GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2013), doi: 10.1111/gcbb.12059

Projecting future grassland productivity to assess the sustainability of potential biofuel feedstock areas in the Greater Platte River Basin

YINGXIN GU*, BRUCE K. WYLIE†, STEPHEN P. BOYTE‡ and KHEM P. PHUYAL‡

*ASRC Research & Technology Solutions, Contractor to US Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center, 47914 252nd Street, Sioux Falls, SD, 57198, USA, †USGS EROS, 47914 252nd Street, Sioux Falls, SD, 57198, USA, ‡Stinger Ghaffarian Technologies, Inc, Contractor to USGS EROS, 47914 252nd Street, Sioux Falls, SD, 57198, USA

Abstract

This study projects future (e.g., 2050 and 2099) grassland productivities in the Greater Platte River Basin (GPRB) using ecosystem performance (EP, a surrogate for measuring ecosystem productivity) models and future climate projections. The EP models developed from a previous study were based on the satellite vegetation index, site geophysical and biophysical features, and weather and climate drivers. The future climate data used in this study were derived from the National Center for Atmospheric Research Community Climate System Model 3.0 'SRES A1B' (a 'middle' emissions path). The main objective of this study is to assess the future sustainability of the potential biofuel feedstock areas identified in a previous study. Results show that the potential biofuel feedstock areas (the more mesic eastern part of the GPRB) will remain productive (i.e., aboveground grassland biomass productivity >2750 kg ha^{-1} year^{-1}) with a slight increasing trend in the future. The spatially averaged EPs for these areas are 3519, 3432, 3557, 3605, 3752, and 3583 kg ha^{-1} year^{-1} for current site potential (2000–2008 average), 2020, 2030, 2040, 2050, and 2099, respectively. Therefore, the identified potential biofuel feedstock areas will likely continue to be sustainable for future biofuel development. On the other hand, grasslands identified as having no biofuel potential in the drier western part of the GPRB would be expected to stay unproductive in the future (spatially averaged EPs are 1822, 1691, 1896, 2306, 1994, and 2169 kg ha^{-1} year^{-1} for site potential, 2020, 2030, 2040, 2050, and 2099). These areas should continue to be unsuitable for biofuel feedstock development in the future. These future grassland productivity estimation maps can help land managers to understand and adapt to the expected changes in future EP in the GPRB and to assess the future sustainability and feasibility of potential biofuel feedstock areas.

Keywords: bias corrected and downscaled WCRP CMIP3 climate projections, cellulosic biofuel, ecosystem performance models, grassland productivity, Greater Platte River Basin, land management, potential biofuel feedstock areas, satellite NDVI, sustainability assessment

Received 2 November 2012; revised version received 16 January 2013 and accepted 1 February 2013

Introduction

Demand for biofuel products is expected to increase as the world seeks alternatives to fossil fuels (Simpson, 2009; Schnepf & Yacobucci, 2010). The most common biofuel product today in the United States is corn-based ethanol (Solomon *et al.*, 2007; Schnepf & Yacobucci, 2010); however, its development is limited because of concerns about global food shortages, livestock and food price increases, water demand increases for irrigation and ethanol production, and negative environmental effects (e.g., soil erosion and water quality impairment from pesticides and fertilizer) (Trostle, 2008; Searchinger *et al.*, 2008; Gelfand *et al.*, 2010; Pala, 2010; Pimentel, 2010; Schnepf & Yacobucci, 2010; Buyx & Tait, 2011). Production of cellulosic ethanol [e.g., ethanol produced from switchgrass *Panicum virgatum* and corn stover] is expected to increase in the future (Mclaughlin & Kszos, 2005; Liebig, 2006; Sanderson *et al.*, 2006; Perrin *et al.*, 2008; Vadas *et al.*, 2008; Bracmort, 2010; Bracmort *et al.*, 2010; Schmer *et al.*, 2010; Schnepf & Yacobucci, 2010; Guretzky *et al.*, 2011; Monti *et al.*, 2012). The existing productive grasslands which have not yet been farmed may be a good source for cellulosic biofuel feedstock development (Gu *et al.*, 2012).

Correspondence: Yingxin Gu, tel. + 1 605 594 6576, fax + 1 605 594 6529, e-mail: ygu@usgs.gov

In previous studies, we used vegetation condition information from archival records of satellite data [i.e., long-term time series of Normalized Difference Vegetation Index (NDVI) data], site geophysical and biophysical features (e.g., elevation, slope and aspect, and soils), and weather and climate drivers to build ecosystem performance (EP, a surrogate approach for measuring ecosystem productivity) models for dynamic monitoring of ecosystem performance (DMEP) in several ecoregions in the United States (Wylie *et al*., 2008, 2012; Gu & Wylie, 2010; Gu *et al*., 2012). Validation of EP and EP anomaly results using ground observations (e.g., crop yield data, percentage of bare soil, and stocking rate) demonstrated the reliability of these EP models (Wylie *et al*., 2008, 2012; Gu & Wylie, 2010).

Moreover, in a previous study, we applied the DMEP approach to identify grasslands that are potentially suitable for cellulosic biofuel feedstock (e.g., switchgrass) development in the Greater Platte River Basin (GPRB) (Gu *et al*., 2012). This previous study demonstrates the power of EP models and biophysical information extracted from the extensive satellite image archives to identify future potential biofuel feedstock source areas. Results from this previous study provide useful information to land managers and decision makers to make optimal land use decisions regarding cellulosic biofuel feedstock development (Gu *et al*., 2012). However, this previous research only represents the first step in identifying grasslands that are potentially suitable for cellulosic feedstock production. Further evaluations and assessments on the environmental sustainability (e.g., future climate-based projections of grassland productivity) of these biofuel feedstock areas are needed.

The development and the availability of the 'Bias Corrected and Downscaled World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) Climate and Hydrology Projections' data archives (http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/) provides an opportunity for scientists to assess potential future climate change impacts on local ecosystems and to project future ecosystem performance based on the EP models. Therefore, this study has the following three objectives. First, we apply the existing EP model with future climate projections to project future (e.g., 2020–2099) expected EP (EEP) for the GPRB grassland systems. The EP grassland model was developed in the previous study, and the CMIP3 future climate projections under climate scenario 'A1B' (intermediate emissions path) were used to drive the predictions. Second, we assess the changes (compared to the current conditions) and the trends of the future grassland EEP in the GPRB. Third, we examine the future sustainability of potential biofuel and nonbiofuel feedstock areas (Gu *et al*., 2012). The resulting future grassland productivity estimation maps can help land managers to better understand the future ecosystem function and service (under the 'A1B' climate scenario) of the GPRB grassland systems and can be used as a reference to assess the future sustainability and feasibility of potential biofuel feedstock areas.

Materials and methods

Study area

This study is a continuation of our previous Greater Platte River Basin research (Gu *et al*., 2012). The GPRB covers parts of Wyoming, Colorado, South Dakota, Kansas, and most of Nebraska (Fig. 1, within the black boundary) and includes a broad range of plant productivity. The main vegetation cover types are grassland (~50%) and cultivated crops (~30%) (Homer *et al*., 2004). More detailed information on the GPRB can be found in Gu *et al*. (2012).

Basic concepts

Ecosystem performance is a surrogate approximating ecosystem productivity (Tieszen *et al*., 1997). EP is usually affected by site geophysical and biophysical conditions (e.g., drainage, elevation, slope, aspect, soils, and surface geology) (Viereck *et al*., 1984, 1992; Saxon *et al*., 2005; White *et al*., 2005), climate and weather conditions (e.g., precipitation and surface temperature) (Rupp *et al*., 2000; Bunn *et al*., 2005; Kang *et al*., 2006; Kimball *et al*., 2006; Dunn *et al*., 2007), ecological disturbances (e.g., wildfires and insect infestations) (Kang *et al*., 2006), and management activities (e.g., irrigation and grazing control) (Asner *et al*., 2004; Launchbaugh *et al*., 2008). There are currently a number of data sources available to monitor or inventory EP, including flux tower observations, National Agricultural Statistics Service (NASS) crop yield data, and Soil Survey Geographic (SSURGO) productivity. However, all of these have limitations for dynamic monitoring of EP, including a lack of continuous spatial coverage (e.g., sparse field observations), low spatial resolution (e.g., county level statistics), spatial discontinuities (e.g., differences across state and county lines), and significant time lags in the annual estimates (Gu *et al*., 2013). Satellite-derived growing season averaged NDVI (GSN), which has been used as a proxy for EP (Wylie *et al*., 1995; Tieszen *et al*., 1997; Gu *et al*., 2013), can be reliably and consistently mapped across time and space at a 250 m resolution. GSN became an essential tool for measuring and monitoring EP over large areas.

Ecosystem site potential is defined as the long-term ecosystem productivity (i.e., long-term EP) (Wylie *et al*., 2008), and it averages out variations in weather but accounts for spatial patterns in long-term EP associated with site environmental and climate conditions (Wylie *et al*., 2008; Gu & Wylie, 2010). Highly productive sites will have higher ecosystem site potential than sites with poorer soils, drier climates, or other conditions that are not conducive to vegetation growth.

Weather and site characteristic-based expected EP (i.e., EEP) is defined as the expected relatively undisturbed EP for a site in a particular year based on the weather conditions of that year and site potential. Favorable weather years will have

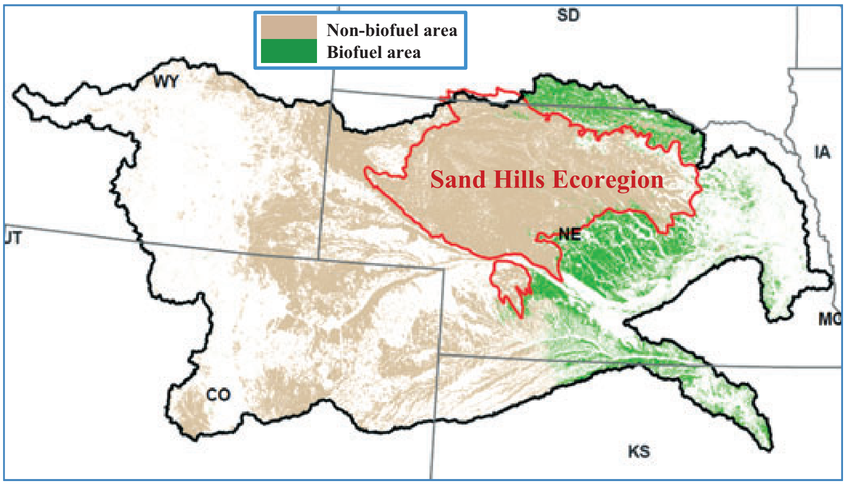

Fig. 1 Grassland areas that are potentially suitable (green) or not suitable (tan) for cellulosic biofuel feedstock developments in the Greater Platte River Basin identified by Gu *et al.* (2012).

higher EEP than years with unfavorable conditions (e.g., too hot or too cold, too wet or too dry) (Wylie *et al.*, 2008; Gu & Wylie, 2010; Gu *et al.*, 2012).

Modeling grassland ecosystem performance

In a previous study, we built a data-driven rule-based piecewise regression grassland EP model based on the satellite-derived GSN, site biophysical and geophysical data, and weather and climate variables (Gu *et al.*, 2012). Fig. 2 is a flowchart illustrating how the EP model was developed by Gu *et al.* (2012) and how the future EP was estimated in this study. The main procedures for building grassland EP models included the following steps:

1 Calculating the EP (i.e., growing season averaged NDVI, GSN) and the long-term averaged EP for 2000–2008 using 250-m eMODIS NDVI data (Jenkerson, 2010).
2 Extracting grassland pixels within the GPRB using National Land Cover Database (NLCD) 2001 (Homer *et al.*, 2004). These pixels were then classified as low, medium, or high productivity based on the long-term averaged GSN.

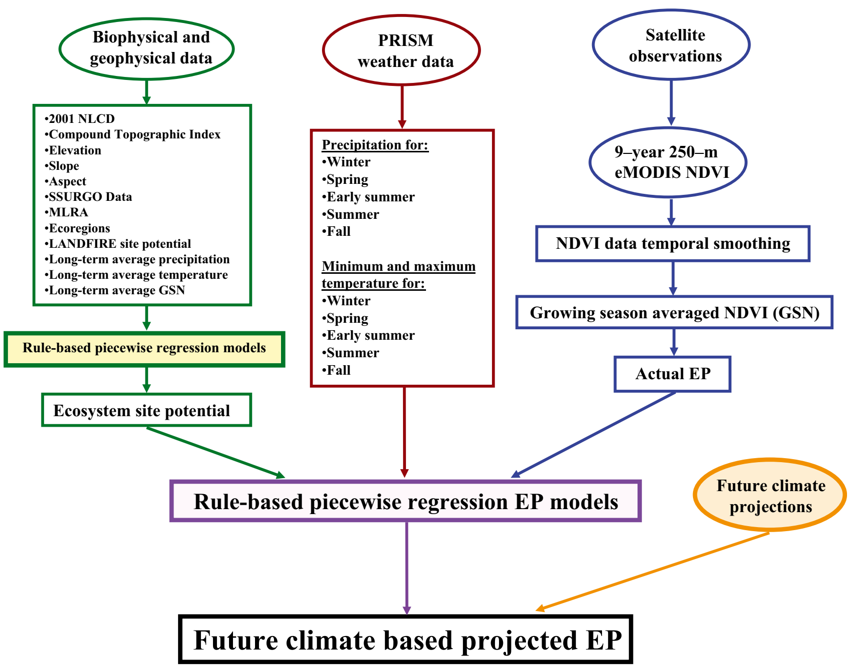

Fig. 2 Flowchart for building EP models and projecting future EP.

3 Extracting site potential attributes [(i) long-term (2000–2008) averaged GSN; (ii) long-term (1971–2000) averaged precipitation, maximum temperature, and minimum temperature; (iii) soil organic carbon; (iv) compound topographic index and digital elevation model; (v) LANDFIRE environmental site potential; (vi) north and south aspect and slope; and (vii) Ecoregions] for ~18 000 grassland pixels in the GPRB. These pixels are located outside of known fire disturbances and were randomly stratified and selected from the three productivity classes (~6000 pixels for each class).
4 Estimating grassland site potential using a conditioned set of piecewise linear regression models (Henderson *et al*., 2005; Wylie *et al*., 2007) derived from the above site potential attributes.
5 Extracting EP attributes for ~16 000 random grassland pixels, which are located outside of known fire disturbances and were stratified and selected across years and the three productivity classes. The EP attributes include (i) 2000–2008 GSN; (ii) grassland site potential; and (iii) 2000–2008 seasonal weather (precipitation and temperature) for the respective year.
6 Developing a data-driven rule-based piecewise regression EP model (using Cubist, http://www.rulequest.com/) to predict EP (i.e., GSN) from grassland site potential (static) and weather (variable).

More detailed information on data sources and procedures for building grassland EP models were fully described by Gu *et al.* (2012). The derived EP model was used to estimate the future climate-based projection of grassland EEP by using future climate projections to replace spatial weather inputs in the EP model during the mapping process.

Potential biofuel feedstock areas in the GPRB

The DMEP method was applied to identify grasslands that are potentially suitable for cellulosic biofuel feedstock (e.g., switchgrass) development in the GPRB (Gu *et al*., 2012). We presumed that areas with consistently moderate to high grassland productivity (i.e., productive grassland, aboveground biomass productivity >2750 kg ha^{-1} $year^{-1}$, Gu *et al*., 2012) and fair-to-good rangeland condition (i.e., with multiyear persistent ecosystem overperformance or normal performance relative to site conditions and weather-based productivity estimates) were potentially suitable for cellulosic feedstock development. On the other hand, we assumed that the following grassland conditions were not appropriate for cellulosic feedstock development: (i) unproductive (i.e., aboveground grassland biomass productivity $\leq$2750 kg ha^{-1} $year^{-1}$, Gu *et al*., 2012); (ii) degraded; or (iii) highly vulnerable to environment or land use changes. Unproductive conditions include grasslands with poor soils, dry climate conditions, or other conditions not conducive to productive grassland growth. Degraded grasslands are characterized by multiyear persistent ecosystem underperformance with poor rangeland conditions caused by heavy grazing or insect infestation. Grasslands that are highly vulnerable to environment changes include the Sand Hills ecoregion in Nebraska (with sandy soil and sand dune systems), where removal of biomass may lead to sand dune reactivation and migration. Fig. 1 shows grassland areas that are potentially suitable (green) or not suitable (tan) for cellulosic feedstock production in the GPRB.

Estimation of future climate-based grassland EEP

In this study, the future (e.g., 2050 and 2099) climate-based projection of grassland EEPs was estimated using a previous grassland EP model (Gu *et al*., 2012) and the future climate projections (Fig. 2). Ecosystem site potential and seasonal weather conditions are important variables and drivers in the EP models for the EEP calculation. The projected future EEPs should be valid under the following conditions: (i) no major changes in management; (ii) no major man- made or natural disturbances (e.g., fires and insect effects) in the future; and (iii) no new invasive species in the study area. The future climate projections (i.e., 2020, 2030, 2040, 2050, and 2099 monthly temperature and precipitation) were derived from the National Center for Atmospheric Research (NCAR) Community Climate System Model 3.0 (CCSM3) 'SRES A1B' and obtained from the 'Bias Corrected and Downscaled WCRP CMIP3 Climate Projections' data archive. We selected the future climate projection data estimated from climate scenario 'A1B' because it represents a 'middle' emissions path that provides a balance across all energy sources and does not heavily rely on one particular energy source (http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/#About). Climate scenario 'A1B' also represents a conservative estimate of future weather conditions.

To make the projected future EEP (the unit of GSN is a dimensionless ratio) directly related to grassland biomass productivity, we estimated grassland biomass productivity using the empirical equation below [Eqn (1)] developed by Gu *et al.* (2013) for the GPRB region:

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

The resulting future grassland productivity maps will be used to assess the sustainability of the potential biofuel feedstock area in the GPRB.

The percent changes of future EEP compared with current ecosystem site potential were also calculated using Eqn (2), which will be used to evaluate the spatial and temporal variations of the future EEP. In addition, to investigate the cause of the future EEP changes, future annual precipitation change (compared with 1971–2000 30-year average annual precipitation) maps for 2050 and 2099 were generated.

$$\text{EEP percent change}_{\text{year}}(\%) = ((\text{EEP}_{\text{year}} - \text{site potential})/\text{site potential}) \times 100 \quad (2)$$

where EEP_{year} represents the projected EP in a future year, and site potential represents the current grassland ecosystem site potential.

Spatially averaged EP for the biofuel and the nonbiofuel areas

To better represent the overall future EEP trends for the entire biofuel and nonbiofuel areas, we computed spatially averaged future EEP for these two areas for current site potential (2000–2008 long-term averaged EP), 2020, 2030, 2040, 2050, and 2099. Since the Sand Hills ecoregion is highly vulnerable to environment changes (removal of biomass may lead to sand dune reactivation and migration), most of the Sand Hills ecoregion is classified as inappropriate for potential biofuel feedstock development even though those areas are very productive (Gu *et al.*, 2012). In order to avoid any biased interpretations on the overall future EEP trends for the biofuel and the nonbiofuel areas, we excluded all pixels located within the Sand Hills ecoregion during the spatially averaged EEP calculation. The spatially averaged future EEP time series plots for the biofuel and nonbiofuel areas were generated and used to examine the future sustainability of these areas. Here, we presume that areas modeled as consistently productive in the future and with increased EEP (or less than 20% decreased) trends will be sustainable for future biofuel feedstock development. On the other hand, we presume that areas that stay unproductive in the future and with decreased (or less than a 20% increase) EEP trends will be unsustainable for future biofuel feedstock development.

Results

Comparison of the future grassland EEP with the current site potential in the GPRB

Figure 3a–f show the spatial distributions and quantities of current grassland site potential and the 2020, 2030, 2040, and 2099 future climate projected EEP for the GPRB. As a result of the diverse biophysical, geophysical, and climate conditions in the GPRB, site potential, which represents the long-term grassland productivity, gradually increases from west to east in the GPRB (Gu *et al.*, 2012). The western part of the GPRB has very low site potential because of unfavorable vegetation growth conditions (e.g., shallow or rocky soils and dry climate condition), and the eastern part of the GPRB has high site potential because of favorable vegetation growth conditions (e.g., good soil and climate conditions) (Gu *et al.*, 2012). Visual comparison of the six maps indicates that the general spatial patterns in the future EEP maps are very similar to the spatial patterns in the site potential map—productivities increase from west to east. Differences among these six maps can also be found because of the different climatic conditions expected during 2020–2099. For example, our models project that future grassland productivity has an increasing trend through time within the red oval region located in the Nebraska Sand Hills ecoregion (Fig. 1b–f), mainly driven by projected favorable future weather conditions (e.g., increased precipitation and suitable temperature during the growing season—see detailed explanations in the next section). Our models also project the decreased future productivity within the cyan circle region located in the southwest GPRB (Fig. 3b and d) for 2020 and 2040 (compared with the current site potential) because of the unfavorable future weather conditions (e.g., drying, too cold, or too hot during the growing season). In summary, these future grassland productivity estimation maps (with a 250-m spatial resolution) can be used as a reference by scientists and land managers to understand how future grassland spatial patterns and productivities are expected to change (under climate scenario 'A1B,' a conservative estimate of future weather conditions) in the GPRB.

Future EEP changes in the GPRB grassland system

To illustrate future EEP changes more clearly, we generated annual precipitation percent change (compared with 30-year average annual precipitation) maps and EEP percent change maps (compared with current site potential) for 2050 and 2099 (Fig. 4a–d). As discussed in the previous section, productivity is expected to increase by more than 5% (Fig. 4c and d) in the red oval region (Fig. 3e and f) in both 2050 and 2099 because of favorable weather conditions (i.e., >5% increase in annual precipitation, Fig. 4a and b). Productivity is expected to decline in the southwestern part of the GPRB in 2050 (black oval in Fig. 4c) and the southeastern part in 2099 (purple oval in Fig. 4d) because of reduced (>5%) annual precipitation in these regions (Fig. 4a and b). This indicates that annual precipitation plays an important role in future EEP calculations (Gu *et al.*, 2012). Additionally, although there are significant annual precipitation decreases in the western part of the GPRB in 2099 (Fig. 4b), the grassland productivity is expected to increase in this area (Fig. 4d). Based on monthly precipitation data, we found that the 2099 growing season (April to September) total precipitation (GSP) is projected to be much higher than the 2050 GSP (i.e., a greater portion of precipitation occurred in the growing season in 2099) in the western part of the GPRB, leading to a higher EEP in this region for 2099. This indicates that GSP plays a more important role in the EEP calculation than annual precipitation does (Smart *et al.*, 2007). In addition, suitable and favorable minimum and maximum temperatures during the growing season (e.g., not too cold and not too hot) are also very important for vegetation growth and affect grassland productivity. Using seasonal climate variables to build EP models is more reliable than using annual climate variables alone.

Spatially averaged future EEP plots for the biofuel and the nonbiofuel areas

Figure 5 demonstrates the spatially averaged future EEP for the biofuel and the nonbiofuel areas for current

 GCB Bioenergy, doi: 10.1111/gcbb.12059

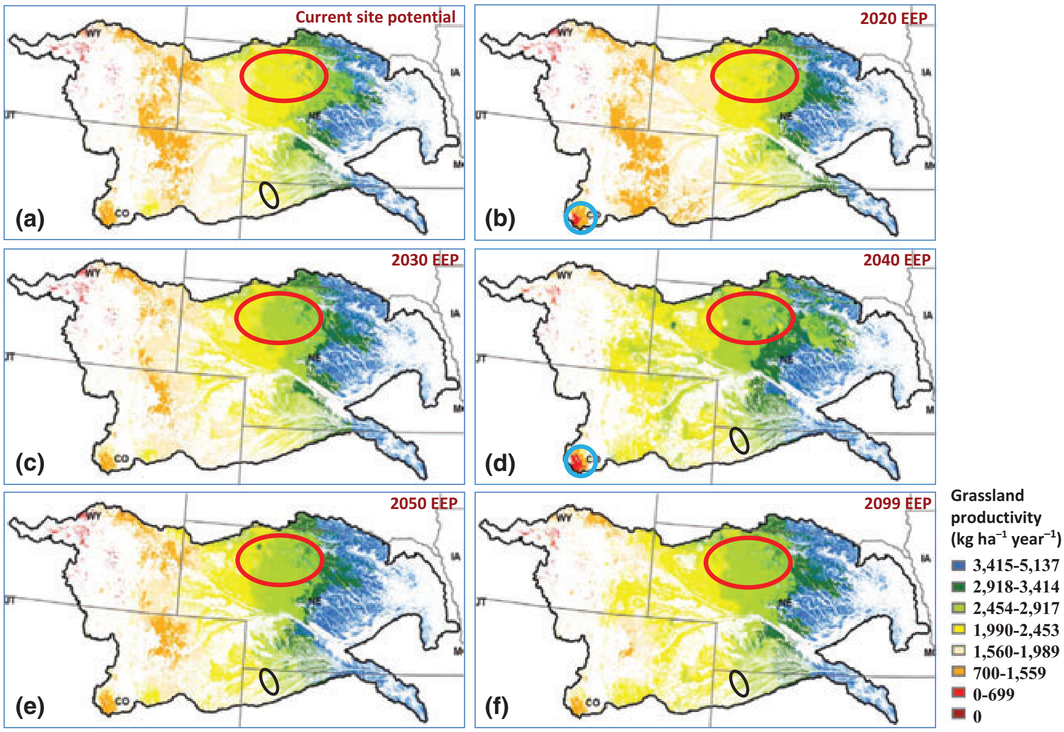

Fig. 3 EEP maps for the GPRB grassland systems. (a) current site potential, (b) 2020 EEP, (c) 2030 EEP, (d) 2040 EEP, (e) 2050 EEP, and (f) 2099 EEP.

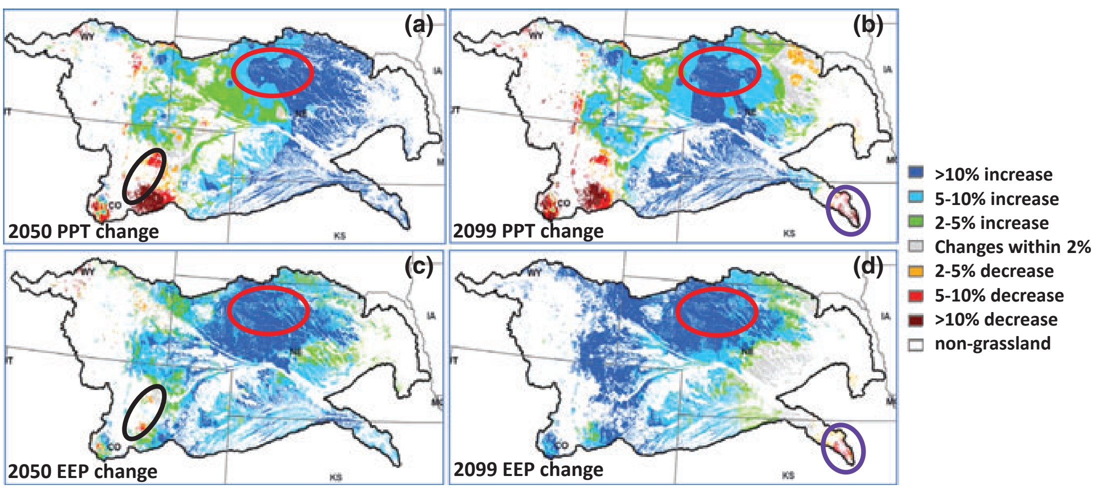

Fig. 4 Future annual precipitation (PPT) change (compare with 30-year average PPT) maps and future grassland EEP change maps (compare with current site potential). (a) 2050 PPT changes, (b) 2099 PPT changes, (c) 2050 EEP changes, and (d) 2099 EEP changes.

site potential, 2020, 2030, 2040, 2050, and 2099 (the Sand Hills ecoregion was excluded during the averaging). We presume that areas that are continually productive and that have increasing future productivity trends will be sustainable for future biofuel feedstock development, and areas that remain unproductive in the future will continue to be unsustainable for future biofuel feedstock development. Results show that under climate scenario 'A1B', the potential biofuel feedstock areas (the wetter eastern part of the GPRB) will remain productive with a slight increasing trend in the future (the spatially averaged EPs for these areas are 3519, 3432, 3557, 3605, 3752, and 3583 kg ha^{-1} year^{-1} for current site potential, 2020, 2030, 2040, 2050, and 2099, respectively) (Fig. 5). Although there is an expected productivity decrease in the biofuel areas located in the southeastern part of the

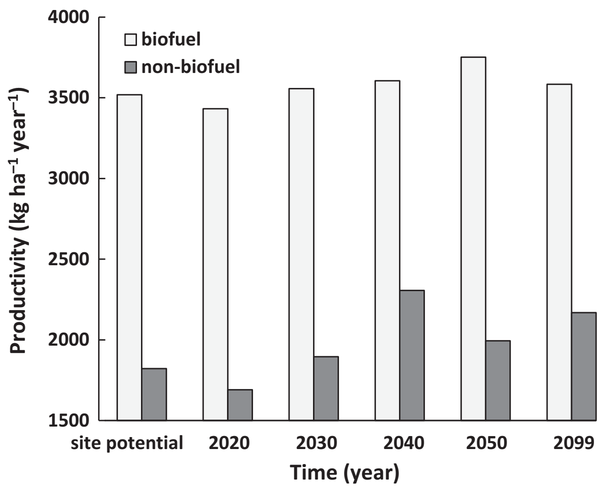

Fig. 5 Spatially averaged (for the biofuel and the nonbiofuel grassland areas) EP values for current site potential, 2020, 2030, 2040, 2050, and 2099.

GPRB in 2099 (purple oval in Fig. 4d) because of an anticipated reduction in annual precipitation, this area is still projected to be very productive in the future (i.e., the EP values are greater than 3400 kg ha^{-1} year^{-1} in this region). Therefore, these identified potential biofuel feedstock areas should continue to be sustainable for future biofuel development.

The spatially averaged EPs for the nonbiofuel areas are 1822, 1691, 1896, 2306, 1994, and 2169 kg ha^{-1} year^{-1} for site potential, 2020, 2030, 2040, 2050, and 2099, respectively. Overall, the identified nonbiofuel grasslands located in the drier western part of the GPRB (Fig. 1) are expected to stay unproductive (EP <2600 kg ha^{-1} year^{-1}, Fig. 3) in the future. A small nonbiofuel region located in the south-central part of the GPRB (within the small black oval in Fig. 3a and d–f) is modeled as moderately productive after 2040 because of the favorable future climate conditions (Fig. 4). Therefore, this small nonbiofuel region is considered to be changed to a potential biofuel region in the future (after 2040). In summary, the spatially averaged future EPs for the nonbiofuel areas are much lower than those for the biofuel areas (Fig. 5), and we conclude that most of the nonbiofuel areas will continue to be unsuitable for biofuel feedstock development in the future.

Discussion

Future climate scenario: a very important driver for estimating future grassland productivity

The future climate projection data (precipitation and temperature data) used to project future EEP in this study were estimated based on the climate scenario 'A1B.' Climate scenario 'A1B' represents an intermediate energy emission path, which means technological change in the energy system is balanced across all fossil and nonfossil energy sources with no heavy reliance on one particular energy source (http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/#About). The future productivity maps derived from this study were mainly driven by a conservative estimate of future weather conditions (i.e., climate scenario 'A1B').

Future weather inputs (temperature and precipitation) may change significantly if they come from a different climate scenario (e.g., climate scenario 'B1,' which represents a low energy emission path with emphasis on clean, sustainable technology). However, there has been no significant energy or technology changes enacted to date that would make scenario 'B1' appear likely. Scenario 'A1B' represents a more moderate scenario than scenario 'A2' ('higher' emissions path) or 'B1' and appears reasonably probable; therefore, we used scenario 'A1B' in this study.

Will the identified grassland biofuel areas remain productive and environmentally sustainable when converting to switchgrass?

Switchgrass is a perennial grass and is being evaluated as a potential feedstock for cellulosic biofuels (Mclaughlin & Kszos, 2005; Liebig, 2006; Sanderson *et al.*, 2006; Schmer *et al.*, 2008; Bracmort, 2010; Bracmort *et al.*, 2010). Switchgrass is a highly productive species with an extensive deep root system and requires a relatively small amount of fertilization and water during its establishment (Dalrymple & Don, 1967; Sladden *et al.*, 1991; Bransby *et al.*, 1998; Frank *et al.*, 2004; Liebig, 2006; Rinehart, 2006). Many studies show that cultivating switchgrass can lead to a carbon sink (especially 2 years after its establishment) and increases ecosystem goods and services (Bransby *et al.*, 1998; Frank *et al.*, 2004; Guretzky *et al.*, 2011; Liebig, 2006, Liebig *et al.*, 2008; Ma *et al.*, 2000; Zeri *et al.*, 2011). Therefore, we presume that, under appropriate management, cultivation of switchgrass in the identified biofuel regions (i.e., current productive grasslands under extensive management with minimal inputs) will remain productive and environmentally sustainable in the future. Harvesting switchgrass for biofuels is often done after senescence (i.e., plant carbohydrates and nutrients have already been translocated to the roots and basal shoots of the vegetation) (Sanderson *et al.*, 1999; Vogel *et al.*, 2002; Rinehart, 2006; Guretzky *et al.*, 2011) and therefore would have minimal impacts on plant vigor. One possible disadvantage for cultivation of switchgrass is that a monoculture of switchgrass may impact the local wildlife habitat and species diversity. In summary, we conclude that, under proper management practices, converting current productive grasslands in the eastern part of the GPRB to switchgrass for biofuels will maintain or improve ecosystem services (e.g., carbon sink, increase soil organic carbon, erosion control, slowed run-off) and minimize the effects of corn-based ethanol developments on global food supplies.

Summary and future work

This study projects future (e.g., 2050 and 2099) grassland productivities and assesses future sustainability of the potential biofuel feedstock areas in the GPRB. Results show that under climate scenario 'A1B' (a conservative estimate of future weather conditions relative to the 'B1' and 'A2' scenarios), the potential biofuel feedstock areas (the wetter eastern part of the GPRB) will remain productive and will be sustainable for future biofuel feedstock development. The identified nonbiofuel grasslands in the drier western part of the GPRB would be expected to stay unproductive and continue to be unsuitable for biofuel feedstock development in the future. This study demonstrates that the DMEP method can successfully identify areas desirable and sustainable for future biofuel feedstock development. The resulting future grassland productivity maps can help scientists and land managers to better understand the future ecosystem function and service (under climate scenario 'A1B') of the GPRB grassland systems and can be used as a reference by land managers and decision makers to assess the future sustainability and feasibility of potential biofuel feedstock areas.

This study represents the first step in projecting future grassland productivity (under a conservative estimate of future weather conditions) and evaluating future sustainability of potential biofuel feedstock areas in the GPRB. In future studies, we plan to employ the new updated climate projections, which are from the IPCC's (Intergovernmental Panel on Climate Change) 5th assessment report (AR5) and are based on Representative Concentration Pathways (RCP) (Moss *et al*., 2010; Meinshausen *et al*., 2011), to develop a future climate scenario-based (e.g., 'RCP2.6' with low radiative forcing, 'RCP4' with medium stabilized forcing, and 'RCP8.5' with a high baseline emission) grassland productivity database from 2020 to 2099 for the GPRB. This future productivity database will help land managers to evaluate and better adapt to probable future ecosystem functions and services in the GPRB.

Acknowledgements

This work was performed under USGS contracts G08PC91508 and G10PC00044, and funded by the USGS Geographic Analysis and Monitoring Program in support of Renewable Energy-Biofuels. We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modeling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy. The authors thank Matthew B. Rigge, 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 U. S. Government.

References

Asner GP, Elmore AJ, Olander LP, Martin RE, Harris T (2004) Grazing systems, ecosystem responses, and global change. *Annual Review of Environment and Resources*, **29**, 261–299.

Bias Corrected and Downscaled World Climate Research Programme. Bias Corrected and Downscaled WCRP CMIP3 Climate Projections. Available at: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections (accessed 20 September 2012).

Bracmort K (2010) Meeting the Renewable Fuel Standard (RFS) Mandate for Cellulosic Biofuels: Questions and Answers. Research Serv. Report for Congress, RL41106.

Bracmort K, Schnepf R, Stubbs M, Yacobucci BD (2010) Cellulosic biofuels: Analysis of policy issues for congress. *Cong. Research Serv. Report for Congress*, RL34738.

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.

Bunn AG, Goetz SJ, Fiske GJ (2005) Observed and predicted responses of plant growth to climate across Canada. *Geophysical Research Letters*, **32**, 1–4.

Buyx A, Tait J (2011) Ethical framework for biofuels. *Science*, **332**(6029), 540–541.

Dalrymple RL, Don DD (1967) Root and shoot growth of five range grasses. *Journal of Range Management*, **20**, 141–145.

Dunn AL, Barford CC, Wofsy SC, Goulden ML, Daube BC (2007) A long-term record of carbon exchange in a boreal black spruce forest: means, responses to interannual variability, and decadal trends. *Global Change Biology*, **13**, 577–590.

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

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.

Gu Y, Wylie BK (2010) Detecting ecosystem performance anomalies for land management in the Upper Colorado River Basin using satellite observations, climate data, and ecosystem models. *Remote Sensing*, **2**(8), 1880–1891.

Gu Y, Boyte SP, Wylie BK, Tieszen LL (2012) 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, Wylie BK, Bliss NB (2013) Mapping grassland productivity with 250-m eMODIS NDVI and SSURGO database over the Greater Platte River Basin, USA. *Ecological Indicators*, **24**, 31–36.

Guretzky JA, Biermacher JT, Cook BJ, Kering MK, Mosali J (2011) Switchgrass for forage and bioenergy: harvest and nitrogen rate effects on biomass yields and nutrient composition. *Plant and Soil*, **399**, 69–81.

Henderson BL, Bui EN, Moran CJ, Simon DAP (2005) Australia-wide predictions of soil properties using decision trees. *Geoderma*, **124**, 383–398.

Homer C, Huang C, Yang L, Wylie B, Coan M (2004) Development of a 2001 national land-cover database for the United States. *Photogrammetric Engineering and Remote Sensing*, **70**, 829–840.

Kang S, Kimball JS, Running SW (2006) Simulating effects of fire disturbance and climate change on boreal forest productivity and evapotranspiration. *Science of the Total Environment*, **362**, 85–102.

Kimball JS, Zhao M, Mcdonald KC, Running SW (2006) Satellite remote sensing of terrestrial net primary production for the pan-Arctic basin and Alaska. *Mitigation and Adaptation Strategies for Global Change*, **11**, 783–804.

Launchbaugh K, Brammer B, Brooks ML *et al*. (2008) *Interactions among livestock grazing, vegetation type, and fire behavior in the Murphy Wildland Fire Complex in Idaho and Nevada, July 2007*. USGS Open-File Report, 2008–1214Reston, VA, USA.

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

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.

Meinshausen M, Smith SJ, Calvin KV *et al.* (2011) The RCP Greenhouse Gas Concentrations and Their Extensions from 1765 to 2300. *Climatic Change*, **109**, 213–241.

Monti A, Barbanti L, Zatta A, Zegada-Lizarazu W (2012) The contribution of switchgrass in reducing GHG emissions. *GCB Bioenergy*, **4**, 420–434.

Moss RH, Edmonds JA, Hibbard KA *et al.* (2010) The next generation of scenarios for climate change research and assessment. *Nature*, **463**, 747–756.

Pala C (2010) Study finds using food grain to make ethanol is energy-inefficient. *Environmental Science & Technology*, **44**, 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 etanol problems and soil erosion.(ed. In: *Soil quality and biofuel production*. (edsLal R, Stewart BA), pp. 119–135. CRC Press, Taylor&Francis Group, Boca Raton, FL, USA.

Rinehart L (2006) Switchgrass as a bioenergy crop. A publication of ATTRA - National Sustainable Agriculture Information Service. Available at: https://attra.ncat.org/attra-pub/summaries/summary.php?pub=311 (accessed 25 February 2013).

Rupp TS, Chapin Iii FS, Starfield AM (2000) Response of subarctic vegetation to transient climatic change on the Seward Peninsula in north-west Alaska. *Global Change Biology*, **6**, 541–555.

Sanderson MA, Read JC, Reed RL (1999) Harvest management of switchgrass for biomass feedstock and forage production. *Agronomy Journal*, **91**, 5–10.

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.

Saxon E, Baker B, Hargrove W, Hoffman F, Zganjar C (2005) Mapping environments at risk under different global climate change scenarios. *Ecology Letters*, **8**, 53–60.

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.

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

Schnepf R, Yacobucci BD (2010) Selected issues related to an expansion of the Renewable Fuel Standard (RFS). Cong. Research Serv. Report for Congress, R40155.

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.

Sladden SE, Bransby DI, Aiken GE (1991) Biomass yield, composition and production costs for 8 switchgrass varieties in Alabama. *Biomass and Bioenergy*, **1**, 119–122.

Smart AJ, Dunn BH, Johnson PS, Xu L, Gates RN (2007) Using weather data to explain herbage yield on three Great Plains plant communities. *Rangeland Ecology and Management*, **60**, 146–153.

Solomon BD, Barnes JR, Halvorsen KE (2007) Grain and cellulosic ethanol: history, economics, and energy policy. *Biomass and Bioenergy*, **31**, 416–425.

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*. Economic Research Service, **WRS-0801**. US Department of Agriculture, Washington, DC, USA.

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.

Viereck LA, Van Cleve K, Dyrness CT (1984) Some aspects of vegetation and temperature relationships in the Alaska taiga. In: *The Potential Effects of Carbon-dioxide-Induced Climate Changes In Alaska*(ed. Mcbeath JH), pp. 129–142. University of Alaska, Fairbanks, AK, USA.

Viereck LA, Dyrness CT, Batten AR, Wenzlick KJ (1992) *The Alaskan vegetation classification*. USDA Pacific Northwest Research Station General Technical ReportPortland, OR, USA.. PNW-GTR-286.

Vogel KP, Brejda JJ, Walters DT, Buxton DR (2002) Switchgrass biomass production in the Midwest USA: harvest and nitrogen management. *Agron J*, **94**, 413–420.

White AB, Kumar P, Tcheng D (2005) A data mining approach for understanding topographic control on climate-induced inter-annual vegetation variability over the United States. *Remote Sensing of Environment*, **98**, 1–20.

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.

Wylie BK, Fosnight EA, Gilmanov TG, Frank AB, Morgan JA, Haferkamp MR, Meyers TP (2007) Adaptive data-driven models for estimating carbon fluxes in the northern Great Plains. *Remote Sensing of Environment*, **106**, 399–413.

Wylie BK, Zhang L, Bliss NB, Ji L, Tieszen LL, Jolly WM (2008) Integrating modelling and remote sensing to identify ecosystem performance anomalies in the boreal forest, Yukon River Basin, Alaska. *International Journal of Digital Earth*, **1**, 196–220.

Wylie BK, Boyte SP, Major DJ (2012) Ecosystem performance monitoring of rangelands by integrating modeling and remote sensing. *Rangeland Ecology and Management*, **65**, 241–252.

Zeri M, Anderson-Teixeira K, Hickman G, Masters M, Delucia E, Bernacchi CJ (2011) Carbon exchange by establishing biofuel crops in Central Illinois. *Agriculture, Ecosystems, & Environment*, **144**, 319–329.