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Net primary production in three bioenergy crop systems following land conversion

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Abstract

Aims

Identifying the amount of production and the partitioning to above- and belowground biomass is generally the first step toward selecting bioenergy systems. There are very few existing studies on the dynamics of production following land conversion. The objectives of this study were to (i) determine the differences in aboveground net primary production (ANPP), belowground net primary production (BNPP), shoot-to-root ratio (S:R) and leaf area index in three bioenergy crop systems and (ii) evaluate the production of these three systems in two different land use conversions.

Methods

This investigation included biometric analysis of NPP on three agricultural sites converted from conservation reserve program (CRP) management to bioenergy crop production (corn, switchgrass and prairie mix) and three sites converted from traditional agriculture production to bioenergy crop production.

Important findings

The site converted from conventional agriculture produced smaller ANPP in corn (19.03 ± 1.90 standard error [SE] Mg ha^{-1} year^{-1}) than the site converted from CRP to corn (24.54 ± 1.43 SE Mg ha^{-1} year^{-1}). The two land conversions were similar in terms of ANPP for switchgrass (4.88 ± 0.43 SE for CRP and 2.04 ± 0.23 SE Mg ha^{-1} year^{-1} for agriculture) and ANPP for prairie mix (4.70 ± 0.50 SE for CRP and 3.38 ± 0.33 SE Mg ha^{-1} year^{-1} for agriculture). The BNPP at the end of the growing season in all the bioenergy crop systems was not significantly different (P = 0.75, N = 8).

Keywords: bioenergy crops, land use change, net primary production, aboveground net primary production, belowground net primary production

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INTRODUCTION

The development of sustainable bioenergy cropping systems has been proposed as one of the solutions for battling the increasing demands for energy in the USA. One key piece of legislation, the Energy Independence and Security Act of 2007, estimated that 36 billion gallons of renewable fuels are to be produced annually by 2022, of which 16 billion gallons are expected to come from cellulosic bioenergy products (http://www.energy.gov/index.htm).

To achieve the impacts of bioenergy policy on sustainability, it is important to understand the amount and partitioning of net primary production (NPP) of any new crop systems under different land conversion strategies as well as the key regulating factors of NPP. The aboveground NPP (ANPP) accumulated in aboveground plant biomass is the harvestable yield for fuel production; whereas the amount of belowground NPP (BNPP) determines the level of soil organic matter (SOM) that contributes to the soil and plays a major role in the long-term sustainability of a system (Post and Kwon 2000).

Understanding the amount and allocation of NPP between above- and belowground components is often the first step in selecting crops for bioenergy production. Currently, there are no investigations available in the literature on the changes in NPP and the partitioning of NPP during land conversion. Tilman *et al.* (2009) investigated long-term changes in soil organic carbon (SOC) and production in multiple bioenergy crop systems, but their report lacked the data tracing the changes and partitioning of NPP during the conversion process. There are few examples of large ecosystem-scale studies directly measuring NPP (e.g. Zenone *et al.* 2011), but no previous effort was made to identify the immediate changes after land conversions.

In general, land available for development of bioenergy systems in the Midwest USA includes sites converted from annual crop production under the Conservation Reserve Program (CRP) and agriculture (AG) lands that are considered marginal for food crop production. The repatriation of CRP and marginal AG land to bioenergy systems may have profound impacts on ecosystem services, soil quality, carbon balance and water quality (Robertson *et al.* 2011). If the land currently under CRP is brought back into production or if marginal AG land is appropriated to cultivate bioenergy crops, it is essential that they be both economically and environmentally sustainable.

Corn (*Zea mays*) is the most widely used crop species in the USA and is considered the first-generation bioenergy feedstock in the production of corn-ethanol biofuels. It is estimated that 25% of corn grown in the USA is being used for bioenergy production (Martin 2010). This commonly used bioenergy feedstock has many negative associations, including the competition for grain with food production. Generally, corn requires more chemical inputs on degraded soil, has less productive root systems and potentially stores less fixed carbon in soil than perennial grasses such as switchgrass (*Panicum virgatum;* Zan *et al.* 2001). The use of perennial crops and low-input, high-diversity mixtures of perennial grasses could increase the sustainability of AG land and enhance the stability of yields in marginal environments (Bhardwaj *et al.* 2011; Robertson *et al.* 2008; Tilman *et al.* 2006) compared with the use of corn. Switchgrass, a warm-season (C_4) perennial grass native to the tall grass prairies of North America, was favored by the US Department of Energy as a candidate species for bioenergy feedstock. Switchgrass is considered a model perennial energy crop in the Southeast due to its high yields, low production costs and little amount of competition from existing industry (Ma *et al.* 2000a). In addition to switchgrass, perennial prairie plantings (i.e. a mixture of grasses and forbs species resembling native Midwestern prairie diversity) offer many benefits to standard monoculture crop rotation (Gardiner *et al.* 2010; Tilman *et al.* 2002; Zhou *et al.* 2009). Mixed-prairie plantings combine the advantages of perennial feedstock species similar to those of switchgrass but also are likely to provide a level of biodiversity in crop fields that is more beneficial to important insects than traditional monoculture plantings (Gardiner *et al.* 2010).

The objectives of this study were to (i) determine the differences in ANPP, BNPP, shoot-to-root ratio (S:R) and leaf area index (LAI) in three bioenergy crop systems and (ii) evaluate the production of these three systems in two different land use conversion strategies. We hypothesize that production levels in the land converted from the CRP will be significantly higher in all three bioenergy crop systems. The retention of nutrients and organic matter buildup in the sites previously under the CRP will directly affect the production levels in all three crop types because rates of production are controlled mainly by temperature, moisture, nutrients and solar radiation (Woodwell and Whittaker 1968). Increased levels of soil moisture and nitrogen will result in higher production of biomass (Zenone *et al.* 2011). Both land use types (CRP and AG) were planted with legumes (i.e. soybeans) in the growing season preceding this study (in 2009). Therefore, the nitrogen fixed by the legumes should be relatively equal in that year, with the only other difference being land use history. While the CRP lands accumulated SOM and soil nutrients, the AG lands were perpetually planted and harvested with the vegetative cover removed. These practices are known to strip fields of SOM and reduce soil nutrients (Woodwell and Whittaker 1968). If the hypothesis is supported by this investigation, then the result would mean that thousands of acres of CRP land are potentially viable for immediate production of bioenergy crops.

METHODOLOGY

Study site

This study was carried out through the US Department of Energy's Great Lakes Bioenergy Research Center (GLBRC, http://glbrc.org/) at Michigan State's Kellogg Biological Station (KBS) located in Southwestern Michigan (42°24′N, 85°22′W; Fig. 1). The climate in the study area is temperate and humid, with a mean annual air temperature of 9.7°C and annual precipitation of 920 mm evenly distributed throughout the year. The soil textural class of all sites is sandy clay loam with a pH range from 5.8 to 6.4. Soil carbon and total soil nitrogen content were significantly higher in the CRP sites compared with those in the AG sites (Table 1).

The sites used in this study represent typical crop fields used in production of bioenergy crops. While land ownership may accommodate larger tracks of bioenergy crop plantings, smaller crop fields (<25 ha) provide useful insight into the dynamics of managed ecosystems. The sites used in this study include six scale-up crop fields ranging from 9 to 21 ha each. These experimental crop fields were established in 2009 by the GLBRC at KBS to provide a large-scale context for biodiversity and biogeochemistry investigations associated with bioenergy crop production. The experimental crop fields were represented by eight sampling locations along with a microclimate monitoring station and an eddy covariance flux tower positioned in the center of each site. Different land management strategies have played out at the six scale-up crop fields.

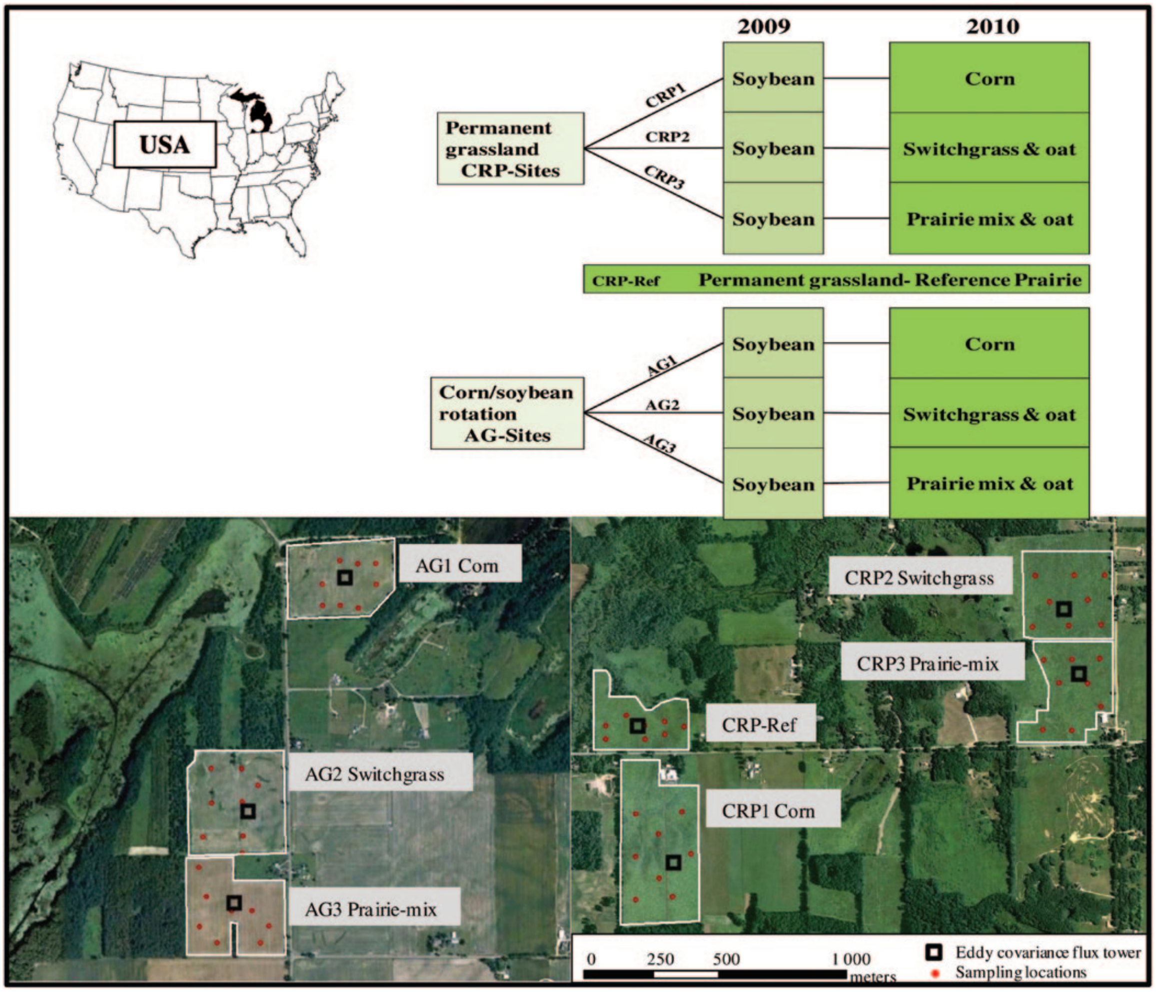

Figure 1: study site location in Western MI, USA, conversion strategy of study sites and experimental layout of scale-up field sites, with location of sampling plots and eddy covariance flux towers. Sites CRP1, CRP2 and CRP3 were converted from CRP management and sites AG1, AG2, AG3 were converted from traditional agriculture production to bioenergy crop production in 2010; site CRP-Ref was left as reference grassland but was not used in this study.

Table 1: chemical and physical properties of soil in 2009 at seven scale-up crop fields in Southwestern Michigan, USA

Site	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Soil pH	Cation exchange capacity [meq (100 g)$^{-1}$]	Bulk density (g m^{-3})	Nitrogen (g kg^{-1})	Carbon (g kg^{-1})
CRP1	670.0^{a}	60.1^{ab}	269.9^{a}	6.1^{a}	6.02^{ab}	1.41^{c}	2.79^{a}	30.94^{a}
CRP2	700.1^{a}	32.5^{b}	267.4^{a}	5.9^{a}	6.00^{ab}	1.42^{c}	2.03^{cd}	23.76^{b}
CRP3	684.9^{a}	47.5^{b}	267.6^{a}	6.2^{a}	5.46^{b}	1.34^{c}	2.27^{bc}	26.40^{ab}
AG1	642.5^{a}	52.6^{ab}	304.9^{a}	6.4^{a}	8.08^{ab}	1.55^{b}	1.32^{e}	14.21^{c}
AG2	624.9^{a}	42.6^{b}	332.5^{a}	6.4^{a}	7.07^{ab}	1.73^{a}	1.34^{e}	13.71^{c}
AG3	535.2^{a}	102.4^{a}	362.4^{a}	5.8^{a}	8.60^{a}	1.61^{b}	1.62^{de}	16.38^{c}

Sites CRP1, CRP2 and CRP3 were converted from CRP management and sites AG1, AG2 and AG3 were converted from traditional agriculture production to bioenergy crop production in 2010. Means followed by same letters are not significantly different by *t*-test ($P < 0.05$).

Sites CRP1, CRP2 and CRP3, located on the historic Marshall family farm, have been maintained under the CRP (www.fsa.usda.gov/FSA, 10 January 2010, date last accessed) since 1987, supporting monoculture grasslands dominated by smooth brome grass (*Bromus inermis* Leyss). It is not clear to the authors why this species was planted instead of a more commercially available CRP seed mix. Sites AG1, AG2 and AG3 were previously managed using conventional agricultural practices and most recently planted with a corn/soybean rotation during the past 10–20 years. These sites were fertilized annually according to conventional agricultural practices. Information on exact fertilization rates was not available. All sites were managed as no-till systems to retain the maximum amount of organic matter and water in the soil and to reduce erosion on the marginal AG sites. During the 2009 growing season, all sites were planted with soybean to homogenize the sites for 1 year prior to switching to different bioenergy crop systems in the 2010 growing season.

Experimental design

This study was carried out in 2010. Of the six scale-up crop fields, two sites (CRP1 and AG1) were planted with conventional corn (Dekalb DK-52) on day of year (DOY) 119 (CRP1) and DOY 120 (AG1), with a *JD-1780* no-till planter (John Deere, Moline, IL, USA); two sites (CRP2 and AG2) were planted with switchgrass and an oat (*Avena sativa*) cover crop (DOY 119 for CRP2 and DOY 120 for AG2); and two sites (CRP3 and AG3) were planted with a conservation prairie mix and an oat cover crop (DOY 119 for CRP3 and DOY 120 for AG3). The two corn sites (CRP1 and AG1) were managed according to conventional agricultural input practices in 2010. On DOY 124 (CRP1) and DOY 120 (AG1), a herbicide mix (*Lumax* [5.9 l ha^{-1}], *Atrazine 4L* [0.78 l ha^{-1}], *Honcho Plus* [2.4 l ha^{-1}] and $(NH_4)_2$ SO_4 [0.92 kg ha^{-1}]) was applied using a pull-type sprayer (Demco Dethmers Mfg Company, Boyden, IA, USA) to reduce the competition from grasses during corn germination and early growth. A custom fertilizer mix (P_2O_5 + K_2O, 168.5 kg ha^{-1}) was applied to AG1 prior to planting (DOY 95) to amend diminished soil nutrient availability (Post and Kwon 2000). Additional nitrogen fertilizer (28% liquid nitrogen, 112.3 kg ha^{-1}) was applied during the growing season at site AG1 (DOY 165) and at CRP1 (DOY 160) using a side-dressing application method, in an effort to increase the availability of nitrogen during the period of maximum growth. This fertilization scheme on AG1 and CRP1 (corn plantings) represents the only inputs applied to the fields during this study. No fertilizer was applied to the perennial grass crop fields in 2010.

Data collection

Measuring plant components at the end of the growing season in cultivated crops provides an estimation of accumulated biomass after some of the products of photosynthesis are exhausted via autotrophic respiration and herbivory. Production in this form is expressed in terms of biomass per unit of ground surface per unit time (e.g. Mg biomass ha^{-1} year^{-1}). NPP can be measured at the ecosystem scale and separated into two main components: aboveground net primary production (ANPP, i.e. shoots, leaves and litter) and belowground net primary production (BNPP, i.e. roots). NPP was measured using biometric approaches (Curtis *et al.* 2002; Frank *et al.* 2004; Schmid 1995), which include the measurement of aboveground (live tissue and litter layer) and belowground (fine roots and SOM) biomass. Biomass samples were collected in eight plots at each of the six sites in 2010. Plots were arranged within the eddy covariance flux tower fetch and geographically referenced using a handheld global positioning system unit (Garmin, Olathe, KS, USA) for easy identification (Fig. 1). ANPP was measured by harvesting the aboveground biomass in 1-m^2 area at each plot at peak biomass stage, which was the end of July 2010 for switchgrass and prairie mix and the first week in October 2010 for corn. Plants from each sampling area were clipped at ground level and placed in drying bags. Surface litter was also captured in the same area and it consisted of fallen leaves from 2010 and dead plant material from the previous year. The litter and live plant components were dried in a forced-air oven at 65°C for at least 4 days until reaching a constant dry mass. ANPP was calculated as the sum of dried crop biomass and litter. The biomass weight from eight plots was averaged to calculate productivity per site. Nondestructive LAI measurements were taken during the peak growing season (DOY 201–205) and near the end of the growing season (DOY 231–232) using an LAI-2000 analyzer (Li-Cor Biosciences; Lincoln, NE, USA) with a 90° view cap and the standard row crop method (Walker *et al.* 1988).

BNPP was estimated using ingrowth root cores (Steingrobe *et al.* 2001) in 2010. Root cores (7-cm diameter × 30-cm length) were installed on DOY 84–97. Two soil cores were taken at each plot with the roots removed and the soil was placed back in the hole within a synthetic mesh bag with 5-mm openings. One root core at each plot was harvested during the peak growing season (DOY 207 and 208; $BNPP_1$) and the other root core at each plot was harvested near the end of the growing season (DOY 281–283; $BNPP_2$). Repeated root core sampling (i.e. $BNPP_1$ and $BNPP_2$) at each plot provided the most accurate estimation of root production. Following collection from the field, samples were stored at 5°C prior to processing and then separated from bulk soil before drying using a hydropneumatic root elutriation system (Gillison's Variety Fabrication; Hart, MI, USA). Root samples were oven-dried at 70°C for 48 hours to achieve a constant mass (Li *et al.* 2007). Soil samples (within 8 cm diameter and 25 cm depth) were taken for measurement of soil properties at the beginning of the study in 2009 at all sites.

Data analysis

NPP was derived from the sum of ANPP and BNPP. ANPP was calculated by totaling all aboveground biomass in a 1-m^2 area and scaling up to the hectare. BNPP was calculated from total root biomass in a core and scaled up to the hectare in the same way. Means and standard errors were calculated for ANPP (Mg ha^{-1} year^{-1}), BNPP (Mg ha^{-1} year^{-1}), shoot-to-root ratio (S:R) and LAI (m^2 m^{-2}) for all sites. Each experimental site had a unique combination of land use history and crop system. This resulted in only having one replicate of each treatment combination and no ability to test for significant difference. True replicates were available for the three bioenergy crop systems (N = 2) and the two land use history scenarios (N = 3).

All analyses were performed using SAS software (version 9.1; SAS Institute, Inc.; Cary, NC, USA), and an α level of 0.05 was used in all tests to determine statistical significance. A series of two-sample t-tests was used to test the equality of the means of all production parameters among the two land use scenarios. The α level of 0.05 was adjusted with the Bonferroni correction for multiple comparisons, where α equals 0.05 divided by 3 tests, one for each crop system. The paired t-test was used to determine differences between peak- and end-of-the-growing-season BNPP.

RESULTS

Biophysical conditions

Measurement of growing season mean soil microclimate, soil properties and LAI give a basis for comparison of the regulating factors among the sites. All six sites were statistically similar in terms of amount of sand, amount of clay, pH and cation exchange capacity when measured in 2009. The sites converted from the CRP had statistically similar values for bulk density and SOC. Likewise, the sites converted from agriculture had statistically similar values for bulk density and SOC (Table 1). Both corn sites (CRP1 and AG1) showed no significant difference in LAI in July or August measurements in 2010. CRP2 (switchgrass) and CRP3 (prairie mix) produced similar mean July 2010 LAI values of 2.96 ± 0.27 standard error (SE) and 2.66 ± 0.53 SE m^2 m^{-2}, respectively, and were not significantly different. Similarly, AG2 (switchgrass) and AG3 (prairie mix) showed no significant difference in July 2010 LAI from one another. Both corn sites (CRP1 and AG1) showed a reduction in LAI from July to August 2010. Similar reduction was seen in the CRP perennial grasses (CRP2 and CRP3) but not in the perennial grasses on the former agriculture sites (AG2 and AG3). At these sites, LAI was significantly higher by August 2010 compared with the July 2010 measurement (Table 2).

Primary production

Corn produced significantly higher ANPP than the perennial grasses for both land conversion scenarios (Fig. 2a) in 2010. Corn on the CRP site (CRP1) had significantly higher ANPP, with a mean value of 24.54 ± 1.43 SE Mg ha^{-1} $year^{-1}$ than the corn on the traditional agriculture site (AG1, 19.03 ± 1.90 SE Mg ha^{-1} $year^{-1}$). On both corn sites (CRP1 and AG1), plant biomass explained the majority of the variance because there was no significant difference in dry mass of litter among the sites. Therefore, all significant site-wise variation in ANPP was attributed solely to live plant biomass in 2010.

The ANPPs of the prairie mix and switchgrass sites converted from CRP in 2010 (CRP2 and CRP3) were statistically similar, with 4.88 ± 0.43 SE and 4.70 ± 0.50 SE Mg ha^{-1} $year^{-1}$, respectively. Likewise, ANPPs for the prairie mix and switchgrass systems on the traditional agriculture sites (AG2 and AG3) were statistically similar, with 2.04 ± 0.23 SE and 3.38 ± 0.33 SE Mg ha^{-1} $year^{-1}$, respectively (Fig. 2a). The ANPP of the switchgrass system in the sites previously under CRP (CRP2) was significantly higher than that on land

Table 2: site area in hectares and biophysical traits including LAI measured in July and August 2010

		LAI	
Site name	Area (ha)	July	August
CRP1	19.5	4.2	3.6
CRP2	17.9	3.0	2.6
CRP3	13.1	2.7	2.1
AG1	11.2	3.4	3.1
AG2	14.1	0.6	1.6
AG3	23.0	2.0	2.4

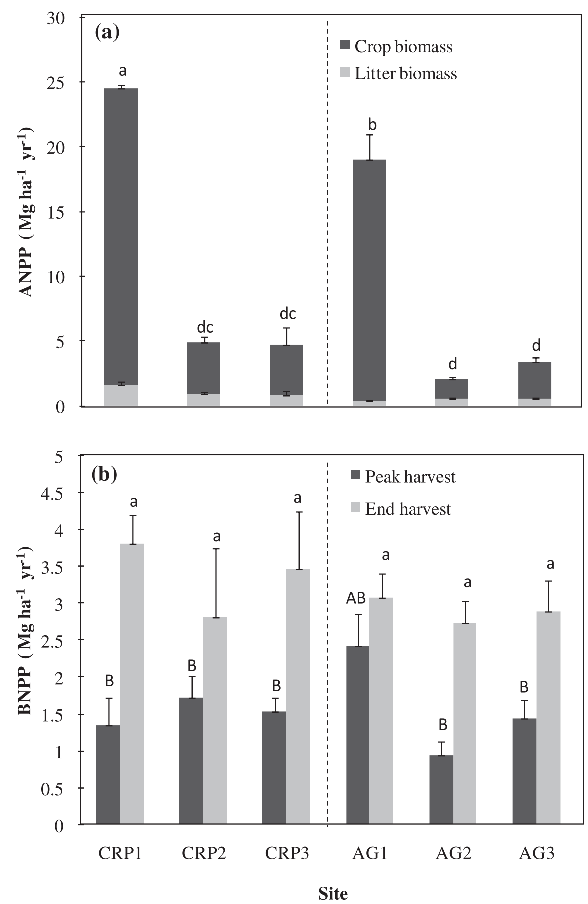

Figure 2: net primary production. (**a**) ANPP of seven bioenergy scale-up crop fields, including live plant tissue and litter. (**b**) BNPP of seven scale-up crop fields harvested during peak and at the end of the growing season. Sites CRP1, CRP2 and CRP3 were converted from CRP management and sites AG1, AG2 and AG3 were converted from traditional agriculture production to bioenergy crop production in 2010. CRP1 and AG1 were planted with corn; CRP2 and AG2 were planted with switchgrass; and CRP3 and AG3 were planted with a prairie mix in 2010. Error bars indicate ± standard error and same letters represent no significant difference among sites by ANOVA ($P < 0.05$).

previously under conventional agriculture (AG3). Likewise, the CRP prairie mix site (CRP3) had significantly higher ANPP than that previously under conventional agriculture (AG3, Fig. 2a) in 2010.

There was no significant difference in ANPP for two of the three crop systems between the two land use histories at an α level of 0.016 in 2010. Results from a *t*-test showed *P* values of 0.0367 for corn, 0.0445 for prairie mix and <0.0001 for switchgrass systems. Variance in measurements of ANPP was explained by plot-level variance nested within bioenergy production site, with 91.6% of the variance explained by crop system and only 3.1% attributed to land use history and with both showing a significant difference (Table 3).

The analysis of relationships between ANPP in 2010 and the 2009 preliminary soil properties showed weak correlations, with the largest correlation coefficient found between ANPP and soil nitrogen, at 0.32.

$BNPP_2$ values were not different for all three crop systems in the sites converted from CRP, with 3.81 ± 0.78 SE, 2.80 ± 0.39 SE and 3.47 ± 0.94 SE Mg ha^{-1} $year^{-1}$ being produced by the end of the growing season in 2010 for corn, switchgrass and prairie mix, respectively (Fig. 2b). The sites converted from agriculture were also similar in BNPP by the end of the growing season in 2010, with production levels of 3.07 ± 0.33 SE, 2.73 ± 0.30 SE and 2.89 ± 0.41 SE Mg ha^{-1} $year^{-1}$ for corn, switchgrass and prairie mix, respectively. There was a significant difference between the end-of-the-growing-season 2010 $BNPP_2$ and the peak-growing-season 2010 $BNPP_1$ within all sites, except the agriculture corn site (AG1) by paired *t*-test ($P < 0.05$). These two exceptions also produced the highest root biomass, as measured at the peak growing season of 2010, but were not significantly different from the other sites, in terms of BNPP, by the end of growing season 2010.

The performance of perennial grasses in different land use histories for both switchgrass sites (CRP2 and AG2) and both prairie mix sites (CRP3 and AG3) were not significantly different in root production from each other during both the peak and the end of the growing season. Standard *t*-tests indicated that there is a marginal and significant difference in $BNPP_2$ for all three crop systems between the two land use histories at an α level of 0.016. The results of the nested analysis of variance (ANOVA) indicate that 2.1% of the variance in $BNPP_2$ is explained by land use scenario. The largest portion of the variance was attributed to the individual plots nested within each crop system although the differences were not significant. $BNPP_2$ had the highest proportion of unexplained variance, with 47.2% ascribed to the error term (Table 3).

The site mean values of $BNPP_2$ showed strong relationships with LAI measurements and multiple preliminary soil properties measured in 2009. There was a strong correlation between $BNPP_2$ and LAI measurements taken in early August 2010. The strongest correlations were observed between $BNPP_2$ and soil properties, including SOC, soil nitrogen (N), soil phosphorus and soil potassium. The results of a multiple regression analysis including several soil properties, such as SOC, N, phosphorus and potassium, showed no significant associations with $BNPP_2$ when all variables were considered together.

At the end of the 2010 growing season, S:R was significantly higher at the CRP corn site (CRP1) and the previous agriculture corn site (AG1) than all of the perennial grass sites (CRP2, CRP3, AG2 and AG3). The S:R of the two corn sites was not significantly different, at 8.82 ± 2.11 SE and 7.04 ± 1.21 SE for CRP1 and AG1, respectively. Similarly, S:R for the switchgrass and prairie mix on both previous land use scenarios were not significantly different from each other. The agriculture sites (AG2 and AG3) showed lower variance of S:R than the CRP sites (CRP2 and CRP3). The *t*-test indicated that there was no significant difference in S:R between the two land use histories for the corn and prairie mix crop systems, but there was a significant difference among land use scenarios for the switchgrass systems. When analyzing the influence of S:R in a nested ANOVA, the results favored the crop system, with 80% of the variance explained by the sampling plots nested within crop system and only 2.2% explained by land use.

DISCUSSION

The environmental impacts of high-input, annual agriculture production are well documented (Robertson *et al.* 2008). Low-input perennial grasses offer a better alternative (Tilman *et al.* 2009), but information specifying production levels and changes in carbon cycling after land conversion is limited. This study showed that perennial grass bioenergy systems, such as switchgrass and conservation prairie mix, offer similar inputs as corn to belowground biomass in the first year of conversion. Zenone *et al.* (2011) reported that land converted from CRP grasslands to bioenergy crop production induced large carbon emissions in the first year converted to soybean. To estimate the effect of land use change from either grassland

Table 3: the overall results of a nested ANOVA comparing land use history scenarios and crop systems for differences in ANPP, BNPP, S:R ratio and LAI of six scale-up crop fields in Southwestern Michigan, USA, in 2010

	ANPP	BNPP	NPP	S:R
Land use	3.1 (0.0012)**	2.1 (0.3175)	4.5 (0.0128)*	2.2 (0.1068)
Crop system	91.6 (<0.0001)***	50.7 (0.4302)	90 (<0.0001)***	80.0 (0.0003)***
Unexplained	5.3	47.2	5.5	17.8

Values represent percentage of variance explained with *P* value in parentheses. **P* < 0.05, ***P* < 0.01, ****P* < 0.001.

or row crops to bioenergy crop systems, it is important to consider not only the implications of the bioenergy crop selection (e.g. annual vs perennial and grain vs cellulosic) and changes in land use but also the management of the land following the conversion. The scale-up crop fields investigated in this study were all managed as no-till systems. The application of conventional soil tillage could induce a larger emission of CO_2, lower soil carbon storage, higher erosion and a larger impact on the global carbon cycle (Robertson *et al.* 2008).

This investigation was designed to understand the allocation of NPP within three bioenergy cropping systems in two different scenarios of land use history. Understanding changes in NPP at the ecosystem scale in bioenergy systems required the development of a fundamental comprehension of the inputs of production to SOM in different crop systems and management scenarios under similar climatic conditions. Rates of belowground production of roots were related to overall inputs of SOM and provide insight into the initial dynamics of production when land is transformed to bioenergy cultivation.

It was hypothesized that there are significant differences in overall NPP, shoot-to-root ratios and belowground biomass allocation between the two scenarios of land use history (i.e. agriculture vs CRP) and also among the bioenergy crop systems. The retention of nutrients and organic matter buildup in the sites previously under the CRP will directly affect the production levels in all the three crop types. Rates of production are controlled mainly by temperature, moisture, nutrients and solar radiation (Woodwell and Whittaker 1968). Increased levels of soil moisture and nitrogen result in higher production of biomass (Zenone *et al.* 2011) and there are distinctive relationships between environmental variables (e.g. microclimate and soil nutrients) and NPP.

Bioenergy crop systems

The results of this investigation clearly indicate that aboveground production of corn with traditional chemical input is superior to any and all perennial grass crop systems in the first year of production. There will most likely be a sharp increase in the amount of aboveground production from the perennial grasses as these sites become established. Frank *et al.* (2004) found that switchgrass cultivars produced 6–8.5 Mg ha^{-1} year^{-1} of aboveground biomass only 2 years after planting in similar soil conditions in North Dakota, USA. However, BNPP and root production are extremely important to the overall sustainability of bioenergy systems (Robertson *et al.* 2008) and are not often measured empirically but derived as a percentage of aboveground biomass (Bolinder *et al.* 2006; Woodwell and Whittaker 1968).

The higher level of BNPP at the end of the growing season, compared with those measured at the peak growing season, supports the idea that root production levels near the end of the growing season are superior to the amount of root turnover from decomposition. This provides evidence that measuring BNPP in bioenergy systems using the ingrowth root core method at the end of the growing season is a proper method for empirically measuring root production. In the latter years following conversion, when perennial grasses become established, there will be less contrast between peak and end BNPP measurements. The amount of SOM left in the soil after crop production is strongly dependent on the production of roots during the growing season (Bolinder *et al.* 2006), and the annual SOM input is paramount to the sustainability of an agricultural system (McLaughlin *et al.* 1994). The results from the study showed that all three bioenergy crop systems (corn, switchgrass and prairie mix) produced statistically similar BNPPs. Because the perennial grass systems produced similar levels of BNPP as corn, they present a more sustainable alternative to corn requiring less inputs and overall less effort for production.

Using alternative energy sources such as bioenergy crops can reduce greenhouse gas (GHG) emissions by replacing fossil fuel alternatives. However, when land is converted to these systems, there is an initial payback period in which excess CO_2 emission from land conversion is offset by the reduced emission from bioenergy-crop-based fuel compared with fossil fuels. Sites converted from grassland (e.g. CRP grasslands) to corn-ethanol bioenergy crop systems require 40 years to pay back the GHG emission from land conversion by the replacement of their fossil fuel alternatives (Gelfand *et al.* 2011). This is comparable to a <1-year payback time for perennial grasses for cellulosic ethanol production (Fargione *et al.* 2008; Gelfand *et al.* 2011). This clearly indicates a greater level of sustainability that can be achieved by using alternatives to high-input corn-ethanol bioenergy systems primarily through inputs of belowground productivity to SOM. Additional, the advantages to SOM and SOC storage that the perennial grass systems provide will be augmented by the enhancement of ecosystem services, including the benefit to arthropod communities, water quality and the reduction of soil erosion. S:R in corn was much higher and more variable than that in the perennial grasses due to the high level of aboveground productivity. The S:R values for both corn sites in this study were compared with those found in previous field studies. Eghball and Maranville (1993) found S:R value in corn of 6.56 and Foth (1962) published a value of 10.70. These assessments are similar to the S:R ratios found in the corn sites in this study (CRP1: 8.82; and AG1: 7.04). The implications of management are extremely important to the overall sustainability and to the level of production in bioenergy crops.

Influence of land use history

The production of bioenergy crops that require changes in land use will have profound environmental impacts. Different scenarios of land use history can alter the limiting components of production in crop systems. Land conversion can have a significant impact on the carbon budget and net ecosystem exchange of bioenergy systems (Zenone *et al.* 2011). Due to the buildup of organic matter in the soil and the coincident storage of soil nutrients, we expected that there would be higher levels of NPP in the lands converted from the CRP. The buildup of organic matter on these soils is the result of >20 years of consistent vegetative cover and has direct implications on the productivity of those lands if the converted marginal agricultural land that has remained in annual production has reduced soil nutrients and would require intensification of production or increasing land area for production to meet the output of cellulosic products from lands formally under the CRP (Bhardwaj *et al.* 2011).

Using the two corn sites in this study as an example, we found a significantly higher level of ANPP in the site converted from CRP (CRP1) than that in the site converted from agriculture (AG1). AG1 had additional fertilizer application (P_2O_5 + K_2O) early in the season, prior to planting, to amend the diminished soil conditions. This additional input was not performed at CRP1 because of the enhanced soil quality resulting from years under perennial vegetation. Even with this supplementary nutrient addition, site AG1 underperformed with reference to site CRP1 in ANPP although BNPP was not significantly different. This provides evidence that land use change had a stronger effect on corn production than what could be overcome by additional chemical inputs.

The effects of differing land use history scenarios were explored using several statistical analyses. Comparing each crop system (corn, switchgrass and prairie mix) between the two land use scenarios using a *t*-test showed consistent results when the nested ANOVA used land use as the main group and crop system as the subgroup. The results of the *t*-test showed that corn and prairie mix were not significantly different between land use scenarios in terms of ANPP, BNPP and S:R. The ANPP and S:R in switchgrass was different between land use scenarios, but BNPP was not. Similar to the *t*-test results, the results of the nested ANOVA showed that land use explained very little of the variance among the sites, whereas the crop system overwhelmingly explained the majority of the variance in all production parameters (ANPP, BNPP, NPP, S:R and LAI; Table 3).

This is the first study of this kind to investigate and compare production on two common types of land available for bioenergy production in the Midwest. The results lead to the conclusion that there was no significantly higher production in lands that were converted from the CRP as originally hypothesized. Conclusions can yet be made about the levels of production in the long term due to the additional variables involved in the extended analyses of crop production. This study should be followed up with a more comprehensive investigation evaluating these differences in a long-term field trial, with increased replication, simultaneous microclimate study and analysis of CO_2, H_2O and energy flux coupled with NPP.

Converting CRP land that is dominated by bromegrass to a continuous corn production system seemed to have limited effect on the SOC reserve if managed as no-till systems (Follett *et al.* 2009). Due to the similarity of results in BNPP among the lands converted from the CRP and marginal agriculture lands in this study, it is recommended that the same methods of no-till management should be used to increase the sustainability and storage of SOC when these sites are converted to corn production for ethanol.

Biophysical regulations of production

This investigation was set out to understand some of the prevailing factors that influence production in agroecosystems under cultivation of bioenergy crops. Because the regulation of productivity is dependent on the temporal scale in question, we focused on the drivers of production in annual or seasonal terms.

The assessment of the connection between soil water content (SWC) and ANPP showed a negative relationship, with an R^2 value of 0.16. A similar negative relationship was found between the S:R and SWC, with an R^2 value of 0.2. This is contrary to traditional studies that identified water as having the strongest control on grassland NPP. The negative relationships found here may be subject to a strong influence of the high ANPP and the S:R ratio of corn. The water footprints of all the six experimental sites used in this study were investigated in 2009 under cultivation of soybean. Bhardwaj *et al.* (2011) found that the ANPP of soybean was closely connected with crop water use, which was determined from the total evapotranspiration, estimated using the eddy covariance method. If a single crop type was used in this investigation, there would have been a stronger relationship between ANPP and SWC.

There is a strong relationship between the levels of SOC present when sites are converted to bioenergy production and the BNPP in the first year of conversion. Although the amount of belowground production was positively related to SOC in the first year of conversion, the levels of SOC in subsequent years will be controlled by BNPP. The land use history and the crop system planted will affect the level of SOC that is stored each year. When lands taken out of intensive agriculture are planted with perennial vegetation, SOC can accrue by processes that reverse some of the impacts responsible for SOC losses during conversion from native perennial vegetation to annual crops (Post and Kwon 2000). The relationship between SOC and BNPP was the most significant and the most important. Similar to the relationship with SWC, the associations between SOC and the two variables ANPP and S:R were strongly influenced by distinctively higher levels of ANPP in the corn sites.

$BNPP_2$ showed a significant positive relationships with individual soil property variables. When several soil properties were considered together in a multiple regression, there was no significant influence. This leads to the conclusion that $BNPP_2$, and the associated annual additions to SOC, is limited by many soil nutrients individually but not as a whole. Further analysis could include increased temporal and spatial measurements of soil nutrients to determine the seasonal impacts and autocorrelations of NPP and certain ecosystem variables. Similar to the biophysical drivers of NPP identified here, the relationships expressed from this data set represent a relatively small sample size and were strongly influenced by the contrastingly different production levels in the corn sites. Generally, the constraints of a large-scale ecosystem study reduced the availability of extensive replication. Future work should focus on analyzing multiple sites in different regions, which would help reduce the influence of site-wise variation. The results of this study allow for some conclusions to be made on conversion of land at three bioenergy crop systems in the first year of conversion. However, the variation in these systems over time and the uncertainty of predicting environmental conditions make it extremely difficult to predict changes in NPP into the future as the grass systems become established. Continued and intensive monitoring of these and other bioenergy systems is necessary to understand the potential impacts from changing land for bioenergy crop cultivation.

CONCLUSIONS

Many factors and processes influence the level of primary production and the overall sustainability of bioenergy crops. Crop species and land use history are two of the primary factors determining the amount of harvestable biomass above ground and the inputs to belowground carbon pools in bioenergy crop systems.

1. All converted sites in this study had statistically similar $BNPP_2$ ($P = 0.75$, $N = 8$). The perennial grasses produced statistically similar $BNPP_2$ to corn in the very first year after planting and perhaps offer a more sustainable alternative for cultivation of bioenergy feedstock. As these grasses become established, the root system will recharge SOM pools and increase storage of SOC.
2. Marginal agricultural lands produced smaller ANPPs (19.03 ± 1.90 SE Mg ha^{-1} year^{-1}) in corn compared with the site converted from the CRP to corn (24.54 ± 1.43 SE Mg ha^{-1} year^{-1}) but were statistically similar in perennial grass production to the CRP sites. This suggests that the influence of land conversion has stronger influence in the production of annual crops (e.g. corn) than in the production of perennial grasses. This supports the use of perennial crop systems in the USA on land that is repatriated from the CRP or transformed from traditional agriculture to bioenergy production.
3. SWC played the most important role in limiting ANPP and S:R, and SOC present before land conversion had the strongest impact on $BNPP_2$. SWC is one of the many regulating factors of photosynthesis in plants and therefore helps to regulate aboveground production in the first year of planting. Belowground production was more closely linked to SOC present at the inception of the study.
4. Future work should focus on long-term analysis in changes in production of biomass and SOC storage in this area and others. Results from these investigations should identify basic expectations for the conversion of land to the production of bioenergy crops. It is important to understand the consequences of changing land for bioenergy cultivation in terms of primary production and sustainability through terrestrial carbon storage in the soil.

HIGHLIGHTS

- We measured NPP and its components—ANPP and BNPP—during the first year of land conversion.
- Our sites were converted from agricultural and CRP lands, in addition to a prairie reference.
- Three types of bioenergy systems were studied: corn, switchgrass and prairie mix.
- ANPP was higher in sites converted from CRP, and BNPP was similar among all sites.
- Soil water content limited ANPP, and soil organic carbon affected BNPP in all sites.

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