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Integrating future scenario-based crop expansion and crop conditions to map switchgrass biofuel potential in eastern Nebraska, USA

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Abstract

Switchgrass (*Panicum virgatum*) has been evaluated as one potential source for cellulosic biofuel feedstocks. Planting switchgrass in marginal croplands and waterway buffers can reduce soil erosion, improve water quality, and improve regional ecosystem services (i.e. it serves as a potential carbon sink). In previous studies, we mapped high risk marginal croplands and highly erodible cropland buffers that are potentially suitable for switchgrass development, which would improve ecosystem services and minimally impact food production. In this study, we advance our previous study results and integrate future crop expansion information to develop a switchgrass biofuel potential ensemble map for current and future croplands in eastern Nebraska. The switchgrass biomass productivity and carbon benefits (i.e. NEP: net ecosystem production) for the identified biofuel potential ensemble areas were quantified. The future scenario-based ('A1B') land use and land cover map for 2050, the US Geological Survey crop type and Compound Topographic Index (CTI) maps, and long-term (1981–2010) averaged annual precipitation data were used to identify future crop expansion regions that are suitable for switchgrass development. Results show that 2528 km^2 of future crop expansion regions (~3.6% of the study area) are potentially suitable for switchgrass development. The total estimated biofuel potential ensemble area (including cropland buffers, marginal croplands, and future crop expansion regions) is 4232 km^2 (~6% of the study area), potentially producing 3.52 million metric tons of switchgrass biomass per year. Converting biofuel ensemble regions to switchgrass leads to potential carbon sinks (the total NEP for biofuel potential areas is 0.45 million metric tons C) and is environmentally sustainable. Results from this study improve our understanding of environmental conditions and ecosystem services of current and future cropland systems in eastern Nebraska and provide useful information to land managers to make land use decisions regarding switchgrass development.

Keywords: annual precipitation, cellulosic biofuel, compound topographic index, future land cover, land management, marginal cropland, net ecosystem production, satellite remote sensing, switchgrass biomass productivity, waterway buffer

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Introduction

Corn-based (*Zea mays*) ethanol, the most common biofuel product in the United States (Simpson, 2009; Schnepf & Yacobucci, 2010, 2013), has been suggested as being environmentally unsustainable because of soil erosion and water quality impairment from pesticide and fertilizer leakage (Searchinger *et al*., 2008; Simpson *et al*., 2008; Gelfand *et al*., 2010; Pimentel, 2010; Schnepf & Yacobucci, 2010, 2013; Buyx & Tait, 2011; Leduc *et al*., 2017). As a result, production of biofuels from cellulosic feedstocks such as grasses and agricultural wastes is expected to increase in the future (Bracmort, 2010; Bracmort *et al*., 2010; Smith *et al*., 2013). Switchgrass (*Panicum virgatum*) has been recommended as one potential source for cellulosic biofuel feedstocks (Sanderson *et al*., 1996, 2006; Mclaughlin & Kszos, 2005; Liebig, 2006; Schmer *et al*., 2008, 2010; Vadas *et al*., 2008; Bracmort, 2010; Bracmort *et al*., 2010; Guretzky *et al*., 2010; Monti *et al*., 2012).

In previous studies, we estimated switchgrass biomass productivity in the Great Plains (GP) of the United States based on satellite vegetation index and site environmental variables (Gu *et al*., 2015). We then mapped high risk and unproductive marginal croplands that are potentially suitable for switchgrass development in the GP (Gu & Wylie, 2016a). We also used satellite-derived vegetation and compound topographic indices to identify highly erodible cropland waterway buffers for cellulosic

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biofuel crop (e.g. switchgrass) developments in eastern Nebraska (Gu & Wylie, 2016b). The derived waterway buffer map was verified using field observation and high-resolution image (Google Earth). The main advantages of planting switchgrass in these marginal croplands and waterway buffers include (i) reducing soil erosion and improving water quality because switchgrass requires less fertilizer and pesticides (Sladden *et al.*, 1991; Bransby *et al.*, 1998; Liebig, 2006); (ii) improving regional ecosystem services and environmental sustainability (i.e. preserving or enhancing soil carbon stocks) (Bransby *et al.*, 1998; Ma *et al.*, 2000; Frank *et al.*, 2004; Liebig *et al.*, 2008; Garland, 2010; Zeri *et al.*, 2011); and (iii) reducing greenhouse gas emissions to the atmosphere (Gelfand *et al.*, 2013; Dwivedi *et al.*, 2015; Hudiburg *et al.*, 2016). Therefore, these land management practices support long-term sustainability and promote long-term continuation of productive farming systems.

Future scenario-based land use and land cover (LULC) maps for the conterminous United States have been recently made available to the public and can be downloaded through a US Geological Survey (USGS) Website (http://landcover-modeling.cr.usgs.gov/projects.php). These future LULC maps (from 2017 to 2100) were generated by the USGS Earth Resources Observation and Science (EROS) Center and were derived from the USGS EROS FORecasting SCEnarios (FORE-SCE) model (Sohl *et al.*, 2007, 2012). The data provide an opportunity for scientists to investigate locations for potential future cropland expansion and identify potential future biofuel crop (e.g. switchgrass) areas within the cropland expansion regions.

The main goal of this study is to advance our previous study results and integrate the future crop expansion information to develop a switchgrass biofuel potential ensemble map for current and future croplands. The main objectives are to (i) identify switchgrass biofuel potential areas in future crop expansion regions for a pilot study area (i.e. eastern Nebraska, USA) based on climate and environmental conditions, (ii) integrate biofuel suitability information for unproductive marginal croplands, highly erodible cropland buffers, and future cropland expansion regions to generate an ensemble map of biofuel potential, and (iii) quantify ecosystem services (i.e. switchgrass biomass production, net ecosystem production) for the above identified biofuel potential regions. Results from this study provide useful information to land managers and biofuel plant investors to make informed land use decisions regarding switchgrass development in eastern Nebraska.

Materials and methods

Study area

This research is an integration of our previous and present studies. Eastern Nebraska (Fig. 1), which was covered by our previous studies, was selected as a pilot study area. The main vegetation cover types in the study area are grasslands/herbaceous (~28%) and cultivated crops (~60%) (Homer *et al.*, 2015). Crops and grasslands are highly productive in the study area because of the humid continental climate. The annual precipitation generally increases from west to east with a range of 598–918 mm within the study area (Fig. 2b) (http://www.prismclimate.org) (Gu & Wylie, 2016b).

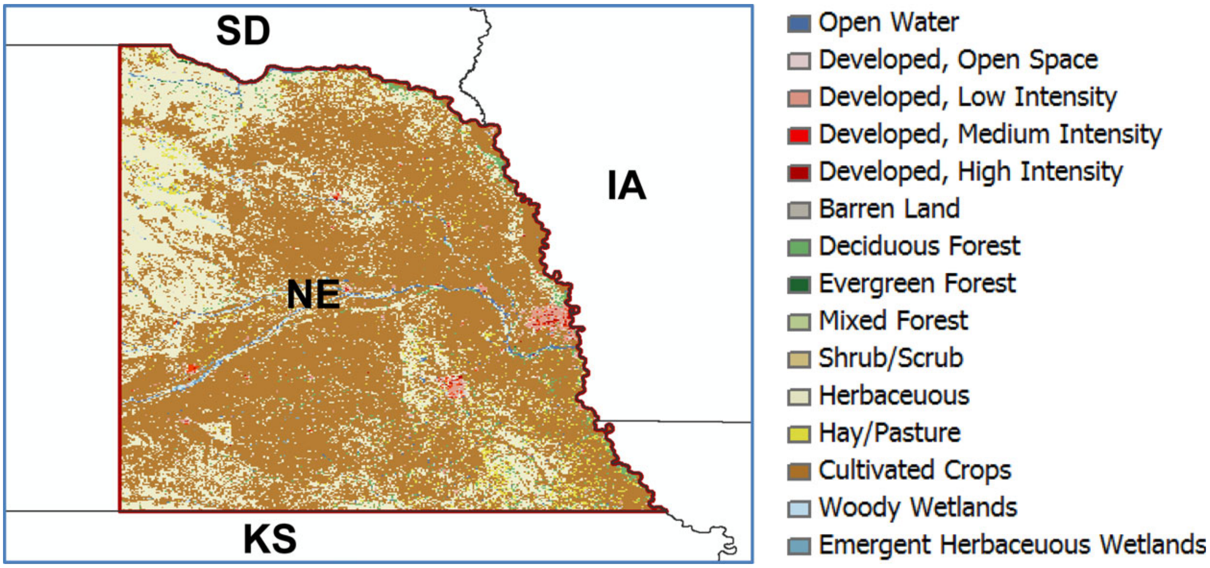

Fig. 1 Land cover type of the study area (within the red boundary in eastern Nebraska).

Mapping future scenario-based cropland expansion regions

The Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) 'A1B' scenario was selected as an example for this investigation. This 'A1B' scenario represents very high economic growth, relatively low population growth, and a convergence of global living standards that result in a high per-capita demand for food, fiber, and energy. As a result, there is an increase in the human footprint on the landscape, with a decline in natural land covers such as grassland, forest, and wetland (https://landcover-modeling.cr.usgs.gov/index_a1b.php). In this study, the year 2050 was selected for illustration and demonstration purposes.

The future scenario-based LULC map for the conterminous United States for 2050 (250-m resolution) was downloaded from the USGS Landcover Modeling website (https://landcover-modeling.cr.usgs.gov/projects.php). The derived LULC map was then clipped to fit the study area. The USGS 3-year (2009–2011) crop type maps (250-m resolution) (Howard *et al.*, 2012) were used to generate a recent cropland mask for the study area. Here, a crop pixel was assigned when 2 or more years were in crops. Finally, a future cropland expansion map was generated for the study area (Fig. 2a) based on the comparison of the 2050 future crop cover map with the recent crop mask.

Identifying areas that are potentially suitable for switchgrass development in the future crop expansion regions

Our approach for identifying biofuel potential areas within the future crop expansion regions is based on the regional climate and environment conditions. The data include (i) 30-year (1981–2010) averaged annual precipitation (Fig. 2b), which was derived from the PRISM (Parameter-elevation Regressions on Independent Slopes Model) database (PRISM Climate Group, http://www.prismclimate.org), and (ii) a 30-m high topographic relief waterway buffer map, which was developed by Gu & Wylie (2016b) based on the Compound Topographic Index (CTI) (Beven & Kirkby, 1979) generated from the 30-m digital elevation product (https://edna.usgs.gov/datalayers/cti.asp). The high topographic relief waterway buffers were defined as (i) $\mathrm{CTI} > (1.2 \times \mathrm{CTI}_{\mathrm{mean}})$, where $\mathrm{CTI}_{\mathrm{mean}}$ is the mean CTI value within a 5 × 5 pixel window for each pixel, and (ii) $12 < \mathrm{CTI} < 20$, which excluded water bodies (e.g. lakes) and extremely high CTI regions associated with larger streams and rivers (Gu & Wylie, 2016b). The percentage of high topographic relief waterway buffers within each 250-m pixel for the study area was calculated (Fig. 2c).

We presumed that future crop expansion regions with moderately dry climate conditions (unproductive regions) and high vulnerable to soil erosion (e.g. high-relief croplands) would be potentially suitable for switchgrass development. Brouwer & Heibloem (1986) indicated that annual precipitation >800 mm would be favorable for commodity cropping systems (e.g. corn and soybeans). In addition, to minimizing potential soil erosion in cropland systems, we constrained future commodity cropping to areas that had <10% high-relief waterway buffers within a 250-m pixel (i.e. cropping commodity crops are mainly flat lands). Therefore, areas with the above desirable commodity cropping conditions were excluded from the future crop expansion for biofuel development regions.

Integrating marginal croplands, highly erodible cropland buffers, and future cropland expansion information to generate a biofuel ensemble map

One goal of this study is to generate a biofuel potential ensemble map for the current croplands and future crop expansion regions in eastern Nebraska. Data used to achieve this goal include (i) unproductive marginal croplands that are potentially suitable for biofuel feedstock crops in the study area developed by Gu & Wylie (2016a) — regions suitable for biofuel are croplands with (a) relatively low crop yield but relatively high productivity potential for switchgrass and (b) high crop insurance payouts (Gu & Wylie, 2016a) (Fig. 3a); (ii) highly erodible cropland buffers (high-relief areas with moderate amounts of run-on moisture anticipating CTI values from 12 to 20) with high switchgrass productivity potential that may be suitable for growing switchgrass within the study area (Gu & Wylie, 2016b) (Fig. 3b); and (iii) future crop expansion areas that are potentially suitable for switchgrass development derived from the previous section (Fig. 3c). The switchgrass biofuel potential ensemble map was produced by integrating

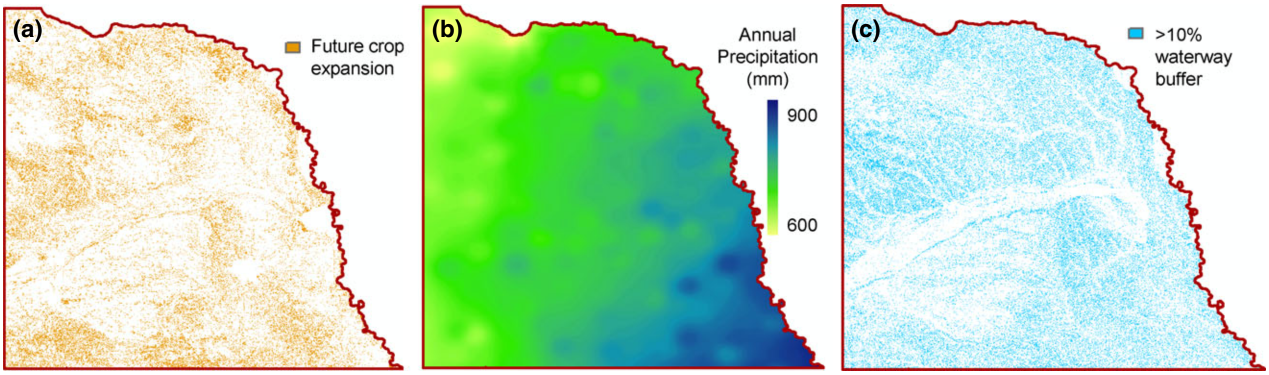

Fig. 2 (a) Future scenario-based cropland expansion ('A1B' Scenario for 2050), (b) long-term averaged annual precipitation, and (c) >10% of high topographic relief waterway buffers within a 250-m pixel for the study area.

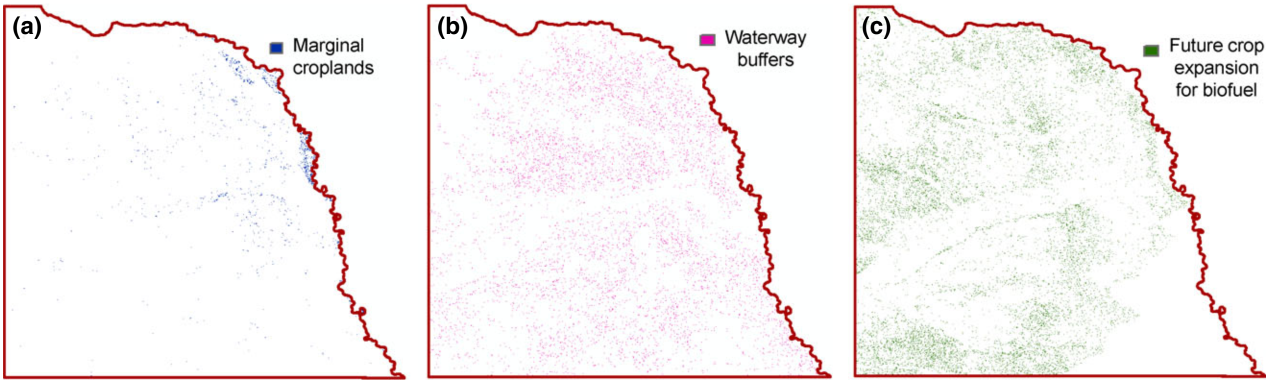

Fig. 3 (a) Unproductive marginal croplands suitable for cellulosic feedstock crops, (b) highly erodible cropland buffers for switchgrass development, and (c) future crop expansion areas that could be converted to switchgrass in eastern Nebraska.

the above three maps and correcting for possible overlap areas. In addition, to prevent any undesirable land use change, the biofuel potential pixels within the Sand Hills ecoregion (Omernik, 1987), which is characterized by vulnerable sand dune systems (Johnsgard, 1995; Lesica & Cooper, 1999), were excluded from the biofuel potential areas to avoid sand dune activation.

Assessing ecosystem services and carbon benefits from the identified switchgrass biofuel potential ensemble areas

To evaluate ecosystem services of the identified biofuel potential ensemble areas, the total switchgrass biomass productivity from the switchgrass potential areas (marginal croplands, cropland buffers, future crop expansions, and biofuel potential ensemble areas) was estimated. The switchgrass biomass productivity map derived from a previous study (Gu *et al.*, 2015), which was based on site environmental and climate conditions and a switchgrass productivity model, was used to estimate switchgrass biomass productivity for the biofuel potential areas (Gu & Wylie, 2016b).

In addition, the carbon benefits (net ecosystem production difference between grass and crop) from the biofuel potential areas were also estimated to assess the future sustainability of this land cover change (Wylie *et al.*, 2016). Net ecosystem production (NEP), a measure of the difference between gross primary production and total ecosystem respiration (Odum, 1956; Chapin *et al.*, 2006), is an important ecosystem-scale characteristic for assessing and understanding terrestrial carbon cycles, ecosystem services, and global climate changes (Randerson *et al.*, 2002; Law, 2005; Xiao *et al.*, 2008). A positive NEP value represents a potential carbon sink and a negative NEP value represents a potential carbon source (Gilmanov *et al.*, 2014). A previous study (Wylie *et al.*, 2016) indicated the strong relationship between long-term annual precipitation and NEP for grassland (and nonirrigated croplands); therefore, grassland (and cropland) NEPs can be calculated using annual precipitation data (Wylie *et al.*, 2016). In this study, the 30-year (1981–2010) averaged annual precipitation data were used to estimate NEP for both grassland and nonirrigated cropland (a mixture of all crops) conditions using the following empirical equations (Eqns 1 and 2) derived from re-analysis of Wylie *et al.* (2016) Table 7 data but using NEP as the dependent variable and precipitation as the independent variable (Wylie *et al.*, 2016):

$$\mathrm{NEP_{grass}}(\mathrm{g\,C\,m^{-2}\,year^{-1}}) = (0.3581 \times \mathrm{PPT}) - 105.95 \quad R^2 = 0.693 \tag{1}$$

$$\mathrm{NEP_{crop}}(\mathrm{g\,C\,m^{-2}\,year^{-1}}) = (0.5572 \times \mathrm{PPT}) - 356.36 \quad R^2 = 0.901, \tag{2}$$

where PPT represents the long-term annual precipitation (mm).

The NEP difference between grassland and nonirrigated cropland for the biofuel potential areas (marginal croplands, cropland buffers, future crop expansions, and the final biofuel potential ensemble areas) was then calculated. The potential carbon benefits (carbon source or sink) for the biofuel potential areas were evaluated based on the NEP difference map. Figure 4 is a flow chart summarizing the processing and evaluation procedures for this study.

Results

Future crop expansion regions suitable for switchgrass development

Figure 3c shows the future crop expansion areas that are potentially suitable for switchgrass development in eastern Nebraska. The biofuel potential areas are located across the entire study area except a small area in the southeast. Sufficient annual precipitation (>800 mm) in the southeastern part of the study area (Fig. 2b) is favorable for crop growth and therefore was excluded from the biofuel potential areas. Results indicate that the total area for the future crop expansion for biofuels development in eastern Nebraska is 2528 km^2 (Table 1).

Switchgrass biofuel potential ensemble map

Figure 5 is the final switchgrass biofuel potential ensemble map for the study area. The final biofuel potential

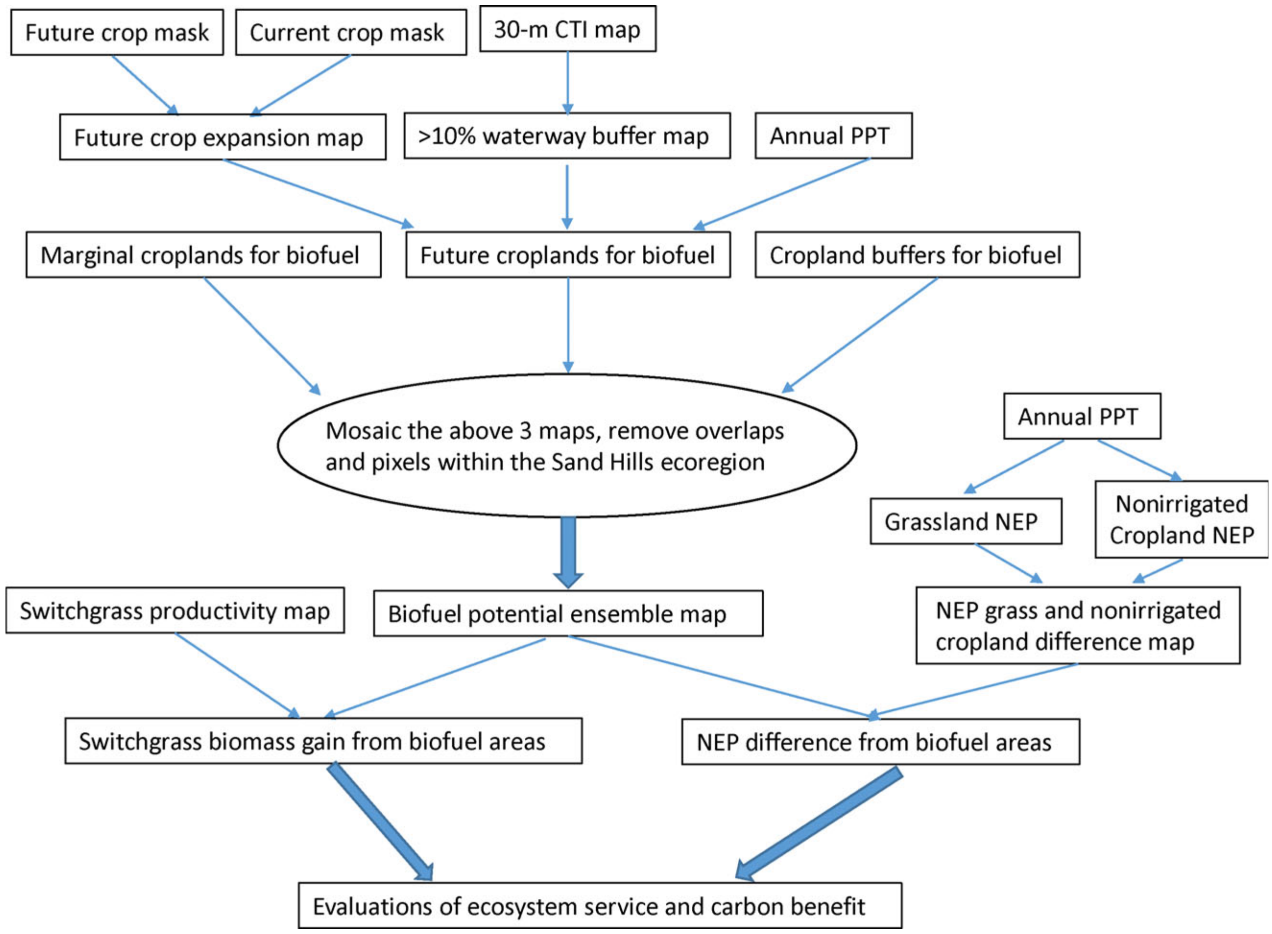

Fig. 4 Flow chart on mapping and evaluating biofuel potential ensemble areas in eastern Nebraska.

Table 1 Summary of switchgrass biomass productivity and total NEP difference (grass minus corn) for the biofuel potential areas in eastern Nebraska

	Total area (km^2)	Contributions to the ensemble areas (%)	% of the total study area (%)	Biomass productivity (million metric tons)	NEP difference (grass minus corn) (million metric tons C)
Waterway buffers (exclude overlaps and SandHills ecoregion)	1352	32	1.9	1.13	0.14
Marginal croplands (exclude SandHills ecoregion)	352	8	0.5	0.33	0.04
Future crop expansions for biofuel (exclude SandHills ecoregion)	2528	60	3.6	2.06	0.27
Biofuel ensemble area (excludes overlaps and SandHills ecoregion)	4232	100	6.0	3.52	0.45

ensemble area (green color in Fig. 5) is an integration of highly eroded cropland buffers, unproductive marginal croplands, and future crop expansion areas (three categories) suitable for switchgrass developments. Details are visible in a zoom box (black box in Fig. 5) in the northeastern part of the study area. Switchgrass biofuel potential pixels for the 250-m marginal croplands, future crop expansion areas, and the 30-m cropland

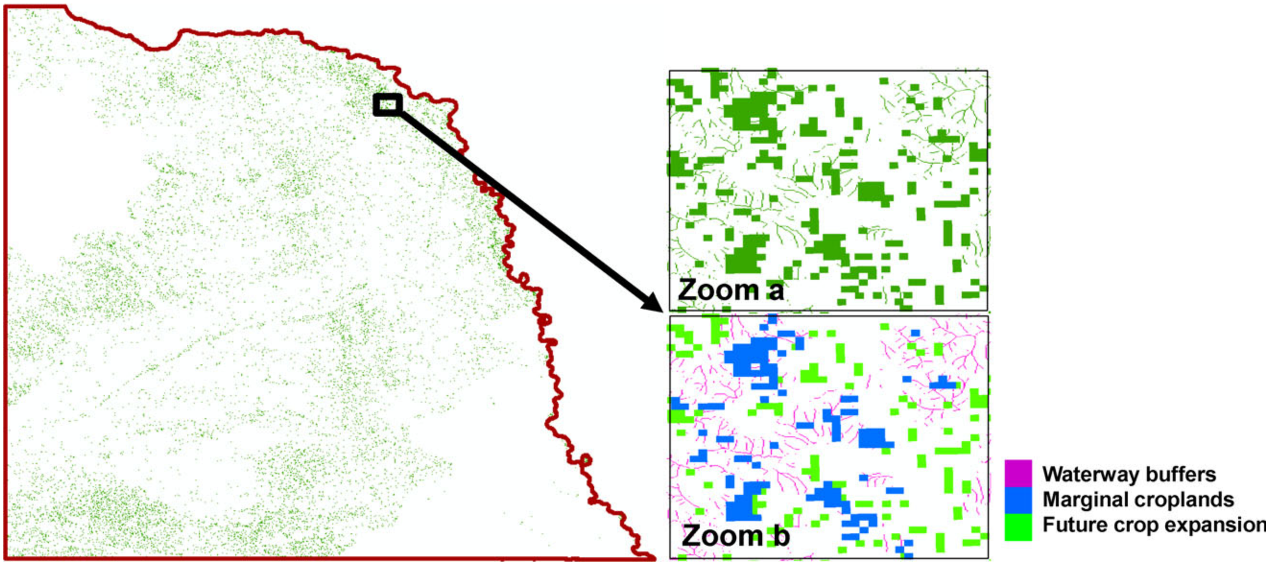

Fig. 5 Switchgrass biofuel potential ensemble (green color) map for eastern Nebraska. Zoom a is an enlargement of the primary map, and Zoom b shows the contribution of each biofuel potential category.

waterway buffers are clearly shown (Fig. 5 Zoom a). The contributions of each category in the final biofuel ensemble map are explicitly shown in Figure 5 Zoom b. The estimated total switchgrass biofuel potential ensemble area for eastern Nebraska is 4232 km^2 (6% of the study area) (Table 1).

Switchgrass biomass productivity and the total NEP difference

Table 1 is a summary of the switchgrass biomass productivity and the total NEP differences (grass vs. corn) for the biofuel potential areas in eastern Nebraska. The identified biofuel potential areas are 1352 km^2, 352 km^2, and 2528 km^2 for cropland buffers (exclude overlaps), marginal croplands, and future crop expansions suitable for biofuel development regions, respectively. The total estimated biofuel potential ensemble area for the above three categories is 4232 km^2.

The estimated switchgrass biomass productivities from the above three biofuel potential categories are 1.13, 0.33, and 2.06 million metric tons, respectively. The total estimated switchgrass biomass productivity for the biofuel potential ensemble area is 3.52 million metric tons (Table 1). The identified future crop expansions for biofuel category have the largest contribution of switchgrass biomass.

The estimated NEP differences (grass vs. crop) for the above three biofuel potential categories are 0.14, 0.04, and 0.27 million metric tons C, respectively. The total estimated NEP difference (grass vs. crop) for the biofuel potential ensemble areas is 0.45 million metric tons C (Table 1). Results indicate that converting the identified biofuel suitable regions to switchgrass will have additional carbon benefit and will be more environmentally sustainable.

Discussion

Results indicate that marginal croplands potentially suitable for biofuel crop development have the smallest contribution (~8%) to the final biofuel potential ensemble areas (Table 1). Because favorable climate and environmental conditions (i.e. humid continental climate, annual precipitation ranges from 598 to 918 mm) in the study area make the crop productivity relatively high, converting croplands to switchgrass for most croplands within the study area is not suitable. We excluded areas with large uncertainty in the estimation of switchgrass productivity from the marginal cropland biofuel potential areas to ensure the high quality of the resulting biofuel potential map (Gu & Wylie, 2016a). Less restrictive assumptions would give a larger area for the cropland biofuel potential than is presented in Table 1. The estimated switchgrass biomass productivity in Table 1 may therefore be underestimated.

Table 1 shows that the future crop expansion for biofuel region has the largest contribution (~60%) to the final biofuel potential ensemble areas, indicating that the future crop expansion regions play an important role for future switchgrass development in the study area. In this study, the 'A1B' scenario for 2050 was used to identify the future crop expansions; the future crop expansion for biofuel region may differ if the other scenarios (e.g. A2 or B1) and date (e.g. 2030) were selected. Moreover, future crop expansion areas may have been overestimated by the FORE-CE model (T. Sohl, personal communication), thus the future crop expansion for biofuel regions in Table 1 may be overestimated.

The NEP difference between grasslands and croplands was used to assess the long-term environmental sustainability in this study. A positive NEP difference (NEP for grassland minus NEP for cropland) indicates that grassland can absorb and preserve more carbon than nonirrigated cropland. Table 1 shows that the NEP difference (grass-crop) for the final biofuel ensemble area is 0.45 million metric tons C, suggesting that converting current (and future) croplands to switchgrass for the biofuel potential areas will improve regional carbon sequestration and ecosystem services (e.g. as potential carbon sinks and preserved carbon). Implementing this land cover change will help retain future environmental sustainability and help mitigate global greenhouse gas concentrations.

Further investigations are needed concerning assessing and evaluating water quantity (e.g. stream flow variability, groundwater recharge) and quality (e.g. nitrogen loading, sediment loading) changes caused by switchgrass development within the identified biofuel areas, as well as local economic impacts (switchgrass price, cost of switchgrass and refiner establishments) caused by these kinds of land use changes.

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