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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 An unconverted CRP field (CRP-Ref) was maintained as a historical reference.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 $\sim 5 \times 10^6$ 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