Mapping cropland waterway buffers for switchgrass development in the eastern Great Plains, USA

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Abstract

Switchgrass (Panicum virgatum L.), a highly productive perennial grass, has been recommended as one potential source for cellulosic biofuel feedstocks. Previous studies indicate that planting perennial grasses (e.g., switchgrass) in high-topographic-relief cropland waterway buffers can improve local environmental conditions and sustainability. The main advantages of this land management practice include (i) reducing soil erosion and improving water quality because switchgrass requires less tillage, fertilizers, and pesticides; and (ii) improving regional ecosystem services (e.g., improving water infiltration, minimizing drought and flood impacts on production, and serving as carbon sinks). In this study, we mapped high-topographic-relief cropland waterway buffers with high switchgrass productivity potential that may be suitable for switchgrass development in the eastern Great Plains (EGP). The US Geological Survey (USGS) Compound Topographic Index map, National Land Cover Database 2011, USGS irrigation map, and a switchgrass biomass productivity map derived from a previous study were used to identify the switchgrass potential areas. Results show that about 16,342 km² (c. 1.3% of the total study area) of cropland waterway buffers in the EGP are potentially suitable for switchgrass development. The total annual estimated switchgrass biomass production for these suitable areas is approximately 15 million metric tons. Results from this study provide useful information on EGP areas with good cellulosic switchgrass biomass production potential and synergistic substantial potential for improvement of ecosystem services.

Keywords: cellulosic biofuel, crop, eastern Great Plains, erosion, land management, riparian zones, switchgrass biomass productivity, waterway

Received 8 December 2017 and accepted 10 March 2018

Introduction

Switchgrass (Panicum virgatum L.) has been recommended as one potential source for cellulosic biofuel feedstocks (McLaughlin & Kszos, 2005; Liebig, 2006; Sanderson et al., 2006; Bracmort, 2010; Bracmort et al., 2010; Monti et al., 2012). Planting switchgrass for biofuel instead of corn-based ethanol can (i) improve regional ecosystem services (i.e., switchgrass is drought-tolerant and serves as a carbon sink) (Ma et al., 2000; Lewandowski et al., 2003; Frank et al., 2004; Perrin et al., 2008; Gelfand et al., 2011; William et al., 2012; Werling et al., 2014), (ii) reduce soil erosion and improve water quality due to improved water infiltration and the lower need for fertilizer and pesticides (Bransby et al., 1998; Liebig, 2006), and (iii) retain higher levels of soil organic matter and reduce greenhouse gas emissions to the atmosphere (Gelfand et al., 2013; Dwivedi et al., 2015; Hudiburg et al., 2016). As bioenergy infrastructure and refineries develop, demand for switchgrass is expected to increase in the future (Bracmort, 2010; Bracmort et al., 2010; Mitchell et al., 2012).

Cultivating annual crops in high-topographic-relief waterway buffers (ephemeral stream buffers) can cause soil erosion and pesticide and fertilizer leakage, which is environmentally unsustainable (Logan, 1990; Spruill, 2000; Dosskey, 2001; Dosskey et al., 2002; Simpson et al., 2008; https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/home/?cid=nrcs143_023568; https://www.epa.gov/sites/production/files/2015-07/documents/2006_8_24_mbsasin_symposia_ia_session4-2.pdf). Growing perennial grasses such as switchgrass for biofuel in riparian zones, stream waterway buffers, and highly erodible cropland areas has been proposed and investigated (Sanderson et al., 2001; Mersie et al., 2006; Sanderson, 2008; Dominguez-Faus et al., 2009; Koh et al., 2009; Powers et al., 2010; http://www.mda.state.mn.us/protecting/conservation/practices/waterway.aspx). Gu & Wylie (2016) developed an approach that combined 30-m hydrological data (i.e., US Geological Survey [USGS] Compound Topographic Index) and switchgrass biomass productivity potential information to map highly

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erodible waterway buffers that might be suitable for switchgrass development. This method was applied to a small pilot study area (eastern Nebraska) for demonstration and illustration (Gu & Wylie, 2016).

In this study, we apply Gu & Wylie’s (2016) method to a larger area (i.e., eastern Great Plains, EGP) to identify switchgrass biofuel potential areas within the high-topographic-relief crop waterway buffers. The main objectives of this study include (i) extending our previous study area to the EGP to map cropland areas with high topographic relief (high runoff potential) and high switchgrass productivity potential that may be suitable for growing switchgrass, (ii) estimating the total switchgrass biomass productivity gain from the identified biofuel potential areas, and (iii) assessing how well our previous eastern Nebraska cropland buffers for switchgrass development study (Gu & Wylie, 2016) represent the larger EGP. This study provides information on the locations, the total areas of switchgrass waterway buffers, and switchgrass biomass gain from the derived biofuel potential areas in the EGP. Results from this study can be used as a reference for land managers for making optimal land use plans regarding switchgrass biofuel development in the EGP.

Materials and methods

Study area

The study area is the eastern part of the US Great Plains (Fig. 1, within the red boundary). The EGP covers 10 states and has a diversity of vegetation cover types but is mainly dominated by grassland and cropland (Homer et al., 2015; Fig. 1). The EGP has a broad range of climate conditions and vegetation productivity. The long-term averaged annual precipitation increases from the western EGP (c. 400 mm) to the eastern EGP (over 1200 mm) (Fig. 2a) (Parameter-elevation Regressions on Independent Slopes Model database, http://www.prismclimate.org). Vegetation biomass productivity is relatively high in the EGP and generally increases from the western EGP to the eastern EGP because of different vegetation growth conditions (e.g., precipitation, elevation, and soil conditions) (Tieszen et al., 1997; Joyce, 2001; Gu et al., 2015).

Data

National Land Cover Database 2011, USGS irrigation, and US ecoregion maps. The 30-m National Land Cover Database 2011 (NLCD 2011) map for the EGP was obtained from the Multi-Resolution Land Characteristics Consortium (https://www.mrlc.gov/nlcd2011.php), and the cultivated crop pixels

Fig. 1 Location and land cover type of the study area (within the red boundary) in eastern Great Plains, USA.

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Fig. 2  (a) Long-term averaged annual precipitation, (b) USGS Compound Topographic Index (CTI), (c) switchgrass productivity potential, and (d) nonirrigated cropland mask maps for the eastern Great Plains.

Fig. 3  Flowchart for identifying and evaluating switchgrass waterway buffers in the eastern Great Plains (EGP).

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were identified based on NLCD 2011. To avoid intensively managed croplands with high recurrent costs (e.g., center pivot irrigation system), the USGS irrigation map (http://earlywarning.usgs.gov/USirrigation; Brown & Pervez, 2014) was used to exclude irrigated cropland pixels. The US ecoregion map, which denotes areas with similar ecosystems and environmental resources (Omernik, 1987), was used to exclude areas with high vulnerability to erosion (i.e., Sand Hills ecoregion) from the final switchgrass biofuel potential regions. Removal of biomass in the Sand Hills ecoregion may lead to sand dune activation (Gu et al., 2012).

**USGS Compound Topographic Index map.** Compound Topographic Index (CTI) is a function of both the slope and the upstream contributing area (Beven & Kirkby, 1979) and is commonly used to characterize the hydrology of a site (i.e., the steady-state wetness of an area; https://edna.usgs.gov/datalayers/cti.asp). CTI can be calculated from the 30-m digital elevation product (https://nationalmap.gov/elevation.html). Pixels with high CTI values (i.e., >12) usually represent water catchment areas (wetlands, lakes, streams, and rivers). The 30-m CTI map developed by the USGS Elevation Derivatives for National Applications program (http://edna.usgs.gov/Edna/datalayers/cti.asp) for the EGP was used in this study (Fig. 2b).

**Switchgrass productivity estimation map for the EGP.** A switchgrass productivity potential (i.e., predicted growing season averaged Normalized Difference Vegetation Index (GSN)) map developed in a previous study (Gu et al., 2015) was used to identify the highly productive switchgrass (GSN ≥ 0.5) regions. The derived switchgrass productivity potential map was based on site environmental and climate conditions and a switchgrass productivity model (Gu et al., 2015). Figure 2c is the estimated switchgrass productivity map in the EGP.

**Method and processing procedures for mapping high-topographic-relief crop waterway buffers for switchgrass development**

The previous study successfully identified the highly erodible crop waterway buffers for switchgrass development using the following criteria: (i) croplands vulnerable to erosion with high topographic relief (i.e., highly erodible sloping draws and swales in croplands) and (ii) high switchgrass productivity potential (Gu & Wylie, 2016). In this study, we applied our previous approach to map highly erodible crop waterway buffers for switchgrass development in the EGP. The main procedure for mapping and evaluating highly erodible crop waterway buffers includes the following steps:

1. Develop a nonirrigated cropland mask for the EGP (Fig. 2d) based on NLCD 2011 and the USGS irrigation map (switchgrass economics are not expected to be able to cover the additional costs of irrigation).
2. Calculate the mean CTI value (CTI mean) within a 5 × 5 pixel window (150 m × 150 m) for each pixel.
3. Map the high-topographic-relief waterway buffers based on (i) CTI > (1.2 × CTI mean) and (ii) 12 < CTI < 20. Water bodies (e.g., lakes) and extremely high CTI regions associated with larger streams and rivers were excluded from the waterway buffer map as the small rivulets or streamlets are to be targeted for potential switchgrass conversion (Gu & Wylie, 2016).
4. Remove pixels from the identified waterway buffers if they are (i) irrigated cropland pixels or (ii) unproductive switchgrass pixels (i.e., switchgrass GSN < 0.5) based on the switchgrass productivity map.
5. Exclude pixels within the Sand Hills ecoregion from the identified biofuel potential areas to avoid any undesirable land use change (i.e., avoid sand dune activation).
6. Estimate the total switchgrass biofuel potential areas in the EGP and the potential total switchgrass biomass potential gain (Gu & Wylie, 2016) from the biofuel potential areas in the EGP. Compare the EGP study results with the results from the previous Nebraska study.
7. Generate a 250-m switchgrass biomass potential map for the EGP to visualize the results.
8. A switchgrass productivity uncertainty map for the EGP region was generated based on our previous study result (Gu et al., 2015).

Figure 3 is a flowchart summarizing our method and approach to identify switchgrass waterway buffers in the EGP.

![Fig. 4 The final biofuel potential (switchgrass waterway buffer) map for the eastern Great Plains (EGP).](image-url)
Results and discussion

Map of the highly erodible cropland buffers for switchgrass development in the EGP

Figure 4 is a map showing highly erodible cropland buffers (green) that are potentially suitable for switchgrass development in the EGP (https://doi.org/10.5066/f7z60n98). The identified switchgrass waterway buffers are mainly located in the northern and eastern parts of the study area. Most areas in western Texas are considered unsuitable for switchgrass development (Fig. 4) because of the unfavorable vegetation growth conditions (e.g., too hot or too dry) (Fig. 2). It is difficult

Fig. 5 Zoomed (a) CTI map, (b) high-topographic-relief waterway buffers (cyan) overlaid on the CTI map, and (c) the final biofuel potential areas (orange) overlaid on the CTI maps for the selected box 1.

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to illustrate the detailed switchgrass waterway buffers for the entire study area because of its large spatial extent, so three small subsets (zoom boxes 1, 2, and 3, red dots in Fig. 4) were selected to generate higher resolution maps for visualization purposes.

Figure 5 shows the higher resolution maps for box 1 located in the northern part of the EGP and contains (a) the CTI map, (b) the high-topographic-relief waterway buffers (cyan) overlaid on the CTI map, and (c) the final biofuel potential areas (orange) overlaid on the CTI maps. The high-topographic-relief waterway buffers are successfully mapped in Figure 5b (cyan) based on the CTI map. Water bodies and extremely high moisture areas were not included in the waterway buffers as

Fig. 6 Zoomed (a) CTI map, (b) high-topographic-relief waterway buffers (cyan) overlaid on the CTI map, and (c) the final biofuel potential areas (orange) overlaid on the CTI maps for the selected box 2.
these areas are not suitable for switchgrass development and may require riparian trees, a preferred cover type for reducing runoff and withstanding high magnitude flooding. Nearly half of the waterway buffers within box 1 were identified as switchgrass biofuel potential areas (orange color in Fig. 5c). The rest of the waterway buffers (cyan color in Fig. 5c) are either noncropland pixels or unproductive switchgrass pixels (i.e., $\text{GSN} < 0.5$, switchgrass biomass $< 6800$ kg ha$^{-1}$ year$^{-1}$), which are not suitable for switchgrass development.

Figures 6 and 7 are the higher resolution maps for box 2 and box 3 located in the central part of Iowa and northern Texas. High-topographic-relief waterway buffers are shown (Figs 6b and 7b, cyan) with water bodies and major streams and rivers excluded from the waterway buffers. Nearly all the identified waterway buffers were considered as switchgrass biofuel potential areas in box 2 (orange color in Fig. 6c), reflecting favorable vegetation growth conditions (e.g., wet climate and good soil conditions) and extensive cropping systems in...
Iowa. In contrast, nearly all the identified waterway buffers were not considered as switchgrass biofuel potential areas in box 3 (orange color in Fig. 7c), mainly due to the lack of nonirrigated cropland in this region (Fig. 2d). Land managers in the region are aware of water erosion impacts in this high-relief region or found problems with cropping in these areas (two potential explanations based on the observed trend) (Gu & Wylie, 2016).

The total area and the total estimated switchgrass biomass gain for the biofuel potential areas in the EGP

There are approximately 16 342 km² (c. 1.3% of the total study area) of highly erodible cropland buffers identified as suitable regions for switchgrass development in the EGP. The identified biofuel potential areas in the EGP are nearly 11.7 times larger than the biofuel potential areas identified in eastern Nebraska (1400 km², c. 1.9% of the total study area) in our previous study (Gu & Wylie, 2016). The total annual estimated switchgrass biomass production gain for these suitable areas is approximately 15 million metric tons, which is about 12.5 times higher than the switchgrass production estimated from eastern Nebraska (c. 1.2 million metric tons). Both percentages of switchgrass potential areas within the total study area (c. 1.3% vs. c. 1.9%) and the mean switchgrass biomass within the total study areas (119 kg ha⁻¹ vs. 163 kg ha⁻¹) are different for the two studies (EGP vs. eastern Nebraska). These results imply that the Nebraska study results could not be appropriately extrapolated across the EGP due to the different climate and environmental conditions.

Switchgrass waterway buffer biomass productivity map at 250 m resolution

To provide a better visualization of the quantity of biomass the switchgrass waterway buffer areas could produce and the spatial pattern of the biomass productivity, the 30-m switchgrass biomass productivity potential map for the EGP was summed up to 250 m resolution (Fig. 8a). Highly productive (i.e., >400 kg ha⁻¹ year⁻¹) switchgrass water buffers are mainly located in the northern and eastern parts of the EGP (Fig. 8a). Particularly, Iowa has the highest switchgrass biomass productivity potential compared with the other regions within the EGP. Iowa is dominated by cropland (Fig. 1) with favorable environmental and climatic conditions for the production of switchgrass (Fig. 2). As a result, a large proportion of the high-relief waterway buffers in Iowa could be used for switchgrass development in the future.

Discussion

Because of the special biophysical, geophysical, and biogeochemical characteristics of the Sand Hills ecoregion

Fig. 8  (a) Switchgrass waterway buffer biomass productivity potential map (250 m resolution) for the eastern Great Plains (EGP). (b) Switchgrass productivity uncertainty map for the EGP.
(e.g., sand dune systems, sandy soil, native grassland, and semiarid climate conditions; https://www.worldwildlife.org/ecoregions/na0809), areas within the ecoregion (Fig. 4, within the purple color boundary) were not considered as suitable for switchgrass development in this study. The switchgrass biomass productivity map used in this study was based on a satellite vegetation index, site environmental variables, and ground observations (Gu et al., 2015), and there is high uncertainty for productivity in the northeastern part of the EGP (Fig. 8b, eastern North Dakota and western Minnesota) because of a lack of ground observations in this region. Therefore, the identified switchgrass waterway buffer areas (Fig. 4) and productivity (Fig. 8a) may be overestimated or underestimated in the northeastern part of the EGP.

Results from this study indicate that a large proportion of the high-relief waterway buffers in Iowa could be used for switchgrass development in the future (Fig. 8a). However, these productive farmland areas in Iowa are very expensive and have a high land tax, so farmers are unlikely to change from corn to switchgrass production without subsidies. Therefore, additional research may be needed to refine the switchgrass waterway buffer map based on economic considerations. Nevertheless, results from this study provide quantity estimates to land managers and biofuel plant investors on locations, total areas, and biomass productivity where suitable switchgrass development could occur in the EGP.

In future studies, we plan to integrate results from this study and future scenario-based crop expansion and crop condition information to generate a switchgrass biofuel potential ensemble map for current and future croplands in the EGP. We also plan to investigate how economic considerations influence suitable site selection (e.g., identifying existing roads and railways for biomass transportation and centralization, and assessing the nearest starch-based ethanol production plants that could be modified for cellulosic ethanol production) and validate the results derived from this study using ground observations.

Acknowledgements

This work was performed under USGS contract G13PC00028 and funded by the USGS Land Change Science Program in support of Renewable Energy-Biofuels. The authors thank Sandra Poppenga and Bruce Worstell for providing the USGS 30-m high-resolution CTI data. The authors also thank Norman B. Bliss, Thomas Adamson, and two anonymous reviewers for their valuable suggestions and comments. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the US Government.

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