr}^{-1}$  during the first and second post conversion years, respectively.  $R_{\text{eco}}$  showed a similar temporal change to GPP with cumulative values of  $496 \text{ g C m}^{-2} \text{ yr}^{-1}$  and  $710 \text{ g C m}^{-2} \text{ yr}^{-1}$  for the first and second years, respectively (Fig. 6A).

Three main factors influenced the NEP of the CRP site: (a) overall low productivity of the site during the establishment year, perhaps because a larger proportion of the productivity was being allocated belowground (Anderson-Teixeira et al., 2013), (b) enhanced SOC oxidation induced by conversion, and (c) phenology of switchgrass growth. During the establishment year (2010), the ANPP of switchgrass was very low and oat productivity, together with switchgrass belowground NPP, dominated C exchange in the system ( $C_{\text{removed}}$ ; Tables 2 and 3). In 2011, switchgrass fully established ( $C_{\text{removed}}$ ; Table 2). In 2011, switchgrass became fully established ( $C_{\text{removed}}$ ; Table 2) and NEP followed productivity (ANPP).

Overall, NEP patterns in the AGR-S systems were similar to those in the CRP-S system. The differences between the two systems were driven by productivity, which was lower at the AGR-S site. Annual NEP in the AGR-S system was  $-8 \pm 23 \text{ g C m}^{-2} \text{ yr}^{-1}$  and  $14 \pm 12 \text{ g C m}^{-2} \text{ yr}^{-1}$ , respectively, and highly positive ( $245 \pm 16 \text{ g C m}^{-2}$ ) during 2010, prior to establishment of the switchgrass stand. Mostly positive NEP across the three study years resulted in a cumulative NEP of  $250 \pm 30 \text{ g C m}^{-2}$ , excluding harvested biomass.

Peak GPP occurred in August for both years, with  $-124$  and  $-318 \text{ g C m}^{-2} \text{ month}^{-1}$  for 2010 and 2011, respectively.  $R_{\text{eco}}$  showed a similar pattern with an emission peak in August of  $95$  and  $187 \text{ g C m}^{-2} \text{ month}^{-1}$  for 2010 and 2011, respectively (Fig. 6B). Most likely, the NEP difference between the two switchgrass sites,  $-112 \pm 51$  vs.  $250 \pm 30 \text{ g C m}^{-2}$  for CRP-S and AGR-S, respectively, also driven by the soil fertility differences, reflected by soil C differences, was similar to the two corn biofuel systems (CRP-C and AGR-C). The AGR-S had the lowest soil organic matter content in comparison to other sites (Zenone et al., 2011; Bhardwaj et al., 2011).

Inclusion of the harvested grain and cellulosic biomass into the C balance of the sites resulted in positive C balances (i.e., net emissions to the atmosphere) in both sites ( $170 \pm 51$  and  $446 \pm 30 \text{ g C m}^{-2}$  for CRP-S and AGR-S, respectively; Table 2).



**Fig. 6.** Changes in monthly NEP, GPP,  $R_{eco}$ , and the cumulative NEP of the switchgrass bioenergy systems over the three-year study period (2009–2011). (A) Site converted from CRP grasslands; (B) Site converted from recently cropped fields.

However, as for the corn systems, the end use of harvested biomass has a strong influence on the net C balance of the switchgrass ecosystems. If the harvested biomass were to be used for cellulosic ethanol production, it would generate fossil fuel offset credits of  $86$  and  $59 \text{ g C m}^{-2}$  for CRP-S and ARG-S, respectively.

These credits, together with first-year credits from soybean biodiesel production ( $77$  and  $53 \text{ g C m}^{-2}$  for CRP-S and AGR-S, respectively; Table 3) would reduce the three-year C emissions to  $8 \pm 51$  and  $334 \pm 30 \text{ g C m}^{-2}$  for CRP-S and AGR-S, respectively (Tables 2 and 3). This makes the CRP-S system virtually neutral in regard to atmospheric  $\text{CO}_2$  if used for cellulosic feedstocks production. We would expect both systems to exhibit negative total C balances if used as cellulosic biofuel feedstocks however these would be at different rates. Lower biomass production in switchgrass (and therefore lower ethanol yield) is common during the initial two to three years post-establishment, before the crop fully matures (Parrish and Fike, 2005).

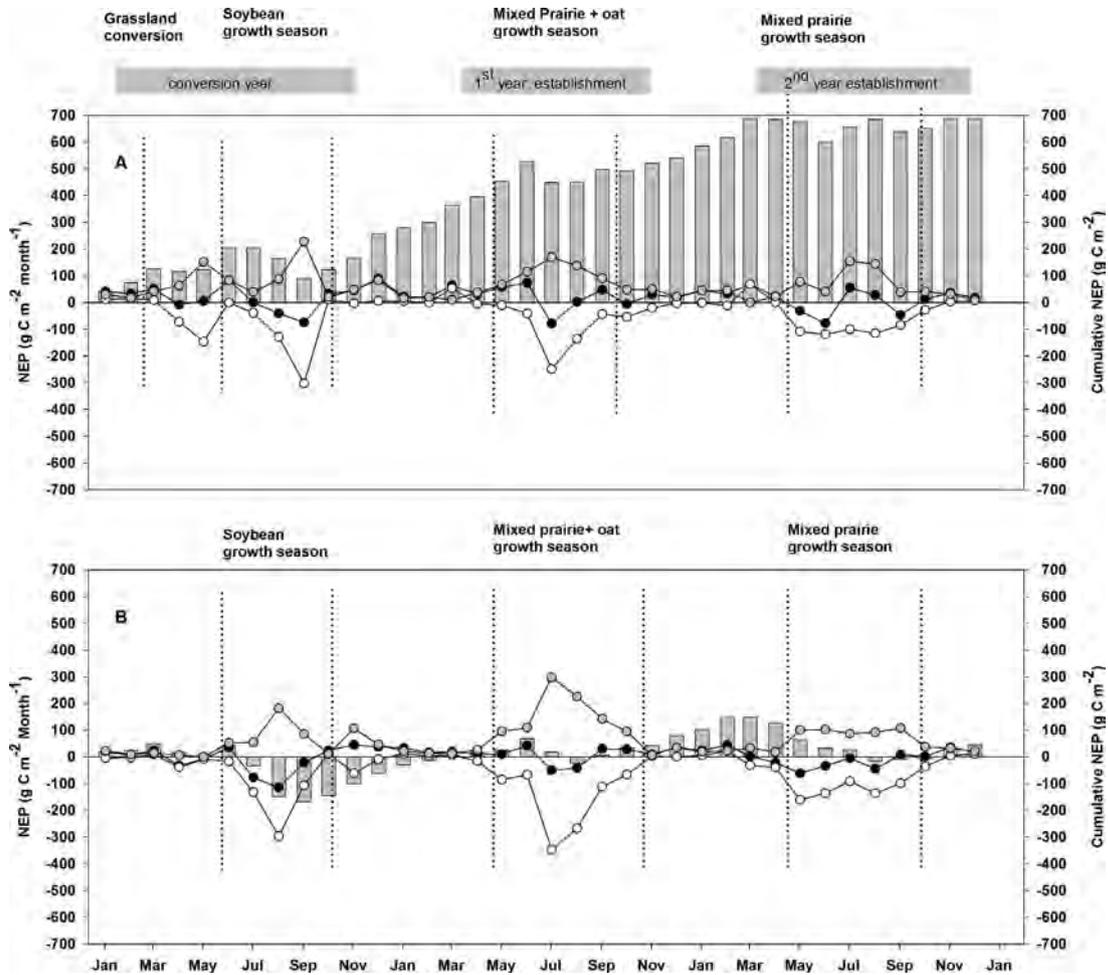
### 3.5. The mixed prairie biofuel system

The CRP-P site emitted a significant amount of C over the three-year period, with a cumulative NEP of  $698 \pm 47 \text{ g C m}^{-2}$ . Annual NEP values were  $258 \pm 31$ ,  $283 \pm 18$ , and  $164 \pm 30 \text{ g C m}^{-2} \text{ yr}^{-1}$  for 2009, 2010, and 2011, respectively. This dynamic is explained by the presence of the oat nurse crop and low ANPP of the site (Table 3). During 2009, high positive NEP ( $258 \pm 31 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) was driven by the balance between soybean productivity and decomposition

of the biomass left on the ground after the conversion, which was similar to other systems converted from CRP grassland into production. In 2010, positive NEP was due to the balance between the productivity of oats, the establishment of mixed prairie plants, and the reduction of the decomposition flux (Table 2). In 2011, increasing ANPP of the mixed prairie grasses, together with the absence of oats and further reduction of the earlier decomposition flux, resulted in a large reduction of NEP (to  $\sim 50\%$  of 2010 values). The presence of oats as a nurse crop induced a peak NEP in July ( $-78 \text{ g C m}^{-2} \text{ month}^{-1}$ ) during 2010 while there was a peak NEP in June during 2011 at  $-77 \text{ g C m}^{-2} \text{ month}^{-1}$  associated with prairie establishment and shift in C uptake phenology.

The temporal trend of GPP in the mixed prairie followed changes in the dominant plant populations. In 2010 the peak gross C uptake occurred in July–August ( $-248$  and  $-135 \text{ g C m}^{-2} \text{ month}^{-1}$ , respectively). These uptake dynamics may be explained by peak productivity of the oat nurse crop in July and of the prairie grasses in August. In 2011, temporal changes in GPP were more tempered, with values from  $-109 \text{ g C m}^{-2} \text{ month}^{-1}$  in May to  $-27 \text{ g C m}^{-2} \text{ month}^{-1}$  in October, related to the GPP dynamics of the prairie species.  $R_{eco}$  showed a similar pattern with July peaks of  $169$  and  $155 \text{ g C m}^{-2} \text{ month}^{-1}$  in 2010 and 2011, respectively (Fig. 7A).

NEP in AGR-P was  $65 \pm 48 \text{ g C m}^{-2}$  over the three-year study period. Annual NEP was  $-63 \pm 28 \text{ g C m}^{-2} \text{ yr}^{-1}$  during the conversion year (2009),  $141 \pm 24 \text{ g C m}^{-2} \text{ yr}^{-1}$  during the first year post establishment (2010), and  $-13 \pm 31 \text{ g C m}^{-2} \text{ yr}^{-1}$  during the second year post establishment (2011). Overall the NEP dynamics of the AGR-P



**Fig. 7.** Changes in monthly NEP, GPP,  $R_{eco}$ , and the cumulative NEP of the mixed-prairie bioenergy systems over the three-year study period (2009–2011). (A) Site converted from CRP grasslands; (B) site converted from recently cropped field.

system can be explained by the interplay among soybean, nurse crop productivity, and prairie grasses, and the lack of the decomposition C flux of the sites converted from the CRP grassland, making the overall three-year NEP balance of the system less positive than that of the CRP-P site ( $65 \pm 28$  vs.  $698 \pm 47$   $\text{g C m}^{-2} \text{ yr}^{-1}$ ).

Seasonal changes in NEP at the AGR-P site were similar to the CRP-P site, with peak values of  $-50$   $\text{g C m}^{-2} \text{ month}^{-1}$  in July for 2010 and  $-44$   $\text{g C m}^{-2} \text{ month}^{-1}$  in August for 2011. The temporal trend of GPP in 2010 was also similar to that in CRP-P and was characterized by a remarkable peak of  $-347$   $\text{g C m}^{-2} \text{ month}^{-1}$  in July, driven by oat productivity. The same month also had the largest  $R_{eco}$  of  $297$   $\text{g C m}^{-2} \text{ month}^{-1}$ . In 2011, the seasonal changes of GPP and  $R_{eco}$  were also consistent with those of the CRP-P system and represented a shift in the dominant plant populations (i.e., uptake phenology): GPP ranged from  $-161$   $\text{g C m}^{-2} \text{ month}^{-1}$  in May to  $-35$   $\text{g C m}^{-2} \text{ month}^{-1}$  in October, while  $R_{eco}$  ranged from  $100$   $\text{g C m}^{-2} \text{ month}^{-1}$  to  $37$   $\text{g C m}^{-2} \text{ month}^{-1}$  during the same period. Similarly to other systems, adjusting NEP for harvested C results in large positive balances (i.e., net C release to the atmosphere) of  $885 \pm 47$  and  $220 \pm 48$   $\text{g C m}^{-2}$  for CRP-P and AGR-P, respectively (Cumulative NEP<sub>adj</sub>; Table 2). However, use of the biomass for renewable fuel production would reduce net C release by 14% and  $\sim 50\%$  in the CRP-P and AGR-P systems, respectively, and result in less positive net C balances of  $764 \pm 47$  and  $114 \pm 48$   $\text{g C m}^{-2}$  for the AGR-P and CRP-P systems, respectively. The presence of oats during establishment contributed strongly to the first-year C balances and likely induced strong competition, leading to lower productivity of the perennial species.

A recent study on the establishment of perennial grasses on a more fertile soil in southern Minnesota (Mangan et al., 2011) found a higher productivity of  $120$ – $600$   $\text{g C m}^{-2}$  during the first year of cultivation. Nevertheless, during the second year after the establishment, due to the absence of competition with the annual species, a larger leaf area index, and a more-developed root system, we expect larger biomass production that potentially will induce a net C sequestration.

### 3.6. Synthesis and comparison of the ecosystem C dynamics during the conversion phase

We can identify land-use history, the amount and temporal distribution of precipitation, and the end-use of biomass as the three main factors that defined ecosystem C dynamics of the conversion year and establishment phases in all studied treatments.

The corn systems were characterized by substantial inter-annual differences in NEP between 2010 and 2011 (Table 2). Productivity was higher in the system converted from the CRP grassland (i.e., it was affected by land use history which in turn affected soil fertility). Higher productivity in 2010 than in 2011 resulted in large amounts of stover C flux into the system and therefore larger decomposition C fluxes that masked sequestration in 2011, while higher productivity in the CRP system caused more negative total C balance.

The inter-annual differences in productivity were due to the different amounts of precipitation that occurred during the growing season (May–September) in 2010 and 2011. These reductions in

productivity (52% in AGR-C and 46% in CRP-C in 2011 compared to 2010) explain the temporal NEP trend in both systems.

Similarly, land use history defined differences in the switchgrass systems. Both NPP and NEP were lower during the second post-establishment year in AGR-S compared to CRP-S systems, potentially due to the lower soil organic matter and lower fertility (Bhardwaj et al., 2011)

The ANPP of CRP-S was significantly higher in 2010 and 2011 leading to the large NEP differences between the sites.

Interplay between poor establishment and decomposition meant that C flux defined C dynamics in the AGR-P and CRP-P systems. ANPP of the CRP-P system was similar across the three studied years and therefore the NEP of the system remained positive (i.e., net C flux into the atmosphere), although less so in the second post-establishment year. In contrast, productivity and decomposition C flux of the AGR-P site were lower overall and therefore resulted in less positive cumulative NEP.

The end use of harvested biomass for biofuels resulted in fossil fuel offset credits that had a major impact on the total net C balance of all of these production systems. Adding the biomass C that was harvested and removed from the field to the NEP measured by eddy covariance resulted in large CO<sub>2</sub> emissions following conversion of both CRP and AGR into the biofuel feedstock production systems. Accounting for fossil fuel offset credits generated from harvested biomass completely attenuated these emissions in the CRP-s site and partially attenuated emissions in other converted sites.

#### 4. Conclusions

In this study we examined the C balances of three different bioenergy crops production systems (corn, switchgrass and mixed prairie) developed from two different land use histories (former CRP grassland and conventional agricultural row crops). C balances by the end of the first two years of production and the preceding conversion year were under the strong influence of C lost during the conversion year as well as the current year C balance including harvested biomass;

We found the soil organic carbon legacy due to the different land use histories a fundamental factor (along with management) that drives the C balances in the years after conversion.

The carbon lost during the conversion year cannot be detected by sampling of soil carbon because of the large size and high spatial variability of soil organic matter stocks (Kravchenko and Robertson, 2011), nor could it have been inferred by simply measuring the biomass production before and after the conversion. The eddy covariance approach was able to detect the short-term C changes necessary to evaluate net C balances in converted biofuel systems.

Using measurements from seven eddy flux towers augmented with measurements of other components of the C balance, we provide robust estimation of the consequences of land-use change from different historical land uses on ecosystem C flows. We emphasize importance of studying ecosystem C balance across right temporal and spatial scales, including, in case of land use change, the initial conversion and post-establishment period.

#### Acknowledgments

Financial support for this work was provided by the DOE Office of Science (DE-FC02-07ER64494) and Office of Energy Efficiency and Renewable Energy (DE-AC05-76RL01830), the U.S. National Science Foundation LTER program (DEB 1027253), and MSU AgBioResearch. We thank K. Kahmark, M. Deal, C. Shao, and J. Xu for help with the EC towers and L. Delp Taylor for editorial assistance. J. Bronson and J. Simmons assisted with field data acquisition. We also thank A. Noormets for use of the EC processor software

package and other LEES Lab members for collecting ancillary data at the tower sites.

#### References

- Aires, L.M.L., Pio, C.A., Pereira, J.S., 2008. Carbon dioxide exchange above a Mediterranean C3/C4 grassland during two climatologically contrasting years. *Global Change Biol.* 14, 539–555.
- Anderson-Teixeira, K., Masters, M., Black, C., Zeri, M., Hussain, M., Bernacchi, C., DeLucia, E., 2013. Altered belowground carbon cycling following land-use change to perennial bioenergy crops. *Ecosystems* 16, 508–520.
- Baldocchi, D.D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. *Global Change Biology* 9, 1–24.
- Bhardwaj, A.K., Zenone, T., Jasrotia, P., Robertson, G.P., Chen, J., Hamilton, S.K., 2011. Water and energy footprints of bioenergy crop production on marginal lands. *Global Change Biol. Bioenergy* 3, 208–222.
- Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., Smith, B., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biol.* 13, 679–706.
- Cava, D., Contini, D., Donateo, A., Martano, P., 2008. Analysis of short-term closure of the surface energy balance above short vegetation. *Agric. For. Meteorol.* 148, 82–89, 3.
- Chapin, F.S., Woodwell, G.M., Randerson, J.T., Rastetter, E.B., Lovett, G.M., Baldocchi, D.D., Clark, D.A., Harmon, M.E., Schimel, D.S., Valentini, R., Wirth, C., Aber, J.D., Cole, J.J., Goulden, M.L., Harden, J.W., Heimann, M., Howarth, R.W., Matson, P.A., McGuire, A.D., Melillo, J.M., Mooney, H.A., Neff, J.C., Houghton, R.A., Pace, M.L., Ryan, M.G., Running, S.V., Sala, O.E., Schlesinger, W.H., Schulze, E.-D., 2006. Reconciling Carbon-cycle Concepts. Terminology, and Methods *Ecosystems* 9, 1041–1050.
- Chen, S., Chen, J., Lin, G., Zhang, W., Miao, H., Wei, L., Huang, J., Han, X., 2009. Energy balance and partition in Inner Mongolia steppe ecosystems with different land use types. *Agric. For. Meteorol.* 149, 1800–1809.
- Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P., 2008. Land clearing and the biofuel carbon debt. *Science* 319, 1235–1238.
- Feddema, J., Oleson, K., Bonan, G., Mearns, L., Washington, W., Meehl, G., Nychka, D., 2005a. A comparison of a GCM response to historical anthropogenic land cover change and model sensitivity to uncertainty in present-day land cover representations. *Clim. Dyn.* 25, 581–609.
- Flanagan, L.B., Wever, L.A., Carlson, J.P., 2002. Seasonal and interannual variation in carbon dioxide exchange and carbon balance in a northern temperate grassland. *Global Change Biol.* 8, 599–615.
- Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. *Science* 309, 570–574.
- Follett, R., Varvel, G.E., Kimble, J.M., Vogel, K.P., 2009. No-till corn after bromegrass: effect on soil carbon and soil aggregates. *Agron. J.* 101, 261–268.
- Gelfand, I., Zenone, T., Jasrotia, P., Chen, J., Hamilton, S.K., Robertson, G.P., 2011. Carbon debt of CRP grasslands converted to bioenergy production. *PNAS* 108, 13864–13869.
- Gilmanov, G.T., Aires, L., Barcza, Z., Baron, V.S., Belelli, L., Beringer, J., Billesbach, D., Bonal, D., Bradford, J., Ceschia, E., Cook, D., Corradi, C., Frank, A., Gianelle, D., Gimeno, C., Gruenwald, T., Guo, H., Hanan, N., Haszpra, L., Heilmann, J., Jacobs, A., Jones, M.B., Johnson, D.A., Kiely, G., Li, S., Magliulo, V., Moors, E., Nagy, Z., Nasyrov, M., Owensby, C., Pinter, K., Pio, C., Reichstein, M., Sanz, M.J., Scott, R., Soussana, J.F., Stoy, P.C., Svejcar, T., Tuba, Z., Zhou, G., 2010. Productivity, respiration, and light-response parameters of world grassland and agroecosystems derived from flux-tower measurements. *Rangeland Ecol. Manage.* 63, 16–39.
- Grelle, A., Burba, G., 2007. Fine-wire thermometer to correct CO<sub>2</sub> fluxes by open-path analyzers for artificial density fluctuations. *Agric. For. Meteorol.* 147, 48–57.
- Houghton, R.A., Hackler, J.L., 1999. Emissions of carbon from forestry and land-use change in tropical Asia. *Global Change Biol.* 5, 481–492.
- Kravchenko, A.N., Robertson, G.P., 2011. Whole-profile soil carbon stocks: the danger of assuming too much from analyses of too little. *Soil Sci. Soc. Am. J.* 75, 235–240.
- Lal, R., 2002. Soil carbon sequestration in China through agricultural intensification, and restoration of degraded and desertified ecosystems. *Land Degrad. Dev.* 13, 469–478.
- Lemus, R., Lal, R., 2005. Bioenergy crops and carbon sequestration. *Crit. Rev. Plant Sci.* 24, 1–21.
- Leuning, R., 2004. Measurements of trace gas fluxes in the atmosphere using eddy covariance: WPL corrections revisited. In: Lee, X., Massman, W.J., Law, B.E. (Eds.), *Handbook of Micrometeorology. A Guide to Surface Flux Measurement and Analysis*, pp. 119–132.
- Ma, S., Baldocchi, D.D., Xu, L., Hehn, T., 2007. Inter-annual variability in carbon dioxide exchange of an oak/grass savanna and open grassland in California. *Agric. For. Meteorol.* 147, 157–171.
- Mangan, M.E., Sheaffer, C., Wyse, D.L., Ehler, N.J., Reich, P.B., 2011. Native perennial grassland species for bioenergy: establishment and biomass productivity. *Agron. J.* 103, 509–519.
- McCaughy, J.H., 1985. Energy balance storage terms in a mature mixed forest at Petawawa, Ontario—a case study. *Boundary Layer Meteorol.* 31, 89–101.

- Meyers, T.P., 2001. A comparison of summertime water and CO<sub>2</sub> fluxes over rangeland for well watered and drought conditions. *Agric. For. Meteorol.* 106, 205–214.
- Moffat, A.M., Papale, D., Reichstein, M., Hollinger, D.Y., Richardson, A.D., Barr, A.G., Beckstein, C., Braswell, B.H., Churkina, G., Desai, A.R., Falge, E., Gove, J.H., Heimann, M., Hui, D., Jarvis, A.J., Kattge, J., Noormets, A., Stauch, V.J., 2007. Comprehensive comparison of gap-filling techniques for eddy covariance net carbon fluxes. *Agric. For. Meteorol.* 147, 209–232.
- Moore, C.J., Fisch, G., 1986. Estimating heat storage in Amazonian tropical forest. *Agric. For. Meteorol.* 38, 147–169.
- Nagy, Z., Pintér, K., Czóbel, S., Balogh, J., Horváth, L., Fóti, S.Z., Barcza, Z., Weidinger, T., Csintalan, Z.S., Dinh, N.Q., Grosz, B., Tuba, Z., 2007. The carbon budget of semi-arid grassland in a wet and a dry year in Hungary. *Agric. Ecosyst. Environ.* 121, 21–29.
- Noormets, A., McNulty, S.G., De Forest, J.L., Sun, G., Li, Q., Chen, J., 2008. Drought during canopy development has lasting effect on annual carbon balance in a deciduous temperate forest. *New Phytol.* 179, 818–828.
- Papale, D., Reichstein, M., Aubinet, M., 2006. Towards a standardized processing of net ecosystem exchange measured with eddy covariance technique: algorithms and uncertainty estimation. *Biogeosciences* 3, 571–583.
- Parrish, D.J., Fike, J.H., 2005. The biology and agronomy of switchgrass for biofuels. *Plant Sci.* 24, 423–459.
- Ramirez, H.G., Hatfield, J.L., Prueger, J.H., Sauer, T.J., 2010. Energy balance and turbulent flux partitioning in a corn–soybean rotation in the Midwestern US. *Theor. Appl. Climatol.* 100, 79–92.
- Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havr'ankov'a, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.-M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., Valentini, R., 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. *Global Change Biol.* 11, 1424–1439.
- Richter, D.D., Markewitz, D., Trumbore, S.E., Wells, C.G., 1999. Rapid accumulation and turnover of soil carbon in a re-establishing forest. *Nature* 400, 56–58.
- Robertson, G.P., Dale, V.H., Doering, O.C., Hamburg, S.P., Melillo, J.M., Wander, M.M., Parton, W.J., Adler, P.R., Barney, J.N., Cruse, R.M., Duke, C.S., Fearnside, P.M., Follett, R.F., Gibbs, H.K., Goldemberg, J., Mladenoff, D.J., Ojima, D.W., Palmer, M.W., Sharpley, A., Wallace, L., Weathers, K.C., Wiens, J.A., Wilhelm, W.W., 2008. Sustainable biofuels redux. *Science* 322, 49–50.
- Schotanus, P., Nieuwstadt, F.T.M., De Bruin, H.A.R., 1983. Temperature measurement with a sonic anemometer and its application to heat and moisture fluxes. *Boundary Layer Meteorol.* 26, 81–93.
- USDA Conservation Reserve Program, 2008. Summary and Enrollment Statistics: A Review. (<http://www.fsa.usda.gov>).
- Webb, E.K., Pearman, G.I., Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapor transfer. *Q. J. R. Meteorol. Soc.* 106, 85–106.
- Wilczak, J.M., Oncley, S.P., Stage, S.A., 2001. Sonic anemometer tilt correction algorithms. *Boundary Layer Meteorol.* 99, 127–150.
- Wilson, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C., Ceulemans, R., Dolman, H., Field, C., Grelle, A., Ibrom, A., Law, B.E., Kowalski, A., Meyers, T., Moncrieff, J., Monson, R., Oechel, W., Tenhunen, J., Valentini, R., Verma, S., 2002. Energy balance closure at FLUXNET sites. *Agric. For. Meteorol.* 113, 223–243.
- Wright, C.K., Wimberly, M.C., 2013. Recent land use change in the Western corn belt threatens grasslands and wetlands. *PNAS* 110, no. 10 4134–4139.
- Zeeman, M.J., Hiller, R., Gilgen, A.K., Michna, P., Plüss, P., Buchmann, N., Eugster, W., 2010. Management and climate impacts on net CO<sub>2</sub> fluxes and carbon budgets of three grasslands along an elevational gradient in Switzerland. *Agric. For. Meteorol.* 150, 519–530.
- Zenone, T., Chen, J., Deal, M.W., Wilske, B., Jasrotia, P., Xu, J., Bhardwaj, A.K., Hamilton, S.K., Robertson, G.P., 2011. CO<sub>2</sub> fluxes of transitional bioenergy crops: effect of land conversion during the first year of cultivation. *Global Change Biol. Bioenergy* 3, 401–412.
- Zhang, K., Dang, H., Tan, S., Cheng, X., Zhang, Q., 2010a. Change in soil organic carbon following the grain for green programme in China. *Land Degrad. Dev.* 21, 13–23.
- Zhang, L., Wylie, B.K., Ji, L., Gilmanov, T.G., Tieszen, L.L., 2010b. Climate-driven interannual variability in net ecosystem exchange in the Northern Great Plains grasslands. *Rangeland Ecol. Manage.* 63, 40–50.