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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

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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 & Tait, 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

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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.

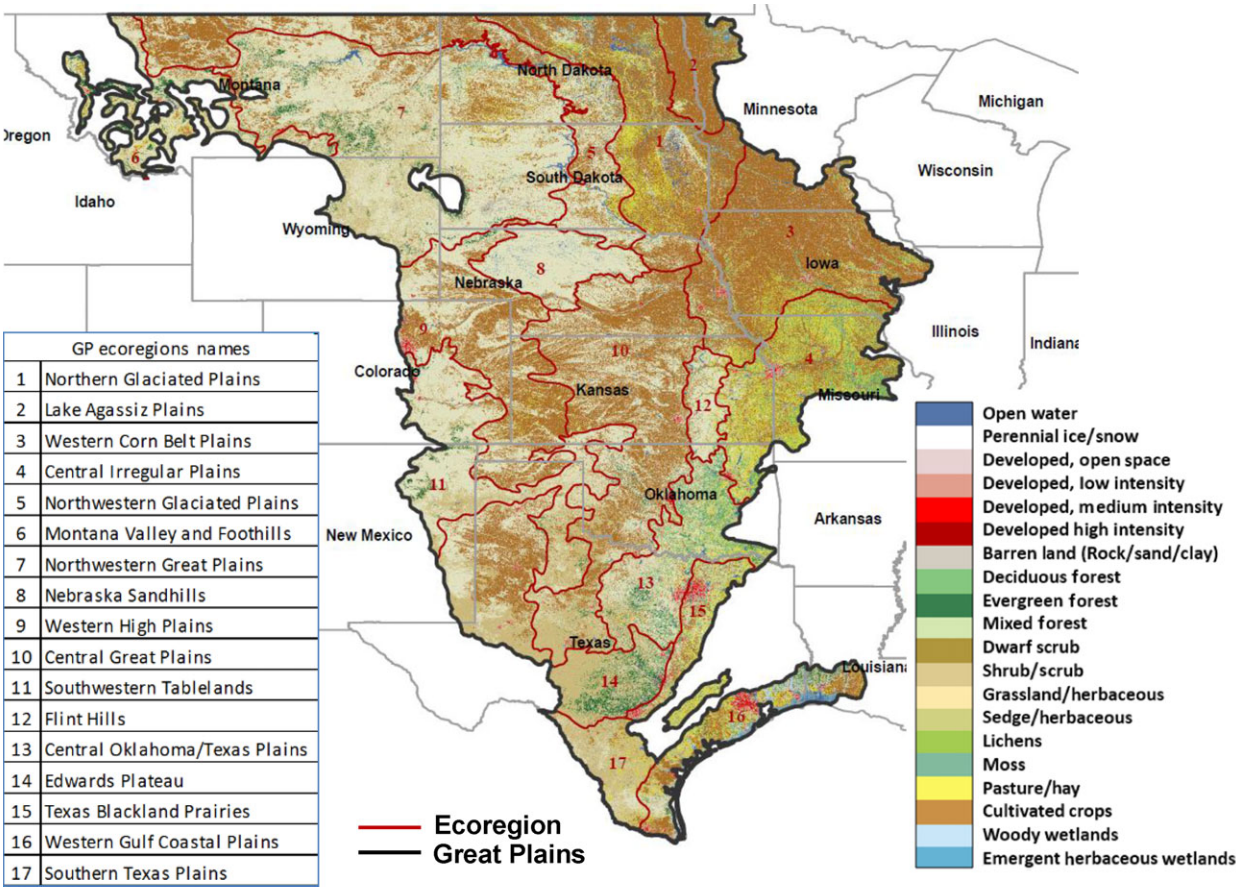
Materials and methods

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



	GP ecoregions names
1	Northern Glaciated Plains
2	Lake Agassiz Plains
3	Western Corn Belt Plains
4	Central Irregular Plains
5	Northwestern Glaciated Plains
6	Montana Valley and Foothills
7	Northwestern Great Plains
8	Nebraska Sandhills
9	Western High Plains
10	Central Great Plains
11	Southwestern Tablelands
12	Flint Hills
13	Central Oklahoma/Texas Plains
14	Edwards Plateau
15	Texas Blackland Prairies
16	Western Gulf Coastal Plains
17	Southern Texas Plains

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

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 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

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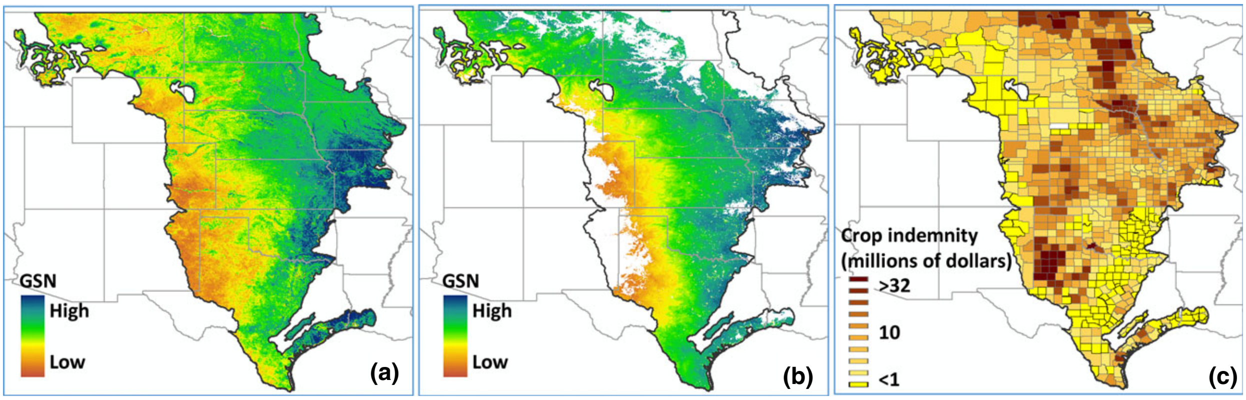

Fig. 2 (a) Cropland productivity (GSN), (b) switchgrass biomass productivity (GSN); white represents high uncertainty areas, and (c) USDA crop indemnity map for the GP.

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.

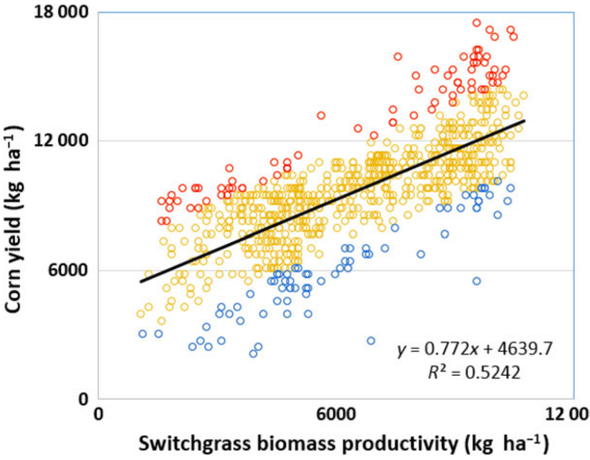

Fig. 3 Scatterplot between switchgrass biomass productivity and corn yield for the randomly selected samples (~900) in the GP. Blue points represent biofuel potential pixels (i.e., switchgrass productivity is relatively higher than crop productivity at 80% confidence level). Red points represents biofuel unsuitable pixels (i.e., switchgrass productivity is relatively lower than crop productivity at 80% confidence level).

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):

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

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

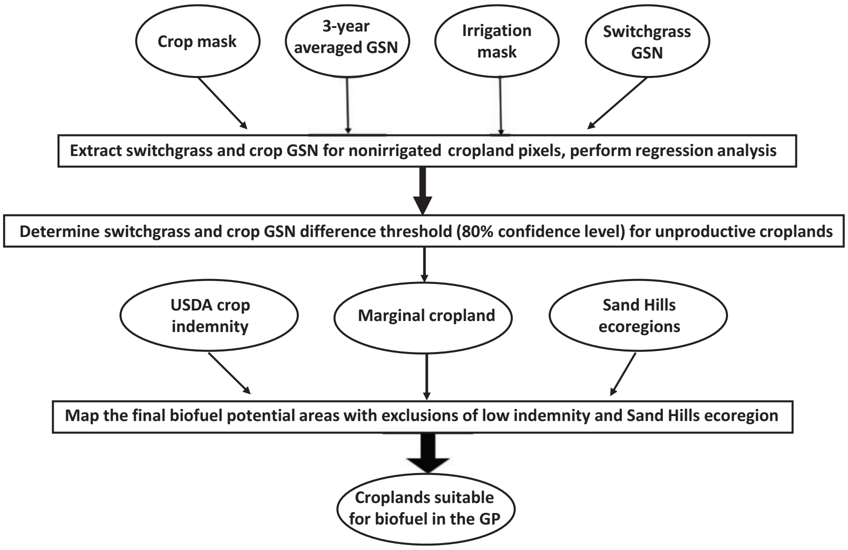

Fig. 4 Flowchart for mapping high cost marginal croplands that are suitable for switchgrass biofuel development in the GP.

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 km^2) 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

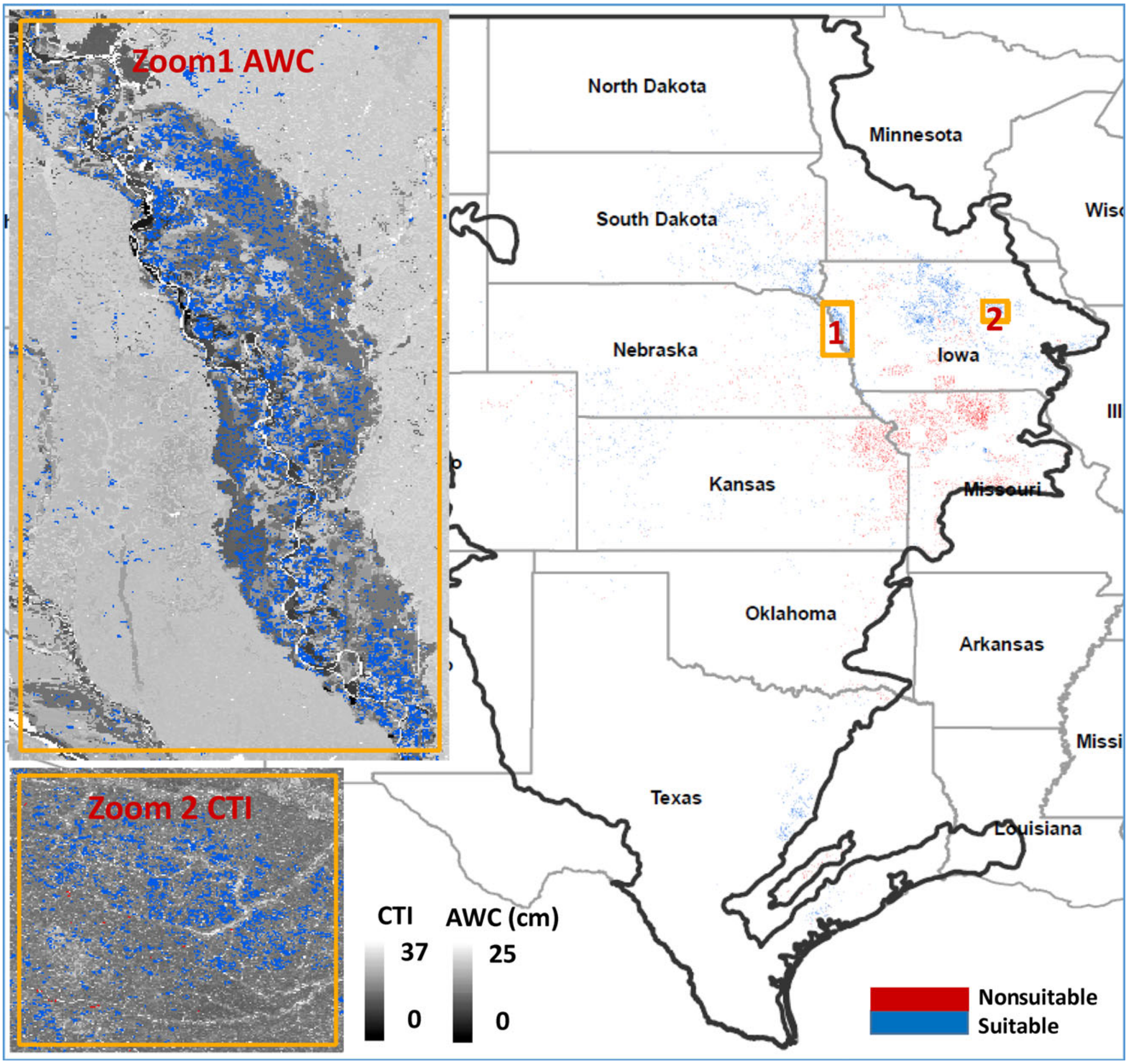

Fig. 5 Biofuel potential areas (blue) and biofuel unsuitable areas (red) in the GP (dark black outline). Zoom box 1 is an example of the lowland biofuel potential pixels overlaid on the AWC map. Zoom box 2 is an example of the upland biofuel potential pixels overlaid on the CTI map.

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} yr^{-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

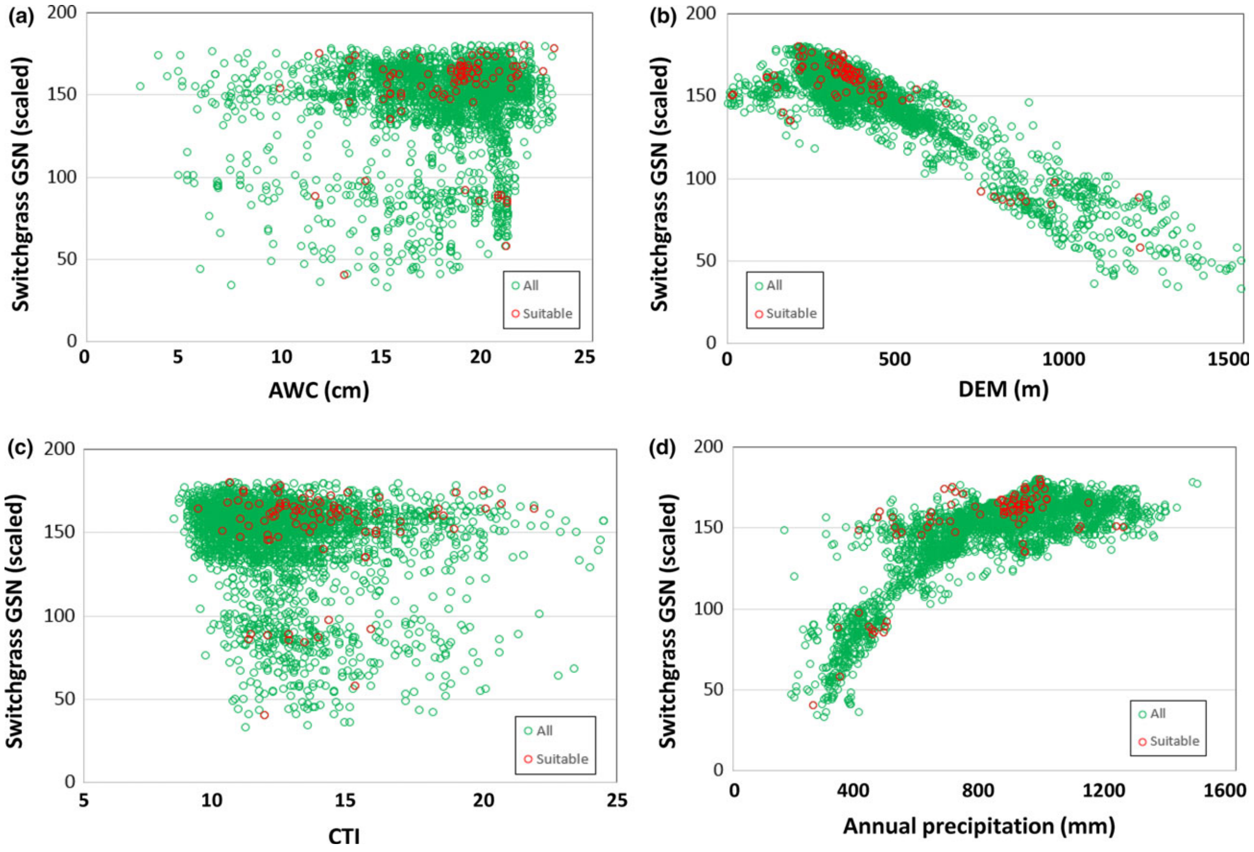

Fig. 6 Scatterplots between environment variables and switchgrass GSN for all the random samples (green) and biofuel potential (red) pixels. (a) AWC, (b) DEM, (c) CTI, (d) annual precipitation.

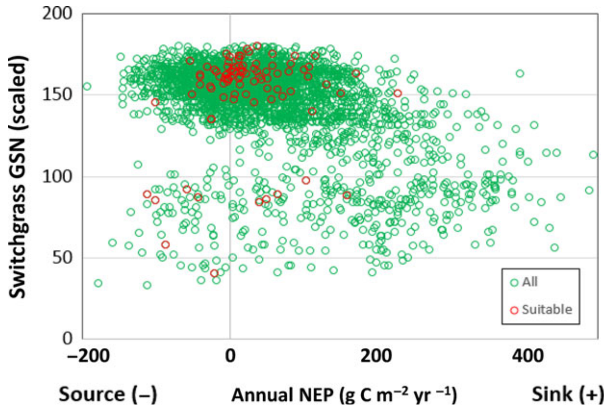

Fig. 7 Scatterplots between annual NEP and switchgrass GSN for all the random samples (green) and biofuel potential (red) pixels.

areas in the GP should be larger than the total areas estimated from this study (i.e., ~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., ~5.9 million metric tons) from this study. In addition, very small isolated areas, which are not large enough (e.g., ≥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 Missouri 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 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 late, 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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References

Anderson-Teixeira KJ, Duval BD, Long SP, Delucia EH (2012) Biofuels on the landscape: is “land sharing” preferable to “land sparing”? *Ecological Applications*, **22**, 2035–2048.

Behrman KD, Kiniry JR, Winchell M, Juenger TE, Keitt TH (2012) Spatial forecasting of switchgrass productivity under current and future climate change scenarios. *Ecological Applications*, **23**, 73–85.

Bonin CL, Lal R (2014) Aboveground productivity and soil carbon storage of biofuel crops in Ohio. *GCB Bioenergy*, **6**, 67–75.

Bracmort K (2010) Meeting the Renewable Fuel Standard (RFS) mandate for cellulosic biofuels: questions and answers. *Research Serv. Report for Congress*, **RL41106**, 1–26.

Bracmort K, Schnepf R, Stubbs M, Yacobucci BD (2011) Cellulosic biofuels: analysis of policy issues for congress. *Cong. Research Serv. Report for Congress*, **RL34738**, 1–23.

Bransby DI, Mclaughlin SB, Parrish DJ (1998) A review of carbon and nitrogen balances in switchgrass grown for energy. *Biomass and Bioenergy*, **14**, 379–384.

Brown JF, Pervez MS (2014) Merging remote sensing data and national agricultural statistics to model change in irrigated agriculture. *Agricultural Systems*, **127**, 28–40.

Buyx A, Tait J (2011) Ethical framework for biofuels. *Science*, **332**, 540–541.

Davis SC, Parton WJ, Grosso SJD, Keough C, Marx E, Adler PR, Delucia EH (2011) Impact of second-generation biofuel agriculture on greenhouse-gas emissions in the corn-growing regions of the US. *Frontiers in Ecology and the Environment*, **10**, 69–74.

DeLucia E. H. (2015), How biofuels can cool our climate and strengthen our ecosystems, *Eos*, **96**, 14–19.

Dwivedi P, Wang W, Hudiburg T *et al.* (2015) Cost of abating greenhouse gas emissions with cellulosic ethanol. *Environmental Science & Technology*, **49**, 2512–2522.

Fike JH, Parrish DJ, Wolf DD, Balasko JA, Green JT Jr, Rasnake M, Reynolds JH (2006) Long-term yield potential of switchgrass-for-biofuel systems. *Biomass and Bioenergy*, **30**, 198–206.

Frank AB, Berdahl JD, Hanson JD, Liebig MA, Johnson HA (2004) Biomass and Carbon Partitioning in Switchgrass. *Crop Science*, **44**, 1391–1396.

Garland CD (2010) *Growing and Harvesting Switchgrass for Ethanol Production in Tennessee*. Tennessee Biofuels Initiative, University of Tennessee Institute of Agriculture, SP701A-5M-5/08 (Rep) R12-4110-070-019-08 08-0120. Available at: https://extension.tennessee.edu/publications/Documents/SP701-A.pdf (accessed 22 August 2016).

Gelfand I, Snapp SS, Robertson GP (2010) Energy efficiency of conventional, organic, and alternative cropping systems for food and fuel at a site in the U.S. Midwest. *Environmental Science & Technology*, **44**, 4006–4011.

Gelfand I, Zenone T, Jasrotia P, Chen J, Hamilton SK, Robertson GP (2011) Carbon debt of Conservation Reserve Program (CRP) grasslands converted to bioenergy production. *Proceedings of the National Academy of Sciences*, **108**, 13864–13869.

Gelfand I, Sahajpal R, Zhang X, Izaurralde RC, Gross KL, Robertson GP (2013) Sustainable bioenergy production from marginal lands in the US Midwest. *Nature*, **493**, 514–517.

Grieve I, Davidson D, Gordon J (1995) Nature, extent and severity of soil erosion in upland Scotland. *Land Degradation & Development*, **6**, 41–55.

Gu Y, Wylie BK (2016) Using satellite vegetation and compound topographic indices to map highly erodible cropland buffers for cellulosic biofuel crop developments in eastern Nebraska, USA. *Ecological Indicators*, **60**, 64–70.

Gu Y, Boyte SP, Wylie BK, Tieszen LL (2012a) Identifying grasslands suitable for cellulosic feedstock crops in the Greater Platte River Basin: dynamic modeling of ecosystem performance with 250 m eMODIS. *GCB Bioenergy*, **4**, 96–106.

Gu Y, Howard D, Wylie B, Zhang L (2012b) Mapping carbon flux uncertainty and selecting optimal locations for future flux towers in the Great Plains. *Landscape Ecology*, **27**, 319–326.

Gu Y, Wylie BK, Bliss NB (2013a) Mapping grassland productivity with 250-m eMODIS NDVI and SSURGO database over the Greater Platte River Basin, USA. *Ecological Indicators*, **24**, 31–36.

Gu Y, Wylie BK, Howard DM, Phuyal KP, Ji L (2013b) NDVI saturation adjustment: a new approach for improving cropland performance estimates in the Greater Platte River Basin, USA. *Ecological Indicators*, **30**, 1–6.

Gu Y, Wylie BK, Howard DM (2015) Estimating switchgrass productivity in the Great Plains using satellite vegetation index and site environmental variables. *Ecological Indicators*, **48**, 472–476.

Guretzky JA, Biermacher JT, Cook BJ, Kering MK, Mosali J (2010) Switchgrass for forage and bioenergy: harvest and nitrogen rate effects on biomass yields and nutrient composition. *Plant and Soil*, **339**, 69–81.

Gyssels G, Poesen J (2003) The importance of plant root characteristics in controlling concentrated flow erosion rates. *Earth Surface Processes and Landforms*, **28**, 371–384.

Homer C, Dewitz J, Yang L *et al.* (2015) Completion of the 2011 National land cover database for the conterminous united states-representing a decade of land cover change information. *Photogrammetric Engineering & Remote Sensing*, **81**, 345–354.

Howard DM, Wylie BK, Tieszen LL (2012) Crop classification modelling using remote sensing and environmental data in the Greater Platte River basin, USA. *International Journal of Remote Sensing*, **33**, 6094–6108.

Hudiburg TW, Wang W, Khanna M *et al*. (2016) Impacts of a 32-billion-gallon bioenergy landscape on land and fossil fuel use in the US. *Nature Energy*, **1**, 15005.

Jager HI, Baskaran LM, Brandt CC, Davis EB, Gunderson CA, Wullschleger SD (2010) Empirical geographic modeling of switchgrass yields in the United States. *GCB Bioenergy*, **2**, 248–257.

Jenkerson CB, Maiersperger TK, Schmidt GL (2010) eMODIS – a user-friendly data source. *U.S. Geological Survey Open-File Report*, **1055**, 10.

Joyce LA, Ojima D, Seielstad GA, Harriss R, Lackett J (2001) *Potential consequences of climate variability and change for the Great Plains*, pp. 191–215.

Kiniry JR, Schmer MR, Vogel KP, Mitchell RB (2008) Switchgrass Biomass Simulation at Diverse Sites in the Northern Great Plains of the U.S. *Bioenergy Research*, **1**, 259–264.

Law BE (2005) Carbon dynamics in response to climate and disturbance: recent progress from multi-scale measurements and modeling in AmeriFlux. *Plant Responses to Air Pollution and Global Change*, pp. 205–213. Springer, Japan.

Leithold EL, Blair NE, Perkey DW (2006) Geomorphologic controls on the age of particulate organic carbon from small mountainous and upland rivers. *Global Biogeochemical Cycles*, **20**, GB3022.

Lewandowski I, Scurlock JMO, Lindvall E, Christou M (2003) The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. *Biomass and Bioenergy*, **25**, 335–361.

Liebig MA (2006) USDA and DOE favor switchgrass for biomass fuel. *Industrial Bioprocessing*, **28**, 7.

Liebig MA, Johnson HA, Hanson JD, Frank AB (2005) Soil carbon under switchgrass stands and cultivated cropland. *Biomass and Bioenergy*, **28**, 347–354.

Liebig M, Schmer M, Vogel K, Mitchell R (2008) Soil carbon storage by switchgrass grown for bioenergy. *Bioenergy Research*, **1**, 215–222.

Ma Z, Wood CW, Bransby DI (2000) Carbon dynamics subsequent to establishment of switchgrass. *Biomass and Bioenergy*, **18**, 93–104.

Mclaughlin SB, Kszos LA (2005) Development of switchgrass (Panicum virgatum) as a bioenergy feedstock in the United States. *Biomass and Bioenergy*, **28**, 515–535.

Mclaughlin SB, Kiniry JR, Taliaferro CM, De La Torre Ugarte D (2006) Projecting yield and utilization potential of switchgrass as an energy crop. *Advances in Agronomy*, **90**, 267–297.

Mitchell R, Vogel KP, Uden DR (2012) The feasibility of switchgrass for biofuel production. *Biofuels*, **3**, 47–59.

Monti A, Barbanti L, Zatta A, Zegada-Lizarazu W (2011) The contribution of switchgrass in reducing GHG emissions. *GCB Bioenergy*, **4**, 420–434.

Murray LD, Best LB, Jacobsen TJ, Braster ML (2003) Potential effects on grassland birds of converting marginal cropland to switchgrass biomass production. *Biomass and Bioenergy*, **25**, 167–175.

Omernik JM (1987) Ecoregions of the conterminous United States. *Annals - Association of American Geographers*, **77**, 118–125.

Pala C (2010) Study finds using food grain to make ethanol is energy-inefficient. *Environmental Science & Technology*, **44**, 3648–3648.

Perrin R, Vogel K, Schmer M, Mitchell R (2008) Farm-Scale Production Cost of Switchgrass for Biomass. *BioEnergy Research*, **1**, 91–97.

Pimentel D (2010) *Corn and cellulosic ethanol problems and soil erosion*, CRC Press, Talor&francis group, Boca Raton, London, New York.

Qin Z, Zhuang Q, Chen M (2011) Impacts of land use change due to biofuel crops on carbon balance, bioenergy production, and agricultural yield, in the conterminous United States. *GCB Bioenergy*, **4**, 277–288.

Randerson JT, Chapin Iii FS, Harden JW, Neff JC, Harmon ME (2002) Net ecosystem production: a comprehensive measure of net carbon accumulation by ecosystems. *Ecological Applications*, **12**, 937–947.

Robertson BA, Rice RA, Sillett TS *et al.* (2012) Are agrofuels a conservation threat or opportunity for grassland birds in the United States? *The Condor*, **114**, 679–688.

Sanderson MA, Adler PR, Boateng AA, Casler MD, Sarath G (2006) Switchgrass as a biofuels feedstock in the USA. *Canadian Journal of Plant Science*, **86**, 1315–1325.

Schmer MR, Vogel KP, Mitchell RB, Perrin RK (2008) Net energy of cellulosic ethanol from switchgrass. *Proceedings of the National Academy of Sciences of the United States of America*, **105**, 464–469.

Schmer MR, Mitchell RB, Vogel KP, Schacht WH, Marx DB (2010) Spatial and temporal effects on switchgrass stands and yield in the Great Plains. *Bioenergy Research*, **3**, 159–171.

Schnepf R, Yacobucci BD (2013) Renewable Fuel Standard (RFS): overview and issues. *CRS Report for Congress*, R40155 1–31.

Searchinger T, Heimlich R, Houghton RA *et al.* (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, **319**, 1238–1240.

Simpson T (2009) Biofuels: the past, present, and a new vision for the future. *BioScience*, **59**, 926–927.

Smith CM, David MB, Mitchell CA, Masters MD, Anderson-Teixeira KJ, Bernacchi CJ, Delucia EH (2013) Reduced nitrogen losses after conversion of row crop agriculture to perennial biofuel crops. *Journal of environmental quality*, **42**, 219–228.

Tieszen LL, Reed BC, Bliss NB, Wylie BK, Dejong DD (1997) NDVI, C_3 AND C_4 production, and distributions in Great Plains grassland land cover classes. *Ecological Applications*, **7**, 59–78.

Trostle R (2008) *Global agricultural supply and demand: factors contributing to the recent increase in food commodity prices USDA Economic Research Service, WRS-0801* 1–30. Available at: http://www.ers.usda.gov/media/218027/wrs0801_1_.pdf (accessed 22 August 2016). (accessed 22 August 2016).

Tulbure MG, Wimberly MC, Boe A, Owens VN (2012) Climatic and genetic controls of yields of switchgrass, a model bioenergy species. *Agriculture, Ecosystems & Environment*, **146**, 121–129.

Vadas PA, Barnett KH, Undersander DJ (2008) Economics and energy of ethanol production from Alfalfa, Corn, and Switchgrass in the Upper Midwest, USA. *Bioenergy Research*, **1**, 44–55.

Vogel KP, Brejda JJ, Walters DT, Buxton DR (2002) Switchgrass biomass production in the midwest USA. *Agronomy Journal*, **94**, 413–420.

Wang J, Rich PM, Price KP, Kettle WD (2004) Relations between NDVI and tree productivity in the central Great Plains. *International Journal of Remote Sensing*, **25**, 3127–3138.

Werling BP, Dickson TL, Isaacs R *et al.* (2014) Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes. *Proceedings of the National Academy of Sciences*, **111**, 1652–1657.

William RM, III, Anand RG, Gary AF, Sarah ML, Larry LD, Eric RM, Thomas EM (2012) *Drought-tolerant biofuel crops could be a critical hedge for biorefineries*. Lawrence Berkeley National Laboratory (LBNL), US Department of Energy. LBNL-5537E, 1–24. Available at: http://eetd.lbl.gov/node/57923 (accessed 22 August 2016).

Wullschleger SD, Davis EB, Borsuk ME, Gunderson CA, Lynd LR (2010) Biomass production in switchgrass across the United States: database description and determinants of yield. *Agronomy Journal*, **102**, 1158–1168.

Wylie BK, Denda I, Pieper RD, Harrington JA, Reed BC, Southward GM (1995) Satellite-based herbaceous biomass estimates in the pastoral zone of Niger. *Journal of Range Management*, **48**, 159–164.

Xiao J, Zhuang Q, Baldocchi DD *et al.* (2008) Estimation of net ecosystem carbon exchange for the conterminous United States by combining MODIS and AmeriFlux data. *Agricultural and Forest Meteorology*, **148**, 1827–1847.

Yacobucci BD, Capehart T (2008) Selected issues related to an expansion of the Renewable Fuel Standard (RFS). *Cong. Research Serv. Report for Congress*, **RL34265**, 1–21.

Yoo K, Amundson R, Heimsath AM, Dietrich WE (2005) Erosion of upland hillslope soil organic carbon: coupling field measurements with a sediment transport model. *Global Biogeochemical Cycles*, **19**, GB3003, 1–17.

Zhang L, Wylie BK, Ji L, Gilmanov TG, Tieszen LL, Howard DM (2011) Upscaling carbon fluxes over the great plains grasslands: sinks and sources. *Journal of Geophysical Research G: Biogeosciences*, **116**, G00J03, 1–13.