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Water and energy footprints of bioenergy crop production on marginal lands

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Abstract

Water and energy demands associated with bioenergy crop production on marginal lands are inextricably linked with land quality and land use history. To illustrate the effect of land marginality on bioenergy crop yield and associated water and energy footprints, we analyzed seven large-scale sites (9–21 ha) converted from either Conservation Reserve Program (CRP) or conventional agricultural land use to no-till soybean for biofuel production. Unmanaged CRP grassland at the same location was used as a reference site. Sites were rated using a land marginality index (LMI) based on land capability classes, slope, soil erodibility, soil hydraulic conductivity, and soil tolerance factors extracted from a soil survey (SSURGO) database. Principal components analysis was used to develop a soil quality index (SQI) for the study sites based on 12 soil physical and chemical properties. The water and energy footprints on these sites were estimated using eddy-covariance flux techniques. Aboveground net primary productivity was inversely related to LMI and positively related to SQI. Water and energy footprints increased with LMI and decreased with SQI. The water footprints for grain, biomass and energy production were higher on lands converted from agricultural land use compared with those converted from the CRP land. The sites which were previously in the CRP had higher SQI than those under agricultural land use, showing that land management affects water footprints through soil quality effects. The analysis of biophysical characteristics of the sites in relation to water and energy use suggests that crops and management systems similar to CRP grasslands may provide a potential strategy to grow biofuels that would minimize environmental degradation while improving the productivity of marginal lands.

Keywords: Eddy covariance flux, land capability, land marginality index, land use suitability, net primary productivity, soil erodibility, soil quality index

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Introduction

Recently, marginal lands have been proposed as viable areas for growing biofuels using mixed prairie grasses (Tilman *et al*., 2006), switchgrass (*Panicum virgatum*), Miscanthus (*Miscanthus giganteus*), and various other plant species that may be more tolerant of adverse conditions than conventional food crops. While production of biofuels, in general, has been questioned on ecological (e.g. Chapin *et al*., 2000; Searchinger *et al*., 2008) as well as socioeconomic grounds (e.g. Pimentel & Patzek, 2005), there is general consensus that the ecological footprints of biofuels depend on the type of feedstock and the type of land. For example, Robertson *et al*. (2008, 2010) suggested that growing cellulosic biofuels on degraded lands or environmentally vulnerable crop lands could increase carbon sequestration and improve water quality. Searchinger *et al*. (2008) suggested that cellulosic biofuels would increase greenhouse gas emissions by 50% if grown on US corn lands, while Fargione *et al*. (2008) noted that growing them on degraded and abandoned lands might incur little or no carbon debt.

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Marginal lands are considered unfit for prime agricultural use because of poor land quality characteristics (United Nations Statistical Division (UNSD), 1997). Although the concept of marginality encompasses bio-physical and social dimensions, it commonly focuses on bio-physical aspects with the assumption that socio-economic marginality originates from bio-physical limitations. And while there is no single best indicator of land quality, a number of indicators have been used earlier such as soil productivity (or suitability) for crop growth, land capability classification (Hardie & Parks, 1997), and specific soil characteristics such as water-holding capacity (Lichtenberg, 1989; Wu and Brorsen, 1995).

Land quality primarily determines the allocation of land to agricultural use. For example, in the United States, lands enrolled in the Conservation Reserve Program (CRP) are typically of lower quality (either lower productivity or at higher risk of environmental degradation) compared with other lands in the same geographic area (Lubowski *et al.*, 2006). CRP is a cost-share and land rental program in the United States that converts highly erodible or otherwise environmentally sensitive crop land to noncrop vegetation.

Land quality is also not an absolute function but must be assessed in relation to the specific land use that one has in mind (Sombroek, 1997). Various land qualities in relation to crop growth, animal production, forest productivity, and input management levels are provided in a framework of land evaluation by FAO (1976). Among these, land qualities for crop productivity include characteristics such as moisture and nutrient availability, resistance to soil erosion, and soil workability for farming operations. Similarly, soil quality, which is a component of land quality, is defined in terms of the capacity of a soil to perform specific functions in relation to human needs or purposes, including maintaining environmental quality and sustaining plant and animal production (Lal, 1998).

Soil quality derives from a variety of particular physical, chemical, and biological properties that support crop growth (Mausbach & Seybold, 1998). Some properties are characterized by optimum levels, and deviation from these optima is associated with reduced soil quality. In addition to soil properties, other characteristics also play a critical role in determining land quality, including aspects of terrain and climate. On any particular parcel of land, some properties of soil and other resources may limit land quality while others do not. Two soil-based measures that are commonly used in the United States to assess the quality of land for agricultural purposes are the Land Capability Classification (USDA, 1973) and USDA's 'prime farmland' designation (Magleby, 2002). The Land Capability Classification system ranks land according to its suitability for crop production based on soil criteria, such as depth and fertility, climate, wetness, and susceptibility to erosion (Heimlich, 1989), and the prime farm land has the best physical and chemical characteristics for crop growth including an adequate and dependable water supply.

In addition to land quality, policy has a large effect on the land use decisions and the resulting consequences for ecosystem goods and services (Robertson & Swinton, 2005). Land quality and land use have a direct relationship with environmental characteristics and processes, including the productivity of the land, species diversity, biogeochemistry, and the hydrologic cycle. If policies are not carefully designed and implemented, a particular land use may yield minimal gain in the ecosystem services of interest and may even diminish production of other services (Daily & Matson, 2008; Nelson *et al.*, 2008). For example, the type of land and the intensity of its use can have substantial impact on both the quantity and quality of water in a region. Together with nutrient cycling, water regulation and supply have been rated as some of the most valuable ecosystem services (Swinton *et al.*, 2007) with average global value as high as US\$ 2800 $ha^{-1} yr^{-1}$ (Costanza *et al.*, 1997). Managing water on a watershed basis helps to address potential impacts of land use change including soil erosion and salinization due to poor land use practices, water flow and storage that may prevent or ameliorate floods and droughts, deterioration of water resources due to increased input of pollutants, and decline in water resources due to excessive use. The relationships between land use and water quality and quantity are also bidirectional. Land management activities have direct impacts on water resources, while water quality and quantity may also influence the selection of land use activities.

To maintain or enhance the ecosystem services associated with marginal lands, it is important to assess the environmental and economic viability of potential land use choices. Such an assessment would help maximize the ecosystem services with economic returns by removing the bottlenecks and developing better management strategies. The aim of the work presented here is to assess land marginality and soil quality impacts on water and energy footprints of soybean production for biodiesel on some newly converted marginal lands in southwest Michigan, and to evaluate the implications of this interaction for better management of land and water resources to maximize ecosystem services.

Materials and methods

Experimental approach

To assess land quality and management effects on the water and energy footprints of bioenergy crop production, large-scale biofuel production experiments were started by converting two types of land uses (CRP grasslands and active agricultural lands) into soybean production for bioenergy. Over a 1 year period of land conversion and soybean production we measured the water and energy exchange, and its relation to land and soil quality characteristics.

Study site and layout

Our study sites were located in southwest Michigan, and constituted seven experimental units of 9–21 ha size (Fig. 1). The data used for this study are from 2009 when all the sites except a reference no-management site were planted to no-till soybean. Before 2009, three of the sites (AG-S1, AG-S2, AG-S3) were in a corn–soybean rotation for >10 years, while the other three (CRP-S1, CRP-S2, CRP-S3) were enrolled in the CRP of the United States Department of Agriculture (USDA) for the past 20 years. A reference site (CRP-REF) was also under CRP for 20 years and remained dominated by Smooth Brome (*Bromus inermis* Leyss) grass. The three sites converted from CRP lands (and CRP-REF) were maintained fol-

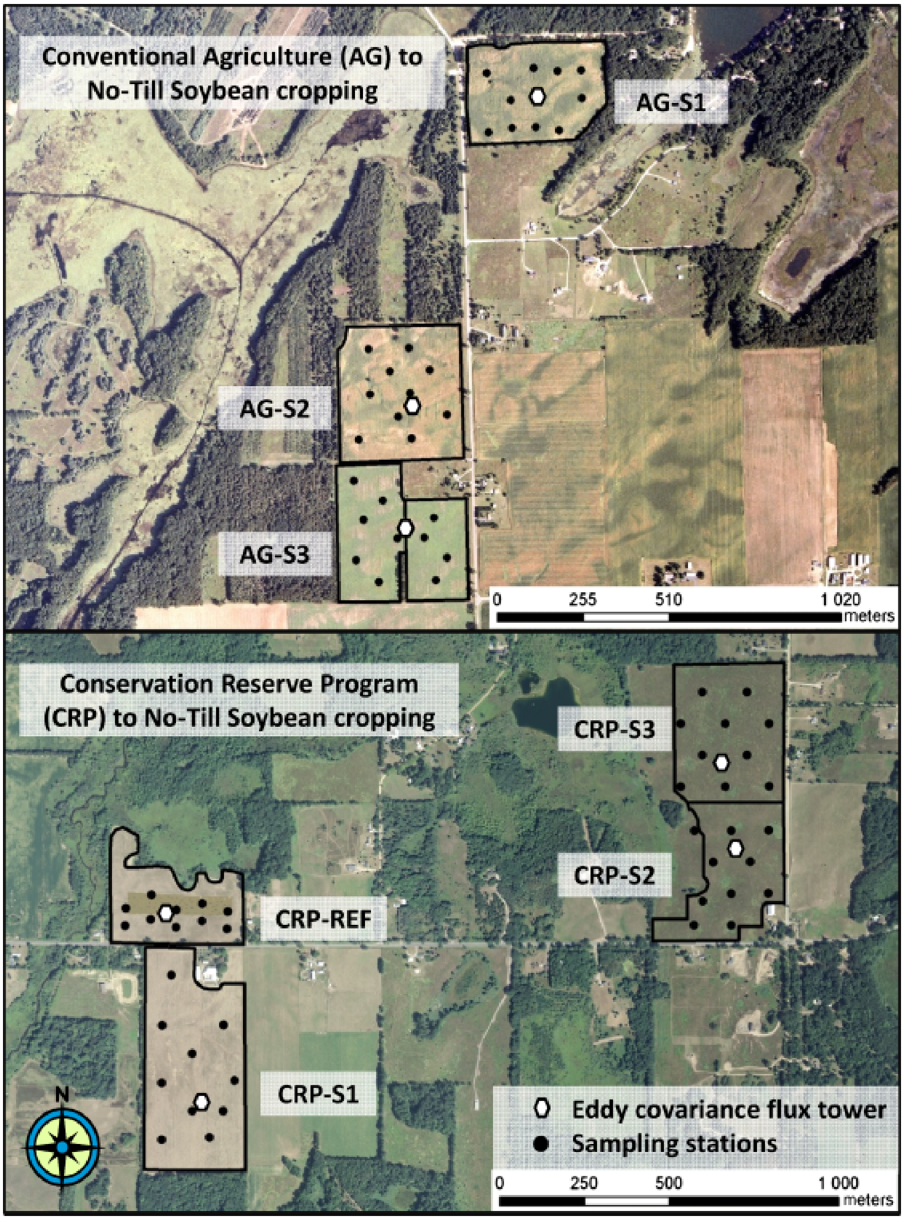

Fig. 1 Experimental layout of the sites and locations of eddy flux towers. AG-S1, -S2, and -S3 were converted from conventional agriculture to no-till soybean; CRP-S1, -S2, and -S3 were converted from Conservation Reserve Program (CRP) to no-till soybean; CRP-REF was the reference site with continued CRP land use.

Table 1 Selected characteristics of the soil map units representing the studied sites

Soil map unit	Soil	Slope (%)	K	Depth of surface soil (inches)	LCC	T	K_s ($\mu m\, s^{-1}$)
6C	Boyer loamy sand	6–12	0.17	9	III e	4	57.4
6D	Boyer loamy sand	12–18	0.17	9	IV e	4	57.4
6E	Boyer loamy sand	18–40	0.17	9	VII e	4	57.4
21	Houghton Muck	Flat		14	V e	3	21.7
22B	Kalamazoo loam	6–12	0.32	10	II e	4	9.0
22C	Kalamazoo loam	12–18	0.32	10	III e	4	9.0
22D	Kalamazoo loam	18–40	0.32	10	IV e	4	9.0
31B	Oshtemo sandy loam	0–6	0.24	9	III s	5	28.0
31C	Oshtemo sandy loam	6–12	0.24	9	III e	5	28.0
31D	Oshtemo sandy loam	12–18	0.24	9	IV e	5	28.0
31E	Oshtemo sandy loam	18–40	0.24	9	VII e	5	28.0

LCC, land capability class and sub class; K, soil erosion factor; T, erosion tolerance factor; K_s, saturated hydraulic conductivity (0–50 cm depth).

lowing CRP management criteria in Smooth Brome grass before conversion. Historically, all seven sites were in either row crops or pasture for at least the past 72 years (based on occasional aerial photos) and cultivated every year for the past 40 years (Michigan land use survey maps). Soils at the sites developed on glacial outwash and are Typic Hapludalfs of the Kalamazoo (fine-loamy), Oshtemo (coarse-loamy), and Boyer (loamy sand) series. Climate is temperate with cool, moist winters and warm, humid summers. The area receives approximately 900 mm of annual precipitation, with about half as snow. Average annual temperature is 9.7 °C. Selected characteristics of the SSURGO soil map units representing the sites are summarized in Table 1.

Site preparation and management

In May 2009, before planting soybean, all vegetation on the three converted CRP sites was killed using glyphosate (N-phosphonomethyl, Syngenta, Greensboro, NC, USA) with a nonionic surfactant ($0.35\,L\,ha^{-1}$) and ammonium sulfate ($1.5\,kg\,ha^{-1}$) for effectiveness. Herbicide was applied using a pull type sprayer (Demco Dethmers MFG Company, Boyden, IA, USA) equipped with a monitor sprayer control, SCS 4400 (Raven Manufacturers, Omaha, NE, USA). Soybean cultivar 92M91 with genetically engineered Glyphosate resistance was planted on day of year (DOY) 160 (CRP-S1, CRP-S2, CRP-S3) and 161–162 (AG-S1, AG-S2, AG-S3) using a no-till planter.

Eddy-covariance measurement of evapotranspiration (ET)

The turbulent exchange of CO_2 and H_2O between the vegetation canopy and atmosphere was measured using eddy-covariance flux methods (Lee *et al*., 2004). A 3-m high tower was located close to the center of each site. The footprint of each eddy covariance tower extended about 150–200 m radius in the upwind direction around the tower. The eddy-covariance system on each tower consisted of a LI-7500 open-path infrared gas analyzer (IRGA) (Li-Cor Biosciences, Lincoln, NE, USA), a CSAT3 three-dimensional sonic anemometer (Campbell Scientific Inc., Logan, UT, USA), and a CR5000 data logger (Campbell Scientific Inc.). The LI-7500 was calibrated every 4 months using zero-grade nitrogen gas. A LI-610 dew-point generator (Li-Cor Biosciences) and (Scott Marrin Inc., Riverside, CA, USA) CO_2 standards were used for setting H_2O and CO_2 spans, respectively.

The 30-min mean flux of latent heat was computed as the covariance of vertical wind speed and water concentration, after correcting sonic temperatures for humidity and pressure (Schotanus *et al*., 1983). The coordinate system was corrected using the formulation of Leuning (2004) in the planar fit coordinate system (Wilczak *et al*., 2001), which was defined from the entire year's mean wind data using the EC-processor (http://research.eeescience.utoledo.edu/lees/ECP/ECP.html; Noormets *et al*., 2008). Data quality was assessed using stationarity and stability criteria (Foken & Wichura, 1996). Thirty minute averages of latent heat was summed to a daily value after discarding latent heat fluxes >800 and $<-250\,W\,m^{-2}$. Daily evapotranspiration (ET) in $mm\,day^{-1}$ was derived by dividing the latent heat by the water vaporization constant.

The gross primary productivity (GPP) was determined by subtracting ecosystem respiration (R_e) from net ecosystem exchange (NEE). Daytime R_e were obtained from the nocturnal NEE-temperature relationship using the partitioning method described in Reichstein *et al*. (2005), which is a standardized flux partitioning technique used by the AmeriFlux and FLUXNET networks.

Soil water content on each of these sites was monitored using an *in situ* time domain reflectometry (TDR) sensor close to the eddy covariance tower. The TDR water sensor was installed vertically from the surface and was 30 cm long. The sensor determined soil water content every 30 min.

Soil sampling and analysis

Soil cores (1-m depth) were collected at 10 geo-referenced stations at each site before soybean planting using a hydraulic corer (Geoprobe Systems, Salina, KS, USA). The cores were divided into different depths (0–0.1, 0.1–0.25, 0.25–0.50, 0.50–1.0 m) and analyzed for various physical and chemical characteristics. The data for the 0–0.25 m layer were used for soil quality evaluation. In total, we collected 70 samples from seven experimental sites.

We used 12 soil characteristics important to crop production for development of a soil quality index (SQI). Bulk density (BD) (1) and soil texture (2) were measured by the core methods (Blake & Hartge, 1986) and Bouyoucos hydrometer method (Gee & Bauder, 1986), respectively. Soil aggregate stability (3) (soil stability ratio; SSR) was determined using the high energy moisture characteristics (HEMC) method (Collis-George & Figueroa, 1984; Pierson & Mulla, 1989; Levy & Miller, 1997; Levy & Mamedov, 2002). In the HEMC method, aggregates are wetted either slowly ($20\,mm\,h^{-1}$) or rapidly ($100\,mm\,h^{-1}$), and moisture characteristic curves at high energies (i.e., up to 500 mm H_2O tension) are measured. Details of this method are provided in Bhardwaj *et al*. (2007). Total soil carbon (4) and nitrogen (5) were determined by dry combustion of dried, ground soil samples using an automatic CN analyzer (Costech Analytical Technologies Inc., Valencia, CA, USA). Other chemical properties including pH (6), cation exchange capacity (CEC) (7), available Phosphorus (P) (8), exchangeable Potassium (K^+) (9), Calcium (Ca^{2+}) (10), and Magnesium (Mg^{2+}) (11), were analyzed at Michigan State University's Soil Testing Laboratory. Determination of P was by extraction using Bray-Kurtz P1 (weak acid) solution, while K^+, Ca^{2+} and Mg^{2+} were extracted using 1.0 N neutral ammonium acetate. P concentrations were determined by colorimetry with a spectrophotometer (Olsen *et al*., 1954), and K^+, Ca^{2+} and Mg^{2+} were determined by inductively coupled plasma-atomic emission spectroscopy. Soil pH and electrical conductivity (EC) (12) were measured in a 1 : 1 soil-to-water suspension with a pH and EC meter, respectively.

Soil quality assessment

The first step followed in the soil quality assessment and development of SQI is to define the primary soil function, which in this case is crop productivity, and then to select a minimum dataset (MDS) to represent this function. We used 12 soil parameters for development of the MDS. The data were reduced to MDS through a series of uni- and multivariate statistical methods. Nonparametric statistics (Kruskal–Wallis χ^2) were used to identify indicators with significant differences among sites. Only variables with significant differences among sites ($P < 0.05$) were chosen for the next step in MDS formation. A standardized principal components analysis (PCA) was performed for each statistically significant variable (Andrews & Carroll, 2001; Andrews *et al*., 2002). Principal components (PCs) are linear combinations of variables that account for maximum variance for a data set; PCs receiving high Eigen values and variables with high factor loading best represent system attributes. Therefore, we examined only PCs with Eigen values ≥ 1.0 (Brejda *et al*., 2000). Within each PC only highly weighted factors (i.e., those with absolute values within 10% of the highest weight) were retained for the MDS. To reduce redundancy and to rule out spurious groupings among the highly weighted variables within PCs, Pearson's correlation coefficients were used to determine the strength of the relationships among variables.

After determining the variables for the MDS, every observation of each MDS indicator was transformed for inclusion in the SQI. A linear scoring technique was followed because of its simplicity of design and because it relies on the observed knowledge of the system (Liebig *et al*., 2001). Indicators were ranked in the ascending or descending order depending on whether a higher value was considered 'beneficial' or 'detrimental' to primary soil function. For 'higher is better' indicators such as C, each observation was divided by the highest observed value such that the highest observed value received a score of 1. For 'lower is better' indicators, such as BD, the lowest observed value (in the numerator) was divided by each observation (in the denominator) such that the lowest observed value received a score of 1. For those indicators, such as pH, where 'neither higher is better nor lower is better', observations were scored as 'higher is better' up to a threshold value and then scored as 'lower is better' above the threshold value (Liebig *et al*., 2001).

Once transformed, the MDS variables for each observation were weighted using the PCA results. Each PC explained a certain amount (%) of the variation in the total data set. This percentage, divided by the total percentage of variation explained by all PCs with eigenvectors >1.0, provided the weighted factor for variables chosen under a given PC. The SQI was determined as:

$$\mathrm{SQI} = \sum_{i=1}^{n} (W_i \times S_i), \tag{1}$$

where W is the PC weighting factor and S is the indicator score for variable i. In the model, higher index scores indicate better soil quality or greater performance of soil function.

Land marginality assessment

Land marginality was assessed by combining five dominant factors in land quality assessment from the standpoints of crop production as well as environmental quality. These factors were land capability class, soil erodibility, slope, hydraulic conductivity and soil tolerance. These constituted five primary land quality characteristics which determine how marginal a land area is for crop/biomass production, in regard to biophysical characteristics. These land characteristics were extracted from Soil Survey Geographic (SSURGO) database for Barry County, Michigan (Soil Survey Staff, 1990). These five characteristics were combined into a land marginality index (LMI) as follows:

$$\mathrm{LMI} = \frac{(\text{Land capability factor}) + (\text{site slope factor}) + (\text{soil erodibility factor})}{(\text{Profile conductivity factor}) + (\text{soil tolerance factor})}. \tag{2}$$

The land capability factor (LCF) was calculated as:

$$\mathrm{LCF} = \sum_{i=1}^{n} (C_i A_i), \tag{3}$$

where C is land capability class number for a soil map unit i and A is the area of the site under the soil map unit i.

The site slope factor (SSF) for the sites was calculated as:

$$\mathrm{SSF} = \sum_{i=1}^{n} (S_i A_i), \tag{4}$$

where S is the average slope for a soil map unit i, and A is the area of the site under the soil map unit i.

The soil erodibility factor (SEF) for the sites was calculated as:

$$\mathrm{SEF} = \sum_{i=1}^{n} (K_i A_i), \tag{5}$$

where K is the soil erosion factor for a soil map unit i, and A is the area of the site under the soil map unit i. Soil erosion is one of the most important factors that affects productivity by reducing infiltration, water holding capacity, soil biota and even soil depth (Pimentel et al., 1995). The soil erosion factor indicates the susceptibility of a soil to sheet and rill erosion by water. It is one of six factors used in the universal soil loss equation (USLE) and the revised universal soil loss equation (RUSLE) to predict the average annual rate of soil loss by sheet and rill erosion (Renard et al., 1991). Values of K range from 0.02 to 0.69. Other factors being equal, the higher the value for K, the more susceptible the soil is to sheet and rill erosion by water (http://websoilsurvey.nrcs.usda.gov/).

The profile conductivity factor (PCF) for the sites was calculated as:

$$\mathrm{PCF} = \sum_{i=1}^{n} (K_{si} A_i), \tag{6}$$

where K_s is the representative saturated hydraulic conductivity for a soil map unit i, and A is the area of the site under the soil map unit i.

The soil tolerance factor (STF) for the sites was calculated as:

$$\mathrm{STF} = \sum_{i=1}^{n} (T_i A_i), \tag{7}$$

where T is the erosion tolerance factor for the soil map unit i, and A is the area of the site under the soil map unit i. The erosion tolerance factor T is an estimate of the maximum average annual rate of soil erosion by wind and/or water that can occur without affecting crop productivity over a sustained period (Renard et al., 1991). The rate is in tons per acre per year.

Finally, for inclusion in the LMI, each of these factors was normalized to the highest observed value at our study sites by dividing each observation by the highest observed value.

Net primary productivity and crop yields

Aboveground net primary production (ANPP) was estimated as the annual maximum plant biomass accumulation. Plant biomass was measured by quantifying the peak dry mass of plants per unit area in each treatment in late September. We sampled by clipping plants within a 1 m^2 area at 10 geo-referenced sampling stations at each site. The crop plants were further separated into grain and stover. The biomass was dried at 60 °C for at least 48 h and weighed. The peak grain plus stover biomass was used for footprint calculations. Crop yields were also determined by harvesting soybeans on each site using a JD 9410 combine with a global positioning system (John Deere Inc., Moline, IL, USA). This area-weighted grain yield was used for determining the harvestable yield potential of the sites.

Water and energy footprints

Water and energy footprints of the soybean production for biofuels were calculated as follows. Water footprint is the volume of water used to produce a product, in our case either grain or total biomass (ANPP).

$$\text{Water footprint (grain)} = \frac{\text{Crop water use (m}^3)}{\text{Grain yield (Mg)}}, \quad (8)$$

$$\text{Water footprint (ANPP)} = \frac{\text{Crop water use (m}^3)}{\text{ANPP (Mg)}}, \quad (9)$$

$$\text{Water footprint (energy)} = \frac{\text{Crop water use (m}^3)}{\text{Biodiesel energy produced (GJ)}}, \quad (10)$$

$$\text{Water use efficiency (grain)} = \frac{\text{Grain yield (kg)}}{\text{Crop water use (m}^3)}, \quad (11)$$

$$\text{Water use efficiency (net photosynthesis)} = \frac{\text{Gross primay productivity (kg)}}{\text{Crop water use (m}^3)}, \quad (12)$$

where crop water use was determined from the total ET as estimated using eddy covariance fluxes.

The energy indices were computed as:

$$\text{Energy efficiency} = \frac{\text{Total energy output (kW h-out)}}{\text{Total energyInput (kW h-in)}}, \quad (13)$$

$$\text{Energy productivity} = \frac{\text{Grain yield(kg)}}{\text{Total energy input (kW h)}}, \quad (14)$$

$$\text{Specific energy} = \frac{\text{Total energy input (kW h)}}{\text{Grain yield (kg)}}. \quad (15)$$

Total energy input included the use of fertilizer, seed, pesticide, and diesel for all operations. The total energy output included biodiesel energy produced. The total energy output was calculated from biodiesel yield from each site using bioenergy conversion factors recommended by the Oak Ridge National Laboratory (ORNL) and available at: http://bioenergy.ornl.gov/papers/misc/energy_conv.html (accessed 21 April 2010).

Statistical analysis

The selection of MDS and the PCA for SQI development was performed using SPSS (1998). Yield and productivity were analyzed statistically using SAS Institute. (2004). All parameters were tested using a one-way analysis of variance (ANOVA) and separation of means was subjected to Tukey's honestly significant difference test (Steel & Torrie, 1960). Correlation analysis was conducted to identify relationships between the measured parameters. All tests were performed at the 0.05 significance level.

Results

During the period of this study the annual average air temperature was 8.5 °C and the precipitation was 920 mm, which tends to be evenly distributed throughout the year. The maximum daily photosynthetically active radiation was recorded during the summer season between 11:00 and 14:00 h, with an average value of 800 μmoles m^{-2} s^{-1}. The meteorology of this period represented an average year.

SQI

There were significant differences in the soil physical and chemical properties of the studied sites (Table 2). On average, BD was 0.1–0.3 Mg m^{-3} higher at historically agricultural sites (AG) compared with sites which had been enrolled in the CRP. There were significant differences in soil pH among the sites. The SSR, an indicator of aggregate stability, was also higher in CRP compared with AG. CRP lands also were higher in available P, exchangeable K^+, total carbon (C) and total nitrogen (N). Ammonium nitrogen (NH_4^+-N) and nitrate-nitrogen (NO_3^--N) contents were more than double in the CRP compared with AG. On the other hand, Ca^{2+} and Magnesium Mg^{2+} contents were higher in AG, possibly due to practice of adding lime which is prevalent in the region on agricultural lands and was also practiced on these AG.

The nonparametric test of soil properties of the sites revealed that out of 12 soil variables, 11 variables were significantly different among the sites at $P<0.01$ (Table 2). For SQI development these 11 variables were selected for PCA. In the PCA of 11 variables, three PCs had Eigen values >1 and explained 77% of the variance in the data (Table 3). Highly weighted variables (those within absolute 10% of the highest weight of factor loading in each PC) under PC1 included C, N, and

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Table 2 Soil physical and chemical properties that were used for the minimum data set (MDS) selection process for the soil quality index (SQI) development

Treatment*	BD	SSR	pH	P	K^+	Ca^{2+}	Mg^{2+}	C	N	NH_4^+-N	NO_3^--N
AG-S1	$1.55^{bc\dagger}$	0.54^{bcd}	6.04^{abc}	29.0^{e}	72.7^{b}	1.14^{a}	127.5^{b}	14.20^{c}	1.32^{d}	0.13^{b}	0.07^{a}
AG-S2	1.73^{a}	0.50^{d}	6.14^{abc}	35.2^{de}	95.7^{b}	1.22^{a}	179.7^{a}	13.70^{c}	1.34^{d}	0.11^{b}	0.05^{a}
AG-S3	1.61^{ab}	0.53^{cd}	5.80^{bc}	27.5^{e}	71.9^{b}	1.13^{a}	190.1^{a}	16.38^{bc}	1.62^{cd}	0.15^{b}	0.05^{a}
CRP-S1	1.41^{cd}	0.83^{a}	5.80^{abc}	85.0^{ab}	170.1^{a}	0.94^{ab}	69.4^{c}	30.94^{a}	2.79^{a}	0.64^{a}	0.10^{a}
CRP-S2	1.34^{d}	0.70^{abc}	6.28^{a}	56.5^{cd}	92.3^{b}	0.93^{ab}	57.8^{c}	26.39^{a}	2.27^{abc}	0.58^{a}	0.08^{a}
CRP-S3	1.42^{cd}	0.72^{ab}	5.72^{c}	63.4^{bc}	110.1^{b}	0.80^{b}	85.7^{c}	23.75^{ab}	2.02^{bcd}	0.50^{a}	0.10^{a}
CRP-REF	1.41^{cd}	0.65^{abcd}	6.15^{ab}	87.2^{a}	181.7^{a}	1.10^{ab}	89.4^{bc}	30.59^{a}	2.69^{ab}	0.50^{a}	0.09^{a}
$P<\alpha$‡	<0.0001	0.0013	0.0020	<0.0001	<0.0001	0.0002	<0.0001	<0.0001	<0.0001	<0.0001	0.0012

*AG-S1, -S2, -S3, no-till agriculture to no-till soybean land use change; CRP-S1, -S2, -S3, Conservation Reserve Program (CRP) land to no-till soybean land use change; CRP-REF, reference site with continued CRP land use.

†For a soil property, treatments followed by same letters are not significantly different at $P<0.01$.

‡α Level of significance of Kruskal–Wallis test.

BD, bulk density ($Mg\,m^{-3}$); SSR, soil stability ratio; P, available phosphorus ($kg\,ha^{-1}$); K^+, exchangeable potassium ($kg\,ha^{-1}$); Ca^{2+}, calcium ($Mg\,ha^{-1}$); Mg^{2+}, magnesium ($kg\,ha^{-1}$); C, soil carbon ($g\,kg^{-1}$); N, soil nitrogen ($g\,kg^{-1}$); NH_4^+-N, ammonium nitrogen ($mg\,kg^{-1}$); NO_3^--N, nitrate nitrogen ($mg\,kg^{-1}$).

Table 3 Results of principal components (PC) analysis of statistically significant soil quality indicators

Statistical parameter	PC1	PC2	PC3
Eigen value	5.80	1.546	1.14
% of variance	52.74	14.05	10.36
Cumulative percent	52.74	66.79	77.16
Soil parameter*		Factor loading/Eigen Vector	
SSR	0.663	−0.408	−0.048
pH	−0.027	0.176	0.890†
BD	−0.643	0.364	−0.108
C	0.869†	−0.277	−0.032
N	0.897†	−0.201	−0.055
P	0.776	−0.395	0.250
K^+	0.866†	0.230	−0.091
Ca	−0.073	0.951†	0.156
Mg	−0.380	0.786	0.002
NH_4^+-N	0.733	−0.559	0.170
NO_3^--N	0.235	−0.514	0.539

*SSR, soil stability ratio; BD, bulk density ($Mg\,m^{-3}$); C, soil carbon ($g\,kg^{-1}$); N, soil nitrogen ($g\,kg^{-1}$); P, available phosphorus ($kg\,ha^{-1}$); K^+, exchangeable potassium ($kg\,ha^{-1}$); Ca^{2+}, calcium ($kg\,ha^{-1}$); Mg^{2+}, magnesium ($kg\,ha^{-1}$); NH_4^+-N, ammonium nitrogen ($mg\,kg^{-1}$); NO_3^--N, nitrate nitrogen ($mg\,kg^{-1}$).

†Factor loadings are considered highly weighted when within 10% of variation of the absolute values of the highest factor loading in each PC.

K^+. Pearson's correlation coefficients for the highly weighted variables under different PCs were determined separately to reduce the redundancy among the variables. Ca^{2+} and pH showed highest weighted values in PC2 and PC3, respectively. The final MDS thus included C, N, K^+, Ca^{2+} and pH, indicating that the most significant differences in the soils of the sites were in their C content and nutrient availability.

These five variables were selected for developing the SQI. The selected MDS variables for each site were transformed using linear scoring functions. Among the selected soil characteristics, C, N, and K^+ were considered as 'the higher the better'. For pH, neutral (7.0) was considered desirable and therefore it was also taken as 'the higher the better' because all values were <7.0. Therefore, for all of the selected soil properties, the parameter values for all sites were divided by the highest value, such that the site with highest value received a score of 1 and all other values were normalized to it. The coefficient of 'weighting factor' for the variables in PC1 (C, N, K^+) was 0.684, and it was 0.182 for PC2 (Ca^{2+}), and 0.132 for PC3 (pH). The SQI was highest for the CRP-REF and CRP-S1 sites, and all of the CRP sites had higher SQIs than the AG sites (Fig. 2). At all sites the soil available N made the highest contribution to SQI, followed by C and K^+.

LMI

There were significant differences between historically agricultural (AG-S1, AG-S2, AG-S3) and conservation reserve (CRP-S1, CRP-S2, CRP-S3, CRP-REF) sites in the SEF, SSF, STF and LCF (Fig. 3). The SEF was higher in AG compared with CRP, while SSF was higher in the more topographically variable CRP landscapes. The LCF was highest for AG-S1 and lowest for CRP-REF site. The LMI, which combines these factors, was higher for AG (LMI = 1.3–1.5) compared with CRP sites (LMI = 0.8–1.2) (Fig. 4).

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ET and consumptive water use

The cumulative ET during the growing season from soybean emergence to harvest is presented in Fig. 5. Prior to emergence of the crop (late May to early June), the ET gradually increased with available solar energy (data not presented). After emergence of crop canopy, ET began increasing rapidly (DOY = 190–260). There was a steady increase in ET for all sites, except AG-S2 and CRP-S2, from first trifoliate (V1) to initial seedling stage (V5). The peak ET ranged from 3 to 6 mm day^{-1} for the soybean sites compared with CRP-REF where it peaked at ~4 mm day^{-1}. The ET values began declining from initial maturity (V6) to full maturity (V8) stage until harvesting at DOY 306.

The total water evapotranspired (crop water use) by the soybean crop varied considerably among the six fields planted in soybeans (Fig. 5). The site AG-S2 had the least consumptive water use followed by CRP-REF and CRP-S2. One of the most probable ways in which land marginality is associated with inferior crop growth and ET is lower soil water availability during the growing season. Measurements of soil water content show that the CRP sites (CRP-S1, CRP-S2 and CRP-S3) maintained higher soil water content than AG sites (AG-S1, AG-S2 and AG-S3) until the middle of the growing season (Fig. 6). On the other hand close to maturity the AG sites maintained higher soil water compared with CRP, until the end of the year. Main-

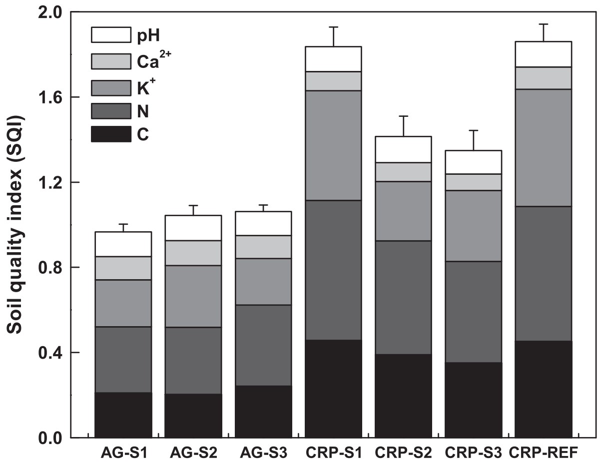

Fig. 2 Soil quality index (SQI) for the sites. Error bars indicate ± 1 SD. AG-S1, -S2, -S3, conventional agriculture to no-till soybean land use change; CRP-S1, -S2, -S3, Conservation Reserve Program (CRP) land to no-till soybean land use change; CRP-REF, reference site with continued CRP land use.

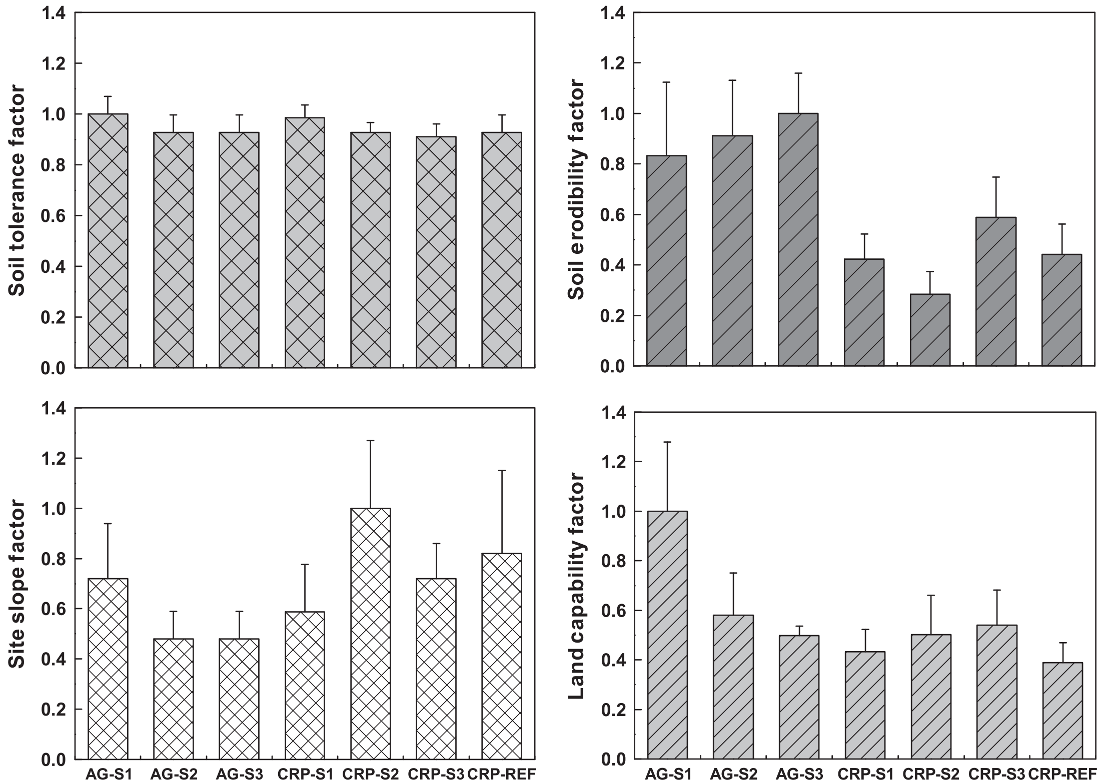

Fig. 3 Selected factors included in the land marginality index (LMI) developed for the sites. Error bars indicate ± 1 SD for soil map unit on a site. AG-S1, -S2, -S3, conventional agriculture to no-till soybean land use change; CRP-S1, -S2, -S3, Conservation Reserve Program (CRP) land to no-till soybean land use change; CRP-REF, reference site with continued CRP land use.

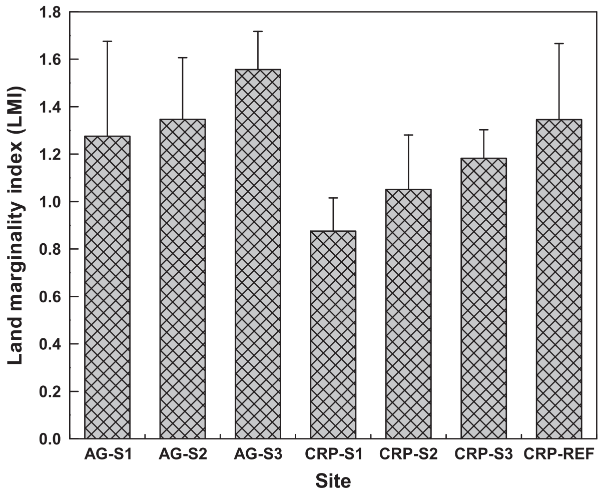

Fig. 4 Land Marginality Index (LMI) for the sites. Error bars indicate ± 1 SD for soil map unit on a site. AG-S1, -S2, -S3, conventional agriculture to no-till soybean land use change; CRP-S1, -S2, -S3, Conservation Reserve Program (CRP) land to no-till soybean land use change; CRP-REF, reference site with continued CRP land use.

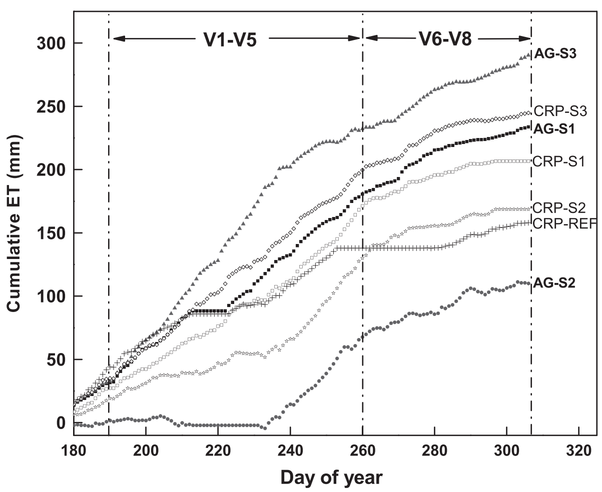

Fig. 5 Changes in cumulative evapotranspiration (ET) of soybeans over the growing period on the sites. AG-S1, -S2, -S3, conventional agriculture to no-till soybean land use change; CRP-S1, -S2, -S3, Conservation Reserve Program (CRP) land to no-till soybean land use change; CRP-REF, reference site with continued CRP land use. V1 = first trifoliate stage, V5 = initial seedling stage, V6 = initial maturity stage, V8 = full maturity stage.

taining higher soil water indicates suitable conditions for crop growth and less effect of drought periods on crop growth and productivity. Since there was only one soil water sensor per site, close to the flux tower, it serves only as a very general indication of land and soil quality effects.

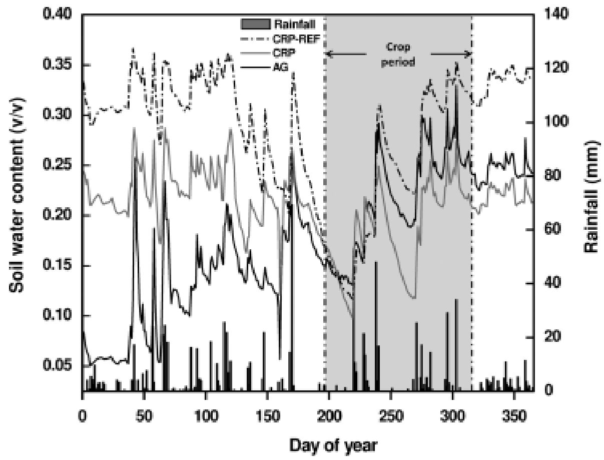

Fig. 6 Average daily soil water content for the sites based on samples taken from 0 to 0.25 m. AG-S, conventional agriculture to no-till soybean land use change; CRP-S, Conservation Reserve Program (CRP) land to no-till soybean land use change; CRP-REF, reference site with continued CRP land use.

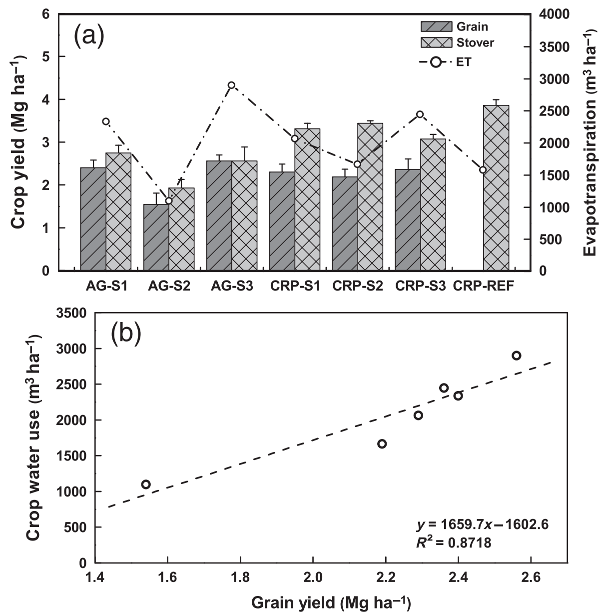

Fig. 7 Total crop water use and soybean biomass yields from the sites. AG-S1, -S2, -S3, conventional agriculture to no-till soybean land use change; CRP-S1, -S2, -S3, Conservation Reserve Program (CRP) land to no-till soybean land use change; CRP-REF, reference site with continued CRP land use.

Yield and productivity

The soybean ANPP was closely related to the crop water use (Fig. 7). Site AG-S3 had the highest grain yield followed by AG-S1 and CRP-S3. Site AG-S2 had the least grain yield as well as crop water use. Similar trends were not evident in the stover yield. The CRP sites (CRP-S1, -S2, -S3) had comparatively higher stover

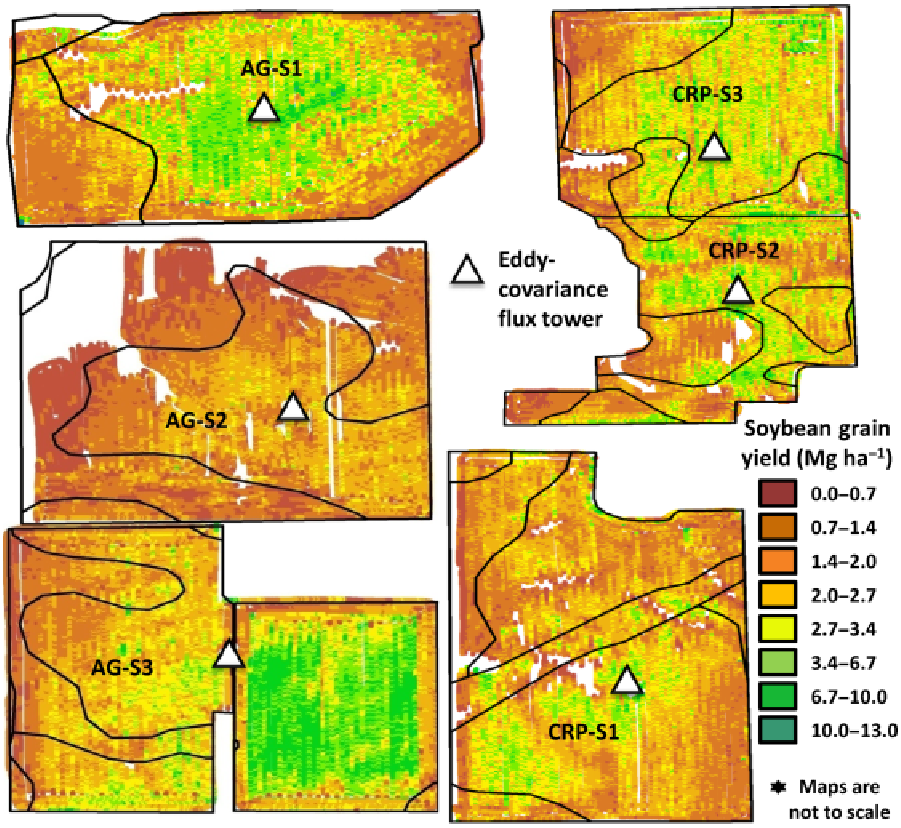

Fig. 8 Harvested soybean grain yield maps of the sites showing spatial variability of productivity. AG-S1, -S2, -S3, conventional agriculture to no-till soybean land use change; CRP-S1, -S2, -S3, Conservation Reserve Program (CRP) land to no-till soybean land use change; CRP-REF, reference site with continued CRP land use. The contoured lines within a site indicate the boundaries of SSURGO soil map units.

yields than the AG sites. The actual harvesting patterns and spatial distribution of grain yield on the sites provided a better indication of how marginality characteristics (land capability class, slope, soil erodibility, erosion tolerance and hydraulic conductivity) interacted with grain productivity (Fig. 8). For example, site AG-S1 had higher LMI than AG-S2, but the productivity on AG-S2 was very low compared with AG-S1. The AG-S2 site was largely affected by sheet and rill (turning into gullies) erosion which was well indicated by the site's erodibility and tolerance factors.

The three way analysis of the interactions of the LMI and SQI with ANPP indicated a direct relationship between ANPP and SQI, and an inverse relationship between ANPP and LMI (Fig. 9). To a lesser extent the relationship was also affected by the management history of the sites. The CRP sites had higher ANPP than the AG sites which was also indicative of the former's higher soil quality (Figs 2 and 4).

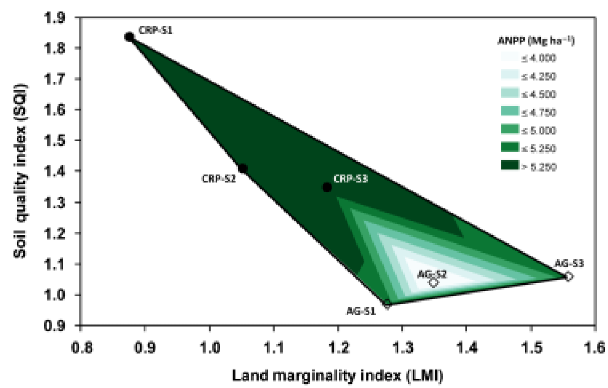

Fig. 9 Contour map of the interactions between aboveground net primary productivity (ANPP), soil quality index (SQI) and land marginality index (LMI). AG-S1, -S2, -S3, conventional agriculture to no-till soybean land use change; CRP-S1, -S2, -S3, Conservation Reserve Program (CRP) land to no-till soybean land use change; CRP-REF, reference site with continued CRP land use.

Water and energy footprints

The water footprints of the soybean crops were related directly with LMI and indirectly with SQI. As LMI increased the water footprint (of total biomass production) increased, while the footprints decreased with increased soil quality (Fig. 10). The water footprint also changed based on whether grain production (for biodiesel) or total biomass was considered as the end product. There were combined effects of LMI and SQI on the water use efficiency and energy efficiency (Table 4). Water use efficiencies based on net photosynthesis, grain yield and total biomass were highest in CRP-S2 and AG-S2 and lowest in AG-S3. There was very close agreement between the water use efficiency based on total biomass produced and the one based on the GPP determined using eddy-covariance measurements.

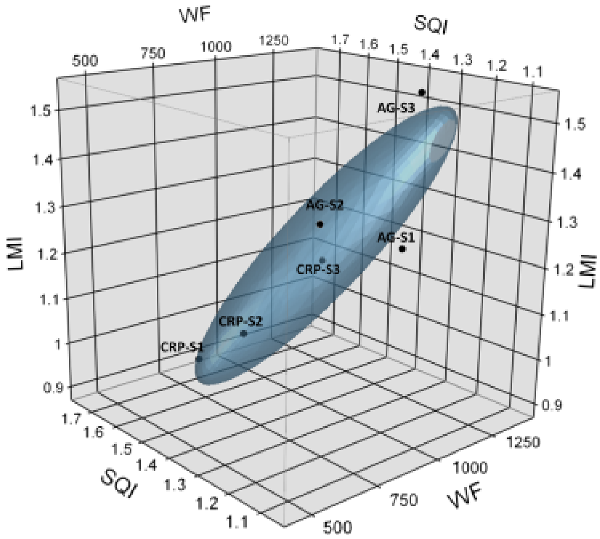

Fig. 10 Interrelationships of water footprints (WF; $m^3 Mg^{-1}$) with the soil quality index (SQI) and Land Marginality Index (LMI) on the studied sites. AG-S1, -S2, -S3, conventional agriculture to no-till soybean land use change; CRP-S1, -S2, -S3, Conservation Reserve Program (CRP) land to no-till soybean land use change; CRP-REF, reference site with continued CRP land use.

The AG sites had larger water footprints compared with CRP sites considering crop water use per unit ANPP. The site CRP-S3 had the largest water footprint per unit energy output (from biodiesel; 172.3 $m^3 GJ^{-1}$) among CRP sites, and AG-S3 had largest (157.6 $m^3 GJ^{-1}$) among AG sites (Table 4). The energy efficiency of all the sites for biofuel production was very low. The only site with energy efficiency higher than one (i.e., net positive energy yield) was AG-S3. The main reason for energy efficiency lower than one during the first year of conversion was because of the use of a large quantity of herbicide on these sites. This initial high-energy input will not be present in subsequent years (Table 4). Although there were no significant interactions between the energy productivity, and land and soil quality, in general the energy productivity of the CRP sites was lower than the AG sites, perhaps due to the same reason (Table 4).

Discussion

We found significant interactions between land quality indices (SQI and LMI) and water as well as energy footprints on the studied sites. The land under CRP had significantly higher land quality in terms of both soil physical (BD, SSR) and chemical (C, N, K^+) characteristics. Water and energy footprints, in general, increased with marginality characteristics. The total biomass produced (ANPP) and grain yield decreased with decreased land quality. Although the extent (but not direction) may vary regionally, marginal lands used to grow biofuels are likely to have bigger water and energy footprints (Fig. 10).

Table 4 Water and energy footprints of soybean crops on the study sites

Treatment*	Water use efficiency (net photosynthesis) ($kg\,m^{-3}$)	Water use efficiency (grain; biomass) ($kg\,m^{-3}$)	Water footprint (grain) ($m^3 Mg^{-1}$)	Water footprint (biomass) ($m^3 Mg^{-1}$)	Water footprint (energy) ($m^3 GJ^{-1}$)†	Energy efficiency (kW h-out/kW h-in)	Energy productivity ($kg\,kW\,h^{-1}$)	Specific energy ($kW\,h\,kg^{-1}$)
AG-S1	2.44	1.03 (2.20)	974	454	148	0.61 (8.97)	0.33 (4.91)	2.99 (0.20)
AG-S2	2.55	1.40 (3.15)	715	317	108	0.49 (6.41)	0.27 (3.51)	3.74 (0.29)
AG-S3	2.23	0.88 (1.76)	1134	567	172	1.29 (12.76)	0.71 (6.98)	1.42 (0.14)
CRP-S1	2.46	1.11 (2.72)	902	368	137	0.51 (9.19)	0.28 (5.02)	3.58 (0.20)
CRP-S2	2.60	1.31 (3.37)	761	297	116	0.36 (7.63)	0.20 (4.17)	5.08 (0.24)
CRP-S3	2.04	0.96 (2.44)	1037	452	158	0.57 (9.71)	0.31 (5.31)	3.20 (0.19)

Figures in parenthesis is the scenario calculated without use of herbicide, which was used in the first year to kill weeds/grasses on the site for planting of soybeans.

*AG-S1, -S2, -S3, conventional agriculture to no-till soybean land use change; CRP-S1, -S2, -S3, Conservation Reserve Program (CRP) land to no-till soybean land use change; CRP-REF, reference site with continued CRP land use.

†Energy from biodiesel yield from soybeans.

Water and energy footprint assessment for marginal lands

Assessment of land quality and its effects on water and energy footprints helps identify the limitations of a land and its management implications. Although the total cropland acreage in United States has remained roughly constant for last 100 years, the less productive 'marginal' cropland has shifted in and out over time (Lubowski *et al*., 2006). Production costs and economic returns are the likely drivers inducing farmers to shift marginal lands in and out of production. Less productive cropland is often more environmentally sensitive than protected land (Wiebe, 2003). Therefore, land use change to grow biofuel crops on marginal fallow or less productive agricultural lands may have undesirable environmental as well as economic consequences without proper consideration of the capabilities and limitations of the land.

Use of multivariate approaches to group and transform data, and incorporation of the appropriate metrics into the soil quality (SQI) and land marginality (LMI) indices, helped us interpret complex land quality characteristics. The SQI approach not only helped identify factors sensitive to management but also the interrelatedness of those factors. Among the numerous variables considered important from crop production as well as environmental standpoints, selection of the most significant ones based on total variance in the data, and their integration into a single index (LMI), helped interpret changes in production potential of the soils of these lands under different land use histories and degrees of marginality. This potential in turn indicated long-term effects (ca. 20 years in CRP vs. row crop production) on the environmental sustainability of land management practices. Assessment of soil quality using a single index (SQI) also helped to identify potential tradeoffs in soil conditions that might result from management choices, as well as to identify improved management practices with enhanced environmental benefits. For example, sites which were under CRP for the past several years maintained higher soil quality which was also evident in the aboveground productivity of these sites.

Land marginality relevance to biofuel induced land use change

Marginal lands have been proposed as viable areas for growing biofuels to avoid competition with food production on prime agricultural land; however, it is uncertain whether energy and water footprints of growing biofuels on marginal lands will be the same as on prime farm lands. The energy and water productivity of the marginal lands will determine how much land will be needed in the vicinity of a biorefinery to achieve targeted energy outputs. The two most important characteristics of marginal lands, low soil quality for crop production and environmental sensitivity, should figure prominently in debates about environmental sustainability.

Any bioenergy production initiative that will entail major land use change would also have significant environmental effects, although they will vary regionally. Our results demonstrate the benefits that are achieved in the soil quality of lands under CRP, and its direct implications for their productivity. If biofuel production systems with high yielding, nutrient-efficient perennial grasses and minimal management are developed and implemented on marginal lands such as the CRP fields under study here, environmental as well as economic benefits over time are more likely.

The fact that every marginal land is not the same in its susceptibility to degradation or in its economic viability is underrated in most of the regional and global assessments. In our study, the area-weighted harvestable grain yield was found to range from 40% to 100% of the prime agricultural land in the county based on the degree of marginality as well as management (Fig. 8). We deduced from this study that using the marginal land areas for conventional biofuel crop production may offset a significant amount of bioenergy demand in this region. But on marginal lands with low productivity, increasing bioenergy production would either require increasing productivity or increasing land area used for production. Although it is unclear whether more intensive management of these marginal lands for increased productivity is possible by intensified management without environmental impacts; our results indicate a good potential for cellulosic biofuel crop production. The sites which were previously under CRP supported perennial grasses with virtually no management. Therefore, the soils on these sites accumulated organic matter over time and were less exposed to erosion and oxidation processes. In contrast, sites with a recent agricultural history (AG) had been intensively managed and showed visible signs of sheet and rill erosion, to varying degrees. The higher soil quality in sites under CRP land use in past years indicated soil conservation advantages of the program. The fact that these benefits might have been achieved in last 20 years after converting the land from agriculture to CRP strengthens the argument that growing perennial grasses on marginal land can provide economic as well as ecological benefits in terms of enhanced ecosystem services. From the crop production point of view, these changes are not trivial, considering the two most significant constraints for crop production in the region are nutrient leaching losses and poor water holding capacity, both of which tend to be exacerbated by coarser soil textures.

Conclusions

Landscape scale analysis and use of multivariate approaches to assess land quality complemented each other in developing conceptual understanding of how land use change on marginal lands may affect water and energy footprints. We offer the following conclusions from this study:

1. An indexing framework can be effectively applied to assess the land and soil quality, and is effective in evaluating the potential of marginal lands for biofuel production. It is important to precisely assess this realistic potential as well as its ecological soundness to inform policy as well as to devise management strategies to maximize ecosystem services.

2. The large differences in soil quality between historically agricultural and CRP sites revealed the potential benefits that can be achieved by growing perennial grasses with low input requirements in place of annual crops. The sites historically under CRP had better soil quality in terms of improved soil physical structure, carbon storage, and nutrient availability, strongly suggesting that crops such as high yielding perennial grasses with management systems similar to these may provide a potential strategy to produce bioenergy by improving the productivity as well as ecosystem services.

3. Marginal lands can be viable areas for growing biofuels; however, water and energy footprints of biofuel crops on marginal lands are likely to be higher than on prime farm lands. Decreases in water and energy footprints can be achieved through improvements in soil quality via management and crop choices. Therefore, proper evaluation of capabilities and limitations of the marginal lands and use of region-specific management strategies can make marginal lands an important asset for bioenergy production.

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