Mapping marginal croplands suitable for cellulosic feedstock crops in the Great Plains, United States

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Abstract

Growing cellulosic feedstock crops (e.g., switchgrass) for biofuel is more environmentally sustainable than corn-based ethanol. Specifically, this practice can reduce soil erosion and water quality impairment from pesticides and fertilizer, improve ecosystem services and sustainability (e.g., serve as carbon sinks), and minimize impacts on global food supplies. The main goal of this study was to identify high-risk marginal croplands that are potentially suitable for growing cellulosic feedstock crops (e.g., switchgrass) in the US Great Plains (GP). Satellite-derived growing season Normalized Difference Vegetation Index, a switchgrass biomass productivity map obtained from a previous study, US Geological Survey (USGS) irrigation and crop masks, and US Department of Agriculture (USDA) crop indemnity maps for the GP were used in this study. Our hypothesis was that croplands with relatively low crop yield but high productivity potential for switchgrass may be suitable for converting to switchgrass. Areas with relatively low crop indemnity (crop indemnity <$2 157 068) were excluded from the suitable areas based on low probability of crop failures. Results show that approximately 650 000 ha of marginal croplands in the GP are potentially suitable for switchgrass development. The total estimated switchgrass biomass productivity gain from these suitable areas is about 5.9 million metric tons. Switchgrass can be cultivated in either lowland or upland regions in the GP depending on the local soil and environmental conditions. This study improves our understanding of ecosystem services and the sustainability of cropland systems in the GP. Results from this study provide useful information to land managers for making informed decisions regarding switchgrass development in the GP.

Keywords: cellulosic biofuel feedstock, crop indemnity, Great Plains, growing season average NDVI (GSN), land management, marginal croplands, satellite remote sensing, switchgrass productivity

Introduction

Ethanol produced from Midwest corn (Zea mays) is the most common biofuel product in the United States (Yacobucci & Capehart, 2008; Simpson, 2009; Schnepf & Yacobucci, 2013; DeLucia, 2015). However, corn-based ethanol development presents concerns about world food shortages and negative environmental effects such as soil erosion and water quality impairment (Searchinger et al., 2008; Trostle, 2008; Yacobucci & Capehart, 2008; Gelfand et al., 2010; Pala, 2010; Pimentel, 2010; Schnepf & Yacobucci 2013; Buyx & Taft, 2011). Biofuels produced from cellulosic feedstocks such as grasses and agricultural wastes have lagged behind corn-based ethanol production because the biochemistry of conversion is more complex. As the technical challenges are met and the bioenergy infrastructures and refineries are further developed, demand for cellulosic feedstock is expected to increase in the future (Yacobucci & Capehart, 2008; Bracmort, 2010; Bracmort et al., 2011; Mitchell et al., 2012).

Previous studies suggest that switchgrass (Panicum virgatum) is one potential source for cellulosic biofuel feedstocks (Mclaughlin & Kszos, 2005; Liebig, 2006; Sanderson et al., 2006; Schmer et al., 2008, 2010; Vadas et al., 2008; Bracmort, 2010; Guretzky et al., 2010; Bracmort et al., 2011; Davis et al., 2011; Monti et al., 2011; Qin et al., 2011). The advantages of planting switchgrass for biofuel include (i) reducing soil erosion and improving water quality due to the lower amounts of fertilizer and pesticides required (Bransby et al., 1998; Liebig, 2006), (ii) decreasing drought impacts on production as switchgrass is tolerant to drought and needs less water during its growing season (Lewandowski et al., 2003; Mclaughlin & Kszos, 2005; William et al., 2012), (iii) reducing greenhouse gas (GHG) emissions to the atmosphere (Gelfand et al., 2013; Dwivedi et al., 2015; Hudiburg et al., 2016), and (iv) improving regional ecosystem
function and service and retaining environmental sustainability (i.e., serves as a carbon sink) (Ma et al., 2000; Frank et al., 2004; Perrin et al., 2008; Gelfand et al., 2011; Werling et al., 2014).

The US Great Plains (GP) has a diversity of vegetation cover types but is mainly dominated by grasslands and croplands (Homer et al., 2015). The main goal of this study was to identify high-risk marginal croplands in the GP that are potentially suitable for cellulosic feedstock crop development (Gelfand et al., 2013; Smith et al., 2013). In this study, the biofuel potential areas were defined as nonirrigated croplands with (i) relatively low productivity for crop but high productivity potential for switchgrass and (ii) high probability of crop failures. Satellite-derived vegetation index, a switchgrass biomass productivity map obtained from a previous study (Gu et al., 2015), and crop indemnity information from the USDA were used in this research. Results from this study will improve our understanding of ecosystem function and service of cropland systems in the GP and provide useful information regarding switchgrass cellulosic feedstock development in the GP.

Materials and methods

Study area

The study area is the US Great Plains (Fig. 1, within the black boundary). The GP covers 14 states and contains 17 ecoregions (Omernik, 1987). Two main vegetation cover types in the GP are grassland (~36%) and cultivated crops (~30%) (Homer et al., 2015) (Fig. 1). The GP has a broad range of climate and environmental conditions and plant productivities. The average annual precipitation increases from the western GP (less than 200 mm) to the eastern GP (over 1100 mm) (http://www.prismclimate.org; Gu et al., 2012b). Vegetation biomass productivity generally increases from the western GP to the eastern GP because of different vegetation growth conditions (e.g., precipitation, elevation, and soil conditions) (Tieszen et al., 1997; Joyce, et al., 2001; Gu et al., 2015).

Criteria for marginal croplands suitable for cellulosic feedstock development

In this study, we identify high-risk farmland marginal croplands that are potentially suitable to convert to cellulosic feedstock crops in the GP. This approach is based on both

Fig. 1 Land cover type (NLCD 2011) with ecoregion map for the GP.

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biophysical and risk conditions of croplands and switchgrass (i.e., productivity, crop indemnity) in the GP. Here, we presumed that croplands with relatively low productivity for crop but high productivity potential for switchgrass are potentially suitable for converting to switchgrass. Irrigated croplands or areas with relatively low crop indemnity (based on the USDA county-level crop indemnity map, which reflects crop failure conditions of each US county, http://www.rma.usda.gov/data/indemnity/archive.html) were excluded from the suitable switchgrass biofuel consideration to minimize the impacts on local economies and livelihoods. To avoid any undesirable land-use changes, areas with high vulnerability to erosion (e.g., the Sand Hills ecoregion in Nebraska where removal of biomass may lead to sand dune activation) (Gu et al., 2012a) were also excluded from the suitable switchgrass biofuel areas.

Datasets for mapping marginal croplands and evaluating the environmental conditions of the identified biofuel potential areas in the GP

Two major datasets used in this investigation are cropland and switchgrass productivities. Previous studies suggested that satellite-derived growing season Normalized Difference Vegetation Index (NDVI) can be used as a proxy for aboveground vegetation biomass productivity (Wylie et al., 1995; Tieszen et al., 1997; Wang et al., 2004; Gu et al., 2013a,b) because it captures the seasonal dynamics throughout the growing season. The recent 3-year (2010–2012) averaged growing season NDVI (GSN) was used as a proxy for cropland productivity in this study. The 3-year GSNs were calculated from the 7-day composite 250-m eMODIS (expedited Moderate Resolution Imaging Spectroradiometer) (Jenkerson et al., 2010) NDVI data (https://lta.cr.usgs.gov/emodis). The switchgrass biomass productivity (using GSN as a proxy) map for the GP region was derived from a previous study (Gu et al., 2015), which was based on site environmental and climate conditions and a switchgrass productivity model.

Other datasets used for mapping marginal croplands for cellulosic feedstock crop development in the GP include (i) the USDA crop indemnity map (http://www.rma.usda.gov/data/indemnity/archive.html), which reflects crop failures (drought, hail, insects, etc.) and low yield conditions of cropland systems in the GP; (ii) the USGS crop mask, which was derived from the USDA National Agricultural Statistics Service Cropland Data Layer (Howard et al., 2012) and was used for identifying cropland pixels; (iii) the USGS irrigation map (http://earlywarning.usgs.gov/USIrrigation) (Brown & Pervez, 2014), which was used to exclude irrigated cropland pixels from the identified biofuel potential areas and to avoid intensively managed croplands with high recurrent costs (e.g., center pivot irrigation system); and (iv) the U.S ecoregion map for the GP, which was used to exclude the erosion-prone Sand Hills ecoregion from the biofuel potential areas.

In addition, climate and environment variables, which play important roles in the switchgrass productivity model (Gu et al., 2015), were used to evaluate the resulting biofuel potential areas. These environment and climate variables include (i) soil available water capacity (AWC) derived from the USDA Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) Database (http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_053627), (ii) elevation (digital elevation model, DEM) obtained from the USGS National Elevation Dataset (http://nationalmap.gov/elevation.html), (iii) compound topographic index (CTI) (http://edna.usgs.gov/Edna/datalayers/cti.asp), and (iv) 30-year (1981–2010) averaged annual precipitation derived from the PRISM (Parameter-elevation Regressions on Independent Slopes Model) database (PRISM Climate Group, http://www.prismclimate.org). AWC is an important soil feature index, which represents the amount of water that can potentially be stored in soil and is available for use by plants. DEM and CTI are related to site topographical features and hydrological (steady-state wetness) conditions.

Furthermore, the long-term (9-year) averaged net ecosystem production (NEP) data were also used to evaluate carbon sequestration of the biofuel potential areas. NEP is an important ecosystem-scale characteristic for assessing terrestrial carbon cycles, ecosystem services, and global climate changes (Randerson et al., 2002; Law, 2005; Xiao et al., 2008). The NEP data were developed by Zhang et al. (2011) (http://lca.usgs.gov/lca/cflux_gplains/dataproducts.php).

Processing procedures for identifying marginal croplands suitable for biofuel crop development in the GP

The main procedures used for mapping marginal croplands for cellulosic feedstock crop development in the GP included the following steps:

1. Calculate the 3-year (2010–2012) averaged GSN based on the quality-improved 250-m eMODIS NDVI data (https://lta.cr.usgs.gov/emodis). Here, we used start of season time as early April (Julian date 100) and end of season time as late October (Julian date 300). This 3-year averaged GSN was used as a proxy for cropland productivity (Fig. 2a).

2. Obtain switchgrass GSN (Fig. 2b), USDA crop indemnity (Fig. 2c), USGS crop mask, USGS irrigation map, and USGS ecoregion map for the GP. To make these maps more reliable, areas with large uncertainty estimation of switchgrass productivity in the GP (Fig. 2b, white color within the GP) (Gu et al., 2015) were excluded from the suitable areas in this study. Explanation and further discussion on this can be found in the ‘Discussion’ section.

3. Generate a nonirrigated GSN map for cropland pixels in the GP region. The GSN map was then classified into three productivity classes (low, medium, and high, with each class having an equal amount of pixels) based on the GSN values.

4. Select ~900 randomly stratified samples for the GP region based on the above three productivity classes (i.e., each productivity category had ~300 random samples).

5. Extract switchgrass GSN and 3-year averaged eMODIS GSN (i.e., cropland productivity) for the selected samples (pixels) and converted them to switchgrass productivity (Gu et al., 2013a); see the ‘Estimation of switchgrass biomass
productivity gain from the suitable area’ section) and corn yield equivalents (Gu et al., 2013b). A regression analysis was performed on the two datasets (Fig. 3).

6 Identify areas (pixels) that have relatively low corn yield and high productivity potential for switchgrass in the GP (i.e., switchgrass productivity is relatively higher than crop productivity at 80% confidence level). These areas are potentially suitable for switchgrass development (e.g., blue points in Fig. 3).

7 Divide the crop indemnity map into three equal numbers of pixel groups based on the indemnity values (from low to high: low: <$2 157 068; medium: between $2 157 068 and $7 277 861; and high: >$7 277 861) and exclude those pixels with low crop indemnities (i.e., crop indemnity <$2 157 068) from the identified suitable areas based on a low crop risk factor.

8 Exclude the Sand Hills ecoregion from the suitable areas to avoid any undesirable land-use changes (e.g., removal of biomass may lead to sand dune activation).

The flowchart in Fig. 4 summarizes how the biofuel potential areas were identified and mapped in this study.

**Evaluation of the resulting biofuel potential areas using climate and environment variables**

About 3000 samples were randomly selected to represent the environmental envelope of the GP. These samples illustrate the climate and environmental conditions that the identified biofuel potential areas represented. Climate and environment variables related to switchgrass productivity (i.e., AWC, DEM, CTI, and long-term annual precipitation) (Gu et al., 2015) and switchgrass GSN were extracted for these random pixels. Scatterplots between the environment variables and switchgrass GSN for all the samples and the biofuel potential pixels were generated. The specific climate and environmental features of the biofuel potential areas were evaluated. In addition, the long-term averaged NEP data were also extracted for these random pixels to assess the environmental sustainability of the identified biofuel potential areas. The carbon sequestration conditions for the biofuel potential areas were evaluated and are discussed below.

**Estimation of switchgrass biomass productivity gain from the suitable area**

The total grassland biomass productivity for the biofuel potential areas in the GP was estimated based on the GSN and an empirical equation Eqn (1) developed by Gu et al., (2013a):

\[
\text{Grassland biomass productivity (kg ha}^{-1}\text{yr}^{-1}) = 9936.5 \times \text{GSN} - 1554 \tag{1}
\]

Based on the previous study results, switchgrass has higher biomass production than most grassland species; therefore, the total estimated switchgrass biomass productivity gain from the identified biofuel potential areas in the GP was assumed to be
double that of the total estimated grassland biomass productivity (Vogel et al., 2002; Fike et al., 2006; Mclaughlin et al., 2006; Kiniry et al., 2008; Jager et al., 2010; Schmer et al., 2010; Wullschleger et al., 2010; Anderson-Teixeira et al., 2012; Behrman et al., 2012; Tulbure et al., 2012; Bonin & Lal, 2014; Gu & Wylie, 2016).

Results

Map of marginal croplands suitable for switchgrass development in the GP

Figure 5 shows marginal croplands that are potentially suitable for switchgrass development in the GP. The biofuel potential areas are mainly located in the central and eastern parts of the GP (blue pixels in Fig. 5). Areas with large uncertainty of switchgrass productivity estimation in the GP (Fig. 2b, white color within the GP) were excluded from the suitable areas. In order to provide a detailed view of the biofuel potential areas, two close-up images (Fig. 5 zoom box 1 and zoom box 2) were selected for illustration. Zoom box 1 is located within the Missouri River flood plain and zoom box 2 is in the central part of Iowa.

In zoom box 1, most biofuel potential areas (blue color) are mainly located in the historic flood plain of the Missouri River. These lowland areas can have locally diverse clay or sandy alluvial-deposited soils with low to moderate AWC values (<15 cm; zoom box 1); consequently, these soils may not retain moisture or nutrients well. As a result, localized areas of these diverse alluvial-deposited soils may not be favorable for crop growth, but may favor switchgrass production.

The common expectation is that most of the biofuel potential areas (blue color in zoom box 2) would be located in the upland areas with relatively low CTI values. Uplands are generally expected to be less optimal for crop production because of relatively low soil carbon and fertility and vulnerability to water erosion (http://www.blm.gov/nstc/library/pdf/TN438.pdf, Grieve et al., 1995; Leithold et al., 2006; Yoo et al., 2005).

The results of this study indicate that switchgrass may be preferential over crops in either lowlands or uplands in the GP depending on the regional soil and environmental conditions.

There are approximately 650 000 ha (6500 km²) of marginal croplands in the GP that are potentially preferential for sustainability through switchgrass production. The total estimated switchgrass biomass productivity gain from these biofuel potential areas is about 5.9 million metric tons.

Environmental and climate conditions for the biofuel potential areas

Figure 6(a–d) presents scatterplots associated with environment variables (i.e., AWC, DEM, CTI, and annual precipitation) and switchgrass GSN for study area random samples (green) and the biofuel potential pixels (red). The general climate and environmental conditions for the biofuel potential areas can be inferred from these scatterplots. Most of the environmental condition plots for favorable switchgrass areas are fairly concise with concentrated high density groupings, except CTI, which ranges from 10 to 20 (Fig. 6). Overall, most of the biofuel potential pixels (red) have high switchgrass productivity (GSN) relative to the random samples (green). A large portion of the biofuel potential areas have moderate to high AWC (Fig. 6a, red), except those areas
located within the Missouri River flood plain (Fig. 5 box 1), discussed in the previous section. The identified biofuel potential areas are mainly located at the low-elevation regions (elevation <500 m) and are distant from mountain areas (Fig. 5, blue pixels, and Fig. 6b, red pixels). Annual precipitation for the biofuel potential areas ranges from 400 to 1200 mm (Fig. 6d, red), indicating that switchgrass is a drought-tolerant species that needs less water for growth than crops. Moreover, the NEP values for the biofuel potential areas are generally in the range of -50 to 50 g C m$^{-2}$ y$^{-1}$ (Fig. 7, red pixels), indicating a weak carbon source or a weak carbon sink (near equilibrium, carbon emitted is nearly equal to carbon absorbed) in these areas.

**Discussion**

In this study, areas with large uncertainty estimation of switchgrass productivity (Fig. 2b, white color within the GP) were excluded from the biofuel potential areas to ensure quality and reliability of the resulting biofuel potential map. Therefore, the actual biofuel potential
areas in the GP should be larger than the total areas estimated from this study (i.e., \( \sim 650,000 \) ha) and the total estimated switchgrass biomass productivity gain from the GP is also expected to be more than the estimated productivity gain (i.e., \( \sim 5.9 \) million metric tons) from this study. In addition, very small isolated areas, which are not large enough (e.g., \( \geq 5 \) hectares) to support a cellulosic harvest and transportation costs, should be excluded from the identified biofuel potential areas based on economic considerations.

Results show that most identified biofuel potential areas have near equilibrium NEP values (i.e., carbon emitted is nearly equal to carbon absorbed) (Fig. 7, mean NEP for the biofuel potential pixels is 24). Previous studies indicate that planting switchgrass can lead to a carbon sink and can improve ecosystem function (Bransby et al., 1998; Ma et al., 2000; Frank et al., 2004; Liebig et al., 2005, 2008; Dwivedi et al., 2015). Therefore, converting these high-risk marginal croplands to switchgrass in the GP can improve regional carbon sequestration (served as carbon sink) and help to retain future environmental sustainability.

Cultivating switchgrass in the flood plains of the Mississippi River (Fig. 5 zoom box 1) and upland croplands (Fig. 5 zoom box 2) can improve local soil nutrient retention through increased soil organic matter and reduce vulnerability to wind and water erosion. The specific advantages of this land-use change include (i) improved water quality due to lower fertilizer and

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**Fig. 6** Scatterplots between environment variables and switchgrass GSN for all the random samples (green) and biofuel potential (red) pixels. (a) AWC, (b) DEM, (c) CTI, (d) annual precipitation.

**Fig. 7** Scatterplots between annual NEP and switchgrass GSN for all the random samples (green) and biofuel potential (red) pixels.
pesticide usage for switchgrass as compared to crops, (ii) reduced soil erosion as switchgrass provides year-round minimization of exposed bare ground, (iii) reduced runoff and stabilized stream banks because of the well-developed rhizome and root systems of switchgrass (Gyssels & Poesen, 2003), and (iv) improved wildlife habitat (e.g., providing cover during critical nesting periods for grassland birds) (Murray et al., 2003; Robertson et al., 2012) as switchgrass has a longer growing season and a later, postsenescence harvesting time (Garland, 2010). Encouragement of future switchgrass land use could augment these regional ecosystem services as well as carbon sequestration in the GP.

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