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Evaluation of Carbon Fluxes and Trends (2000e2008) in the Greater Platte River Basin: A Sustainability Study for Potential Biofuel Feedstock Development

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Evaluation of carbon fluxes and trends (2000–2008) in the Greater Platte River Basin: A sustainability study for potential biofuel feedstock development

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ABSTRACT

This study evaluates the carbon fluxes and trends and examines the environmental sustainability (e.g., carbon budget, source or sink) of the potential biofuel feedstock sites identified in the Greater Platte River Basin (GPRB). A 9-year (2000–2008) time series of net ecosystem production (NEP), a measure of net carbon absorption or emission by ecosystems, was used to assess the historical trends and budgets of carbon flux for grasslands in the GPRB. The spatially averaged annual NEP (ANEP) for grassland areas that are possibly suitable for biofuel expansion (productive grasslands) was 71–169 g C m^{-2} $year^{-1}$ during 2000–2008, indicating a carbon sink (more carbon is absorbed than released) in these areas. The spatially averaged ANEP for areas not suitable for biofuel feedstock development (less productive or degraded grasslands) was –47 to 69 g C m^{-2} $year^{-1}$ during 2000–2008, showing a weak carbon source or a weak carbon sink (carbon emitted is nearly equal to carbon absorbed). The 9-year pre-harvest cumulative ANEP was 1166 g C m^{-2} for the suitable areas (a strong carbon sink) and 200 g C m^{-2} for the non-suitable areas (a weak carbon sink). Results demonstrate and confirm that our method of dynamic modeling of ecosystem performance can successfully identify areas desirable and sustainable for future biofuel feedstock development. This study provides useful information for land managers and decision makers to make optimal land use decisions regarding biofuel feedstock development and sustainability.

1. Introduction

Development of corn-based ethanol is limited because of concerns about world food shortages, livestock and food price increases, and negative environmental effects such as soil erosion and increased demand for water for irrigation [1–7]. As a result, cultivation of cellulosic feedstock crops, such as switchgrass (*Panicum virgatum*) [8–13], is expected to increase in the near future [5,8,9]. In a previous study, we identified grasslands potentially suitable for cellulosic feedstock production (e.g., switchgrass) within the Greater Platte River Basin (GPRB) based on a dynamic modeling of ecosystem

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performance (DMEP) approach [14]. This previous study provided a new monitoring and modeling method that can help land managers and decision makers make optimal land use decisions regarding cellulosic feedstock development. However, this previous study only represents the first step in identifying grassland areas suitable for cellulosic feedstock development. Further evaluating and examining environmental and ecological sustainability (e.g., carbon budgets and carbon trends) of these identified biofuel feedstock areas is important and necessary.

Several studies have been conducted to assess the climate and environmental impacts caused by biofuel feedstock development (e.g., effects on water resources, soil organic carbon, and greenhouse gas emissions) [15–20]. Investigations on the carbon dioxide exchanges at biofuel experimental sites carried out recently [21,22] indicated the potential of perennial biofuel crops to sustainably maintain CO_2-sink activity, but there still is a need to scale-up these observations from experimental sites to large geographic areas.

The main objective of this study is to evaluate the carbon fluxes and carbon trends of the potential biofuel feedstock areas identified by Gu et al. [14] in the GPRB using 9-year time series of net ecosystem production (NEP) data developed by Zhang et al. [23]. NEP is an important ecosystem-scale characteristic for assessing and understanding terrestrial carbon cycles, ecosystem services, and global climate changes [24–31]. In this study, NEP (a comprehensive measure of carbon accumulation [32]) is used as a proxy for long-term environmental sustainability.

This study fills gaps in the previous research to assess the environmental sustainability of the potential biofuel feedstock areas in the GPRB. Results from this study help better understand the terrestrial carbon budget and carbon cycle in the GPRB. This study will further validate that our method of dynamic modeling of ecosystem performance, which uses readily available data and requires much less processing procedures, can successfully identify areas sustainable for biofuel feedstock development. Results from this study will provide useful information to land managers and decision makers to make optimal land use decisions regarding biofuel feedstock development and sustainability.

2. Materials and methods

2.1. Study area

This research is a continuation of our previous study of the Greater Platte River Basin (Fig. 1, within the blue outline). The GPRB is located in the heartland of the United States and covers parts of Wyoming, Colorado, South Dakota, Kansas, and most of Nebraska. The GPRB contains three river basins: the Platte River Basin, the Niobrara River Basin, and the Republican River Basin. The western part of the GPRB (southeastern Wyoming and northeastern Colorado) has very low rangeland productivity because of the unfavorable conditions for vegetation growth (e.g., shallow or rocky soils, low annual precipitation). The annual precipitation in the GPRB increases from west to east from less than 250 mm to greater than 600 mm. The eastern part of the GPRB has high rangeland productivity because of the favorable vegetation growth conditions (e.g., good soil and climate conditions) [14]. Fig. 1 is the National Land Cover Database (NLCD) map for the GPRB [33]. The main vegetation cover types in the GPRB are grassland (~50%) and cultivated crops (~30%). Other land cover types include shrubs, evergreen and deciduous forests, and pasture/hay.

2.2. Potential grassland biofuel feedstock sites

In a previous study, we used biophysical information in the archival records of satellite data (i.e., a 9-year (2000–2008) time series of the Normalized Difference Vegetation Index (NDVI) data with a 250-m spatial resolution), site geophysical and biophysical features (elevation, slope and aspect, and soils), and weather and climate drivers to build ecosystem performance models [14,34,35]. We identified grasslands potentially suitable for cellulosic feedstock production (e.g., switchgrass) within the GPRB. We presumed that areas with consistently high grassland productivity and with fair to good range condition (lack of severe ecological disturbances such as land fire and insect infestation) are potentially suitable for cellulosic feedstock development. Unproductive grasslands (grasslands with poor soils, steeper slopes, dry climate conditions, or other conditions not conducive to vegetation growth), degraded grasslands (multi-year persistent ecosystem underperformance with poor range condition caused by wildfire, insect infestation, or heavy grazing), or grasslands with high vulnerability to erosion (e.g., the Sand Hills ecoregion in Nebraska where removal of biomass may lead to sand dune activation) are not appropriate for cellulosic feedstock development.

Fig. 2 delineates grassland areas that are potentially suitable for cellulosic biofuel feedstock development within the GPRB identified by Gu et al. (2012); the spatial resolution of the map is 250 m. Pixels in green or blue represent productive grasslands and where, according to our model, ecosystems have consistently overperformed or normally performed (lack of severe ecological disturbances with good and healthy vegetation conditions) relative to weather and site condition expectations. The growing season (from early April to late October) averaged NDVIs (GSN) are 0.43–0.52 for the green areas and are greater than 0.52 for the blue areas. The areas identified as suitable for cellulosic biofuel feedstock development are mainly located in the eastern section of the GPRB (Fig. 2). Pixels in tan represent unproductive grasslands (GSN $\leq$ 0.43), grasslands with high vulnerability to erosion (Sand Hills ecoregion), or degraded grasslands that are not appropriate for biofuel feedstock development [14]. The non-suitable areas are mainly located in the western and central parts of the GPRB.

2.3. 9-Year (2000–2008) time series of NEP data

NEP, calculated as the difference between gross photosynthetic assimilation and total ecosystem respiration, is a measure of net carbon absorption or emission by ecosystems [32,36,37]. The data-driven rule-based piecewise regression NEP models developed by Zhang et al. (2011) were derived from multiple flux tower sites and years (2000–2008), satellite

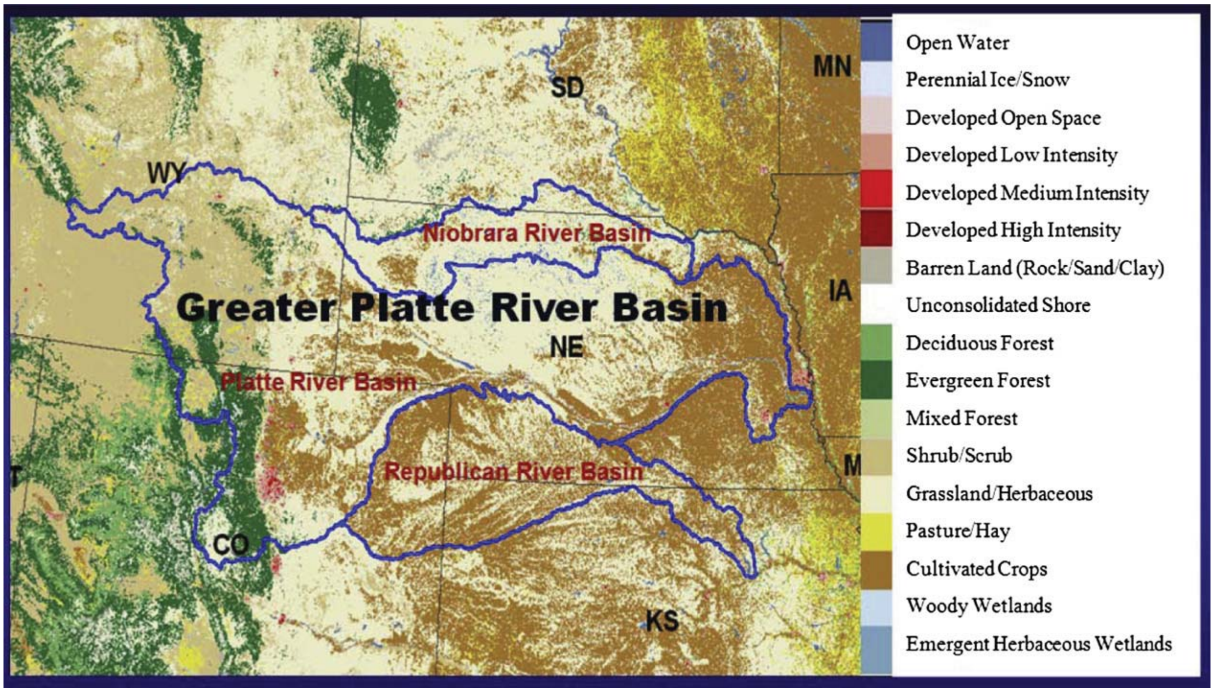

Fig. 1 – Location of the Greater Platte River Basin (inside the blue outline) and the land cover types as identified in the National Land Cover Database (NLCD). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

vegetation index (NDVI), phenological metrics, precipitation and temperature, photosynthetically active radiation, and soil water holding capacity (WHC) [23]. The locations and the detailed site characteristic information of the flux towers were fully described by Zhang et al. [23]. These NEP models were used to map the 9-year weekly time series of NEP for the Great Plains grasslands. The annual NEPs (ANEP, total cumulative NEP for a certain year) for 2000–2008 within the GPRB were then calculated. The 2000–2008 time integrated ANEP (i.e., cumulative ANEP for the whole period) for the GPRB were also computed for evaluation. Since the NEP models did not take into account biomass removal with harvest, the NEP data used in this study are referred to as "pre-harvest" NEP.

2.4. *Extracting time series ANEP data for individual biofuel and non-biofuel sites*

As the first step of this study, we evaluated the carbon budgets and carbon trends for six individual sites within the GPRB, shown with red stars in Fig. 2. We arbitrarily selected two non-biofuel sites ("Non-biofuel site 1" and "Non-biofuel site 2") that represent dry climate condition and unproductive or degraded grassland: one is located in the western part of the GPRB (southeastern Wyoming), and the other one is located in the central part of the GPRB (central Nebraska). Subsequently, we selected two moderate-biofuel sites ("Moderate-biofuel site 1" and "Moderate-biofuel site 2") that represent moderate productive grasslands: one is located in the northern part of the GPRB (southern South Dakota), and the other one is located in the central part of the GPRB (central Nebraska). Finally, we selected two high-biofuel sites ("High-biofuel site 1" and "High-biofuel site 2") that represent high productive grasslands with favorable soil, climate, and biophysical conditions for vegetation growth: both are located in the eastern part of the GPRB (central Nebraska). The 9-year time series of ANEP and the cumulative ANEP data for the above six sites were extracted from the ANEP maps. The 9-year ANEP and the cumulative ANEP time series plots for the six sites were then generated for evaluating carbon trends and assessing carbon budgets (source or sink).

2.5. *Spatially averaged ANEP data for the biofuel and the non-biofuel areas*

In order to evaluate and assess the overall carbon budgets and trends for the entire biofuel and non-biofuel areas, we computed the 2000–2008 time series spatially averaged ANEP and the spatially averaged 9-year cumulative ANEP for the all- (includes both high- and moderate-biofuel areas), the high-, the moderate-, and the non-biofuel areas. These 9-year time series data and plots will be used to evaluate the overall carbon trends and carbon budgets (source or sink) of the identified biofuel and non-biofuel feedstock areas and to assess the environmental sustainability of these potential biofuel feedstock areas within the GPRB.

2.6. *Criteria for environment sustainability*

As discussed in the previous section, NEP is a measure of net carbon absorption or emission by ecosystems. Long-term positive NEP (i.e., carbon sink, more carbon is absorbed from the atmosphere than returned to the atmosphere) means an

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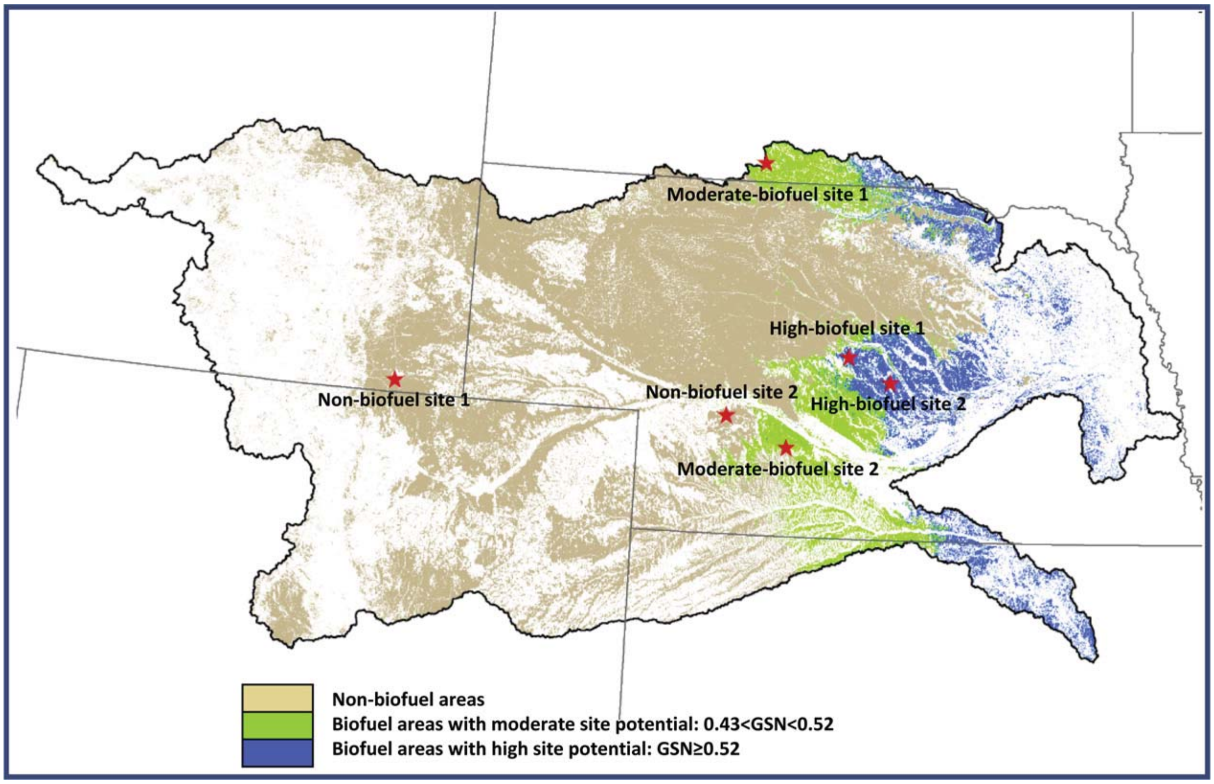

Fig. 2 – Grassland areas that are potentially suitable for cellulosic biofuel feedstock development (green and blue) within the GPRB identified by Gu et al. (2011). Pixels in green and blue represent areas that either overperformed or normally performed for seven of nine years from 2000 to 2008 and with moderate (the averaged GSN are 0.43–0.52) or high (the averaged GSN are greater than 0.52) ecosystem site potential. Grassland areas that are not suitable for biofuel feedstock development are in tan. Locations of the six representative sites are also shown in the figure (red stars).

increase in the total carbon storage in the ecosystem including soil organic carbon (SOC) and soil organic matter (SOM), which indicates more essential plant nutrients are stored and held in the soil [38]. SOM helps maintain healthy soil by improving soil WHC and protecting the soil from water and wind erosion. Low WHC with limited soil moisture will decrease plant production and increase overland flow of water, which is associated with topsoil erosion. An increasing trend of SOM (long-term carbon sinks) implies that an ecosystem is improving in productivity or recovering or climbing to a newer SOM equilibrium. On the other hand, long-term negative NEP (i.e., carbon source, more carbon is released with respiration than is taken up with photosynthesis) means a probable decline in SOC and SOM, which negatively impacts the ability of soil to retain both nutrients and minerals (since SOM increases soil cation exchange capacity) [38]. Therefore, consistent carbon sinks are a much better indicator of a sustainable system than consistent carbon sources; NEP can be used as a proxy for long-term environmental sustainability.

Previous studies indicated that grasslands are generally a net sink for atmospheric CO_2, and growing perennial grass can provide great litter and root biomass for carbon storage [39–44]. Switchgrass is a perennial grass that does not need annual tillage or annual planting after establishment (which can increase SOM and retain a healthy soil condition) [38]. Switchgrass has an extensive deep root system and requires a relatively small amount of fertilization and water (irrigation) [10,39,45–48]. Many studies showed that cultivating switchgrass could lead to a carbon sink (especially 2 years after it is established) [21,39,47,49,50]. Harvesting switchgrass for biofuels is often done after senescence of the vegetation (i.e., plant carbohydrates and nutrients have already been translocated to the roots and basal shoots of the vegetation) and therefore would have minimal impact on plant vigor. Furthermore, native grasses usually store most of their carbon belowground [48]; therefore, removal of senesced switchgrass with appropriate management (e.g., fertilization) will have minimal impact on the SOM and SOC. In summary, we presume that cultivating switchgrass under a good management practice for biofuel will potentially lead to a long-term carbon sink and be environmentally sustainable. The current existing non-irrigated productive grasslands are a good proxy for switchgrass biofuels.

Based on the above discussions, we presume that areas with multi-year persistent positive NEP values (long-term carbon absorption by ecosystem) are environmentally sustainable for future biofuel feedstock development. In contrast, areas with multi-year negative or near zero NEP values (carbon emission exceeds or is nearly equal to carbon absorption) are environmentally unsustainable for future biofuel feedstock development.

3. Results and discussion

3.1. *ANEP and cumulative ANEP time series plots for the six selected sites*

Fig. 3a and b are the 2000–2008 ANEP and cumulative ANEP time series plots for the six selected sites. Strong carbon sinks (high positive ANEP and high positive cumulative ANEP, more carbon is absorbed than emitted, 9-year accumulated ANEP > 2000 g C m^{-2}) can be found for the two high-biofuel sites and one moderate-biofuel site ("Moderate-biofuel site 2" located in the central part of the GPRB), indicating these sites are environmentally sustainable for future biofuel feedstock development. A moderate carbon sink (positive ANEP and positive cumulative ANEP, 9-year accumulated ANEP > 850 g C m^{-2}) is shown in Fig. 3 for the other moderate-biofuel site ("Moderate-biofuel site 1" in southern South Dakota). Although the ANEPs were near equilibrium for 2000 and 2002 because of drought conditions in these two years for "Moderate-biofuel site 1" (Fig. 3a; http://droughtmonitor.unl.edu/archive.html), the cumulative ANEP still showed a generally increasing trend (an overall moderate carbon sink) for this site (Fig. 3b). Therefore, "Moderate-biofuel site 1" is also environmentally sustainable for future biofuel feedstock development.

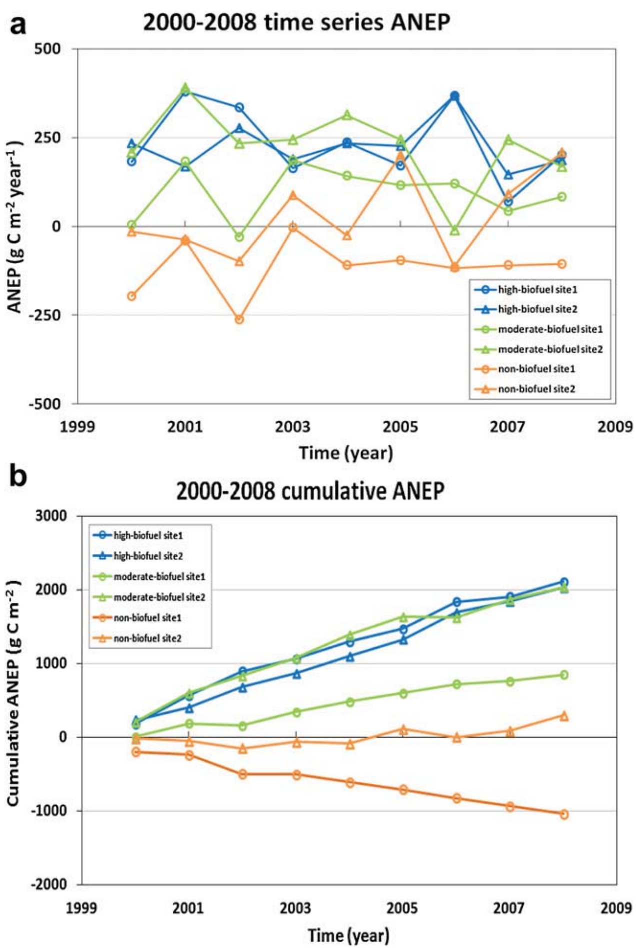

Fig. 3 – 2000–2008 Time series plots for the six representative sites. (a). ANEP, (b). Cumulative ANEP. Locations of the six sites are shown in Fig. 2 (red stars).

Strong carbon sources (negative ANEP and negative cumulative ANEP, more carbon is released than absorbed, 9-year accumulated ANEP < −1040 g C m^{-2}) are found for "Non-biofuel site 1" (Fig. 3a and b), which is located in the western part of the GPRB (southeastern Wyoming) with a dry climate condition and unproductive or degraded grassland. The environmental condition (carbon budget and trend) indicates that this site would be unsustainable for future biofuel feedstock development. Despite the fact that strong carbon sinks occurred in several years (e.g., 2005, 2008) for "Non-biofuel site 2," which is located in the central part of the GPRB (central Nebraska), the cumulative ANEPs were near zero during 2000–2008, indicating that carbon flux (NEP) was consistently near equilibrium for this site. Based on the criteria (Section 2.6) for determining the environmental sustainability of a site for future biofuel feedstock development (i.e., long-term carbon absorptions with multi-year persistent positive NEP values), "Non-biofuel site 2" would be environmentally unsustainable for future biofuel feedstock development.

These evaluations of the carbon fluxes and trends for the six representative sites indicate that the potential biofuel areas identified by Gu et al. (2012) are environmentally sustainable for future biofuel development. These results demonstrate that our DMEP method can successfully identify and separate areas that are desirable (environmentally sustainable) or undesirable (environmentally unsustainable) for future biofuel feedstock development.

3.2. *Carbon fluxes and trends for the all-biofuel areas and the non-biofuel areas in the GPRB*

In order to understand the general carbon trends and budgets in the GPRB, we calculated the spatially averaged ANEP and the spatially averaged cumulative ANEP for 2000–2008 for four categories of biofuel suitability: all-, high-, moderate-, and non-biofuels. The all-biofuels category combines the high- and moderate-biofuels categories. Fig. 4a and b show the 9-year time series spatially averaged ANEP and cumulative ANEP plots for the four categories. During 2000–2008, the spatially averaged ANEP for the all-, the high-, and the moderate-biofuel areas were from 71 to 169 g C m^{-2} $year^{-1}$, 99–161 g C m^{-2} $year^{-1}$, and 18–177 g C m^{-2} $year^{-1}$ (Fig. 4a), respectively, indicating carbon sinks in these areas. The spatially averaged ANEP for the non-biofuel areas was from −47 to 69 g C m^{-2} $year^{-1}$ during 2000–2008 (Fig. 4a), showing a weak carbon source or a weak carbon sink (near equilibrium) in these areas. The 9-year averaged ANEP were 130 g C m^{-2}, 136 g C m^{-2}, and 124 g C m^{-2} for the all-, the high-, and the moderate-biofuel areas (strong carbon sinks) and 22 g C m^{-2} for the non-biofuel areas (near equilibrium). Fig. 4b also exhibits significant cumulative ANEP increasing trends for the three biofuel categories and a near zero trend for the non-biofuel category. The 9-year cumulative ANEP for the all-, the high-, the moderate-, and the non-biofuel areas were 1166, 1225, 1117, and 200 g C m^{-2}, respectively.

In summary, these overall NEP assessment results further support the previous ANEP budget and trend results from the

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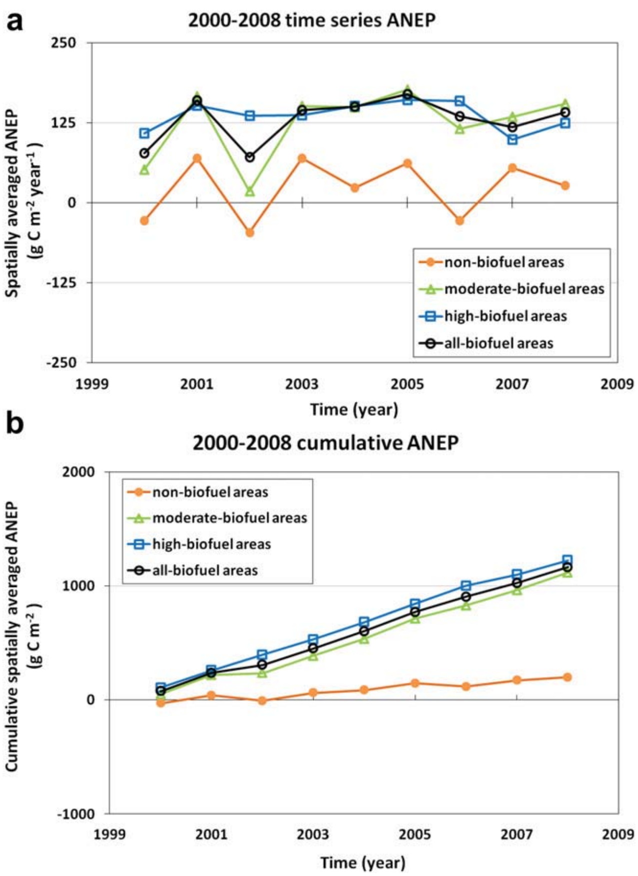

Fig. 4 – 2000–2008 Spatially averaged time series plots for the non-, the moderate-, the high-, and the all-biofuel grasslands. (a) Spatially averaged ANEP, (b) Cumulative spatially averaged ANEP.

six individual sites and demonstrate again that our DMEP method can successfully identify areas desirable (environmentally sustainable) or unsuitable (environmentally unsustainable) for biofuel feedstock development.

3.3. *Discussion of the carbon budgets and trends*

Previous studies have indicated that drought can significantly influence terrestrial carbon sequestration [51–53]. Grassland ecosystems shifted between a carbon sink in a normal year to a carbon source in a drought year [23,51,54–56]. In this study, we found that there are significant ANEP decreases in 2002 for the moderate-biofuel and the non-biofuel areas (Fig. 4a). These decreases are due to the severe-extreme drought that occurred in the moderate-biofuel and the non-biofuel areas during 2002 [23,57]. On the other hand, there was nearly no ANEP decrease in 2002 for the high-biofuel areas. Based on the historical drought condition maps derived from the National Drought Monitor Data Archives [57], we found that there were no severe droughts that affected the high-biofuel areas during 2002 and therefore led to no significant ANEP decrease in 2002.

Additionally, the 9-year spatially averaged cumulative carbon flux (ANEP) for the all-biofuel areas (Fig. 4b) is 1166 g C m^{-2}, indicating large amounts of carbon were absorbed in these areas during 2000–2008. In reality, these grassland ecosystems would not likely store such large amounts of carbon. Therefore, it is important to understand how the carbon is removed and transferred. As we previously mentioned, the NEP data used in this study do not consider biomass removal with harvesting. Therefore, we presume that in addition to possible sequestration of carbon in soil organic matter, the following actions would remove the carbon (e.g., grass): (1) harvesting and transporting (selling) the grass to other regions, (2) animal grazing, and (3) prairie fires (natural or managed by ranchers). Animal grazing would remove carbon from a site, but it would largely be returned eventually by animal manure and decomposition. All these management practices, combined with most carbon storage being belowground for native perennial grass, should maintain the carbon balance for the GPRB grassland biofuel areas.

The identified biofuel feedstock areas with long-term persistent carbon sink have stored more essential plant nutrients and maintained a healthy soil condition. This implies that these areas are improving in productivity or recovering or climbing to a newer SOC equilibrium, which means they are suitable and sustainable for future biofuel development. Moreover, genetic modification of biofuel crops (e.g., switchgrass or other species) may improve future yields.

4. Conclusions

This study extends our previous research to evaluate the carbon flux and examine the environmental sustainability (e.g., carbon source or sink) of the potential biofuel feedstock sites identified by Gu et al. (2012) in the GPRB. We used the 9-year time series of NEP data that was developed by Zhang et al. (2011) to assess the historical carbon budgets and trends for the sites suitable (or unsuitable) for biofuel feedstock development in the GPRB.

The spatially averaged ANEP for the all-biofuel areas was from 71 to 169 g C m^{-2} $year^{-1}$ during 2000–2008, indicating persistent carbon sinks (more carbon was absorbed than emitted) in these areas. The spatially averaged ANEP for the non-biofuel areas was from −47 to 69 g C m^{-2} $year^{-1}$ during 2000–2008, showing a weak carbon source or a weak carbon sink (carbon input and output is near equilibrium) in these areas. The 9-year averaged ANEPs for the all- and the non-biofuel areas were 130 g C m^{-2} (a strong carbon sink) and 22 g C m^{-2} (carbon input and output is near equilibrium), respectively. The 9-year cumulative ANEP plots illustrate the notable increasing trends for the three biofuel categorical areas and a near zero trend for the non-biofuel areas. The 9-year pre-harvest cumulative ANEP was 1166 g C m^{-2} (a strong carbon sink) for the all-biofuel areas and 200 g C m^{-2} (a weak carbon sink) for the non-biofuel areas.

These results further improve our understanding of the environmental sustainability conditions of the potential biofuel feedstock areas previously identified in the GPRB. This study confirms that our DMEP method, which uses readily available data and requires much less processing procedures and could therefore be more available as a tool for land managers, can successfully identify areas that are desirable and sustainable for future biofuel feedstock development.

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