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Empirically modeling carbon fluxes over the northern Great Plains grasslands

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1. Introduction

The grassland ecosystem in the U.S. Great Plains, occupying about 1.5 million km², is characterized by different photosynthetic pathways that shift dramatically from C_3 dominance in the north to C_4 dominance in the south (Tieszen et al., 1997). Previous studies have shown that grassland ecosystems are potential carbon sinks (Jacobs et al., 2003; Frank et al., 2003). However, grassland ecosystems may also release carbon into the atmosphere during drought (Kim et al., 1992). An understanding of carbon fluxes and their relationship to the atmosphere-vegetation interaction across the northern Great Plains (NGP) (Fig. 1) is essential for developing carbon budget models at regional, national, and global scales.

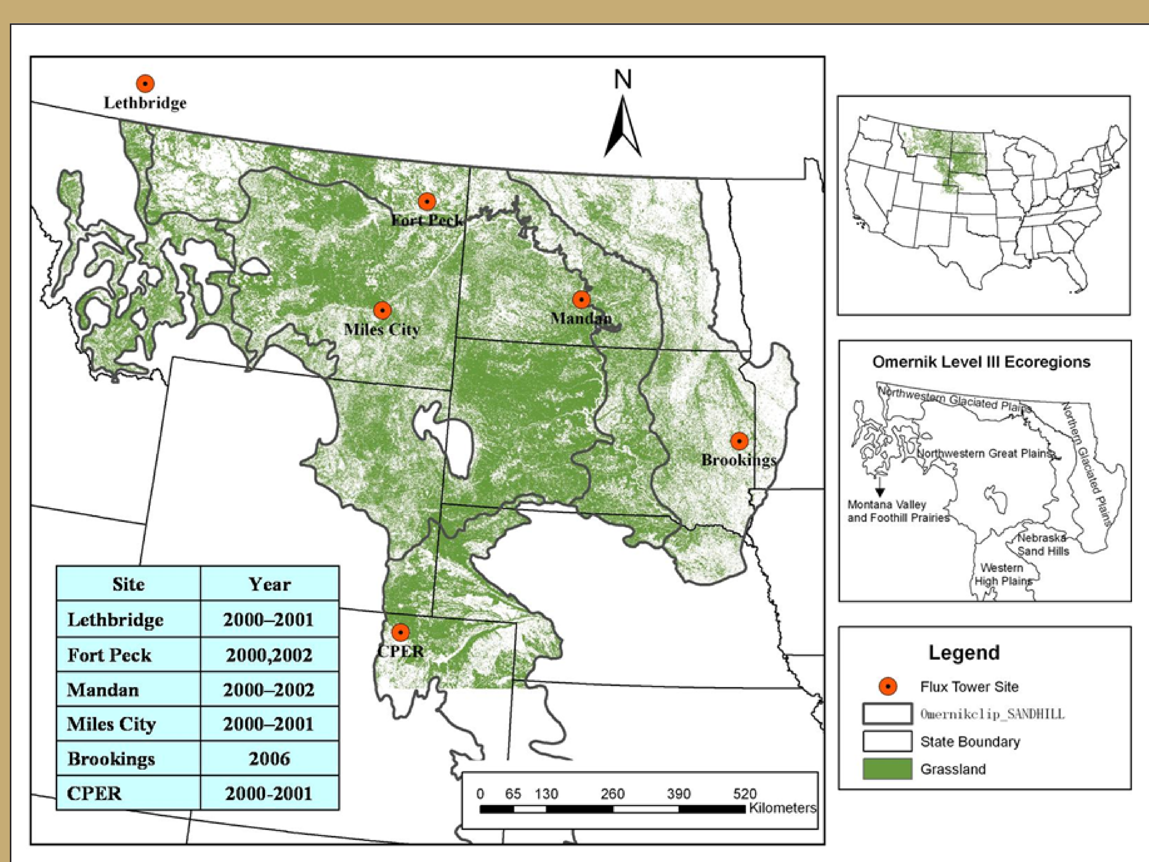


Figure 1. Grassland flux towers over the northern Great Plains.

2. Objectives

In this study, we used and modified a remote sensing-based empirical model, the piecewise regression (PWR) model (Wylie et al., 2007; Zhang et al., 2007), to estimate the grassland carbon fluxes over the NGP for 2000–2006 at 500-m resolution and at 8-day intervals. We then conducted the analysis based upon the estimated net ecosystem exchange (NEE) and gross primary production (GPP) in the region to 1) quantify the inter- and intra-annual variations of NEE and GPP, 2) identify the carbon sink and source areas, 3) identify the drought impact on grassland ecosystems, and 4) determine the trends of GPP.

3. Methods and Materials

We integrated spatial datasets and flux data from six grassland towers to estimate the spatiotemporal carbon fluxes across the study area (Fig. 1) by exploring the empirical relationship among environmental variables and tower-based measurements. The predictors include the 8-day composite MODIS normalized difference vegetation index (NDVI) and normalized difference water index (NDWI) at 500-m resolution, 8-day precipitation, 8-day temperature, photosynthetically active radiation, and phenological metrics. We also incorporated the actual vegetation evapotranspiration data derived from a Vegetation Evapotranspiration (VegET) model (Senay and Henebry, 2007), which takes into account soil moisture and land surface phenology. Based on model simulations, we mapped the carbon fluxes at 8-day intervals and 500-m resolution for 2000–2006 in the NGP grasslands.

4. Model Assessment

Cross-validation was applied to evaluate the estimation accuracy of the PWR model. We compared NEE and GPP from the PWR model with tower-based NEE and GPP by withholding each site and each year. We found high agreement between tower-measured and PWR-estimated carbon fluxes in the grasslands. The results indicate $r = 0.92–0.96$ for GPP estimation and $r = 0.75–0.91$ for NEE estimation by withholding site (Fig. 2), and = 0.92–0.96 for GPP estimation and $r = 0.76–0.84$ for NEE estimation by withholding year. The estimates of NEE and GPP capture the seasonal trends of tower NEE and GPP for most of the sites (Fig. 3).

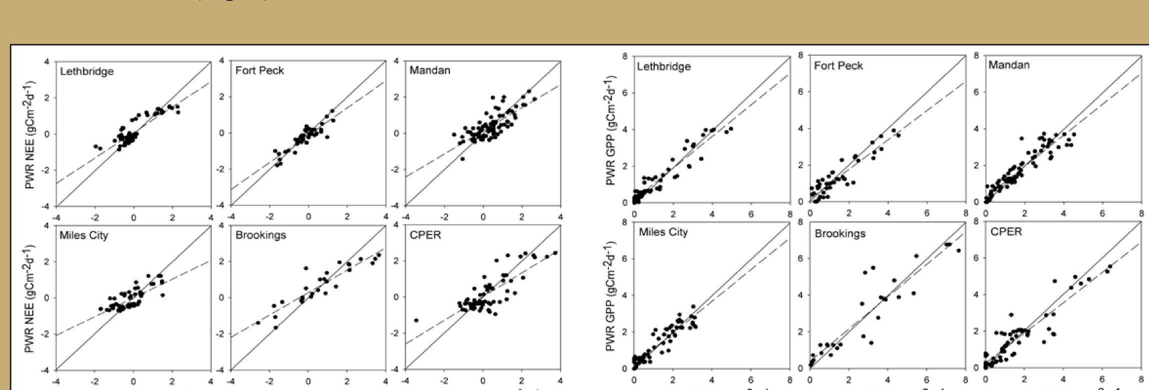


Figure 2. Cross-validation by withholding each site, comparing NEE and GPP between tower-based measurements and the PWR model. Points represent each 10-day interval. Graphs are labeled with the name of the withheld site. The dashed line represents the regression line. The solid line represents the 1:1 line.

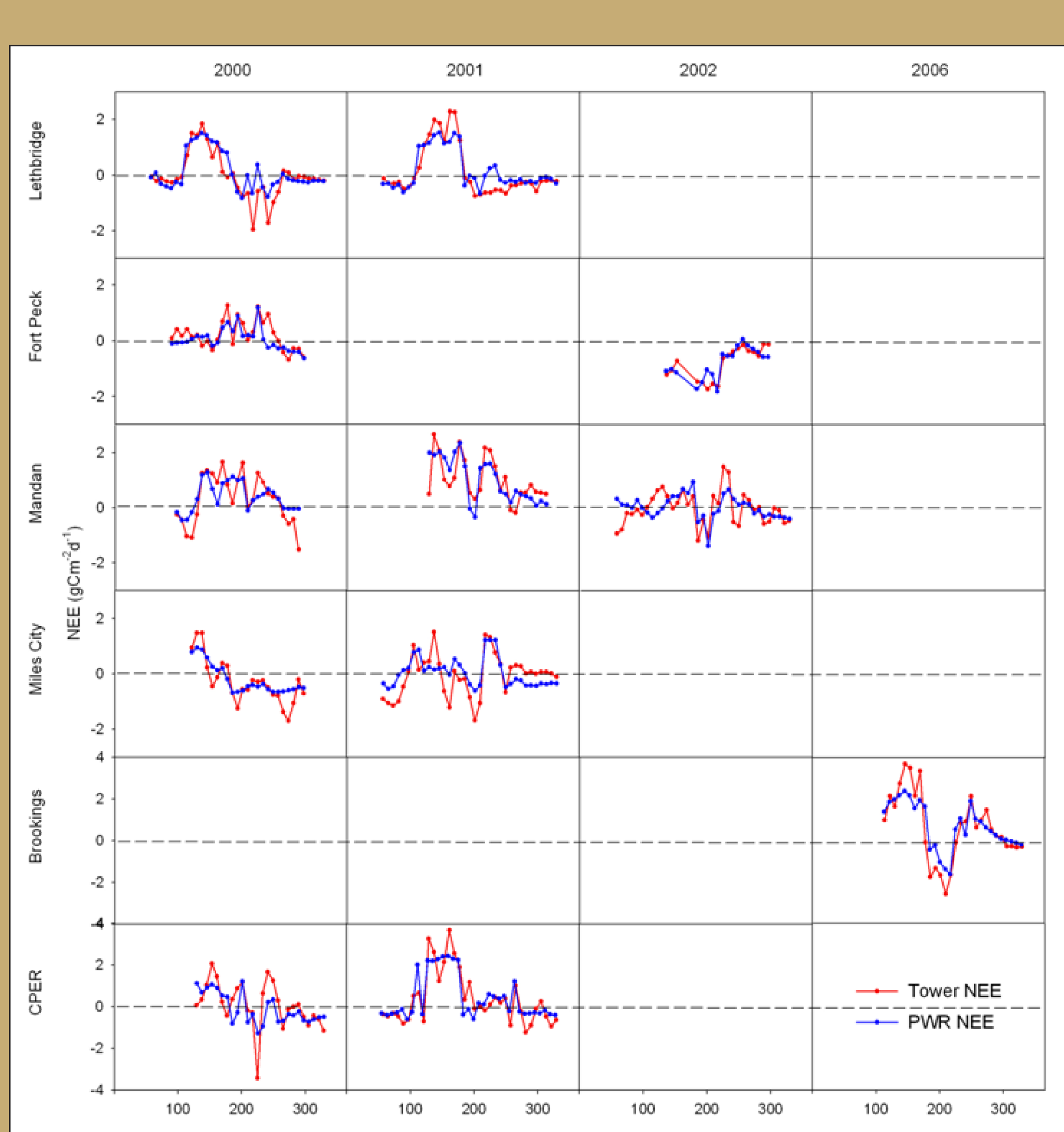


Figure 3. The agreement of seasonal dynamics of measured and estimated NEE at flux towers.

5. Net ecosystem exchange (NEE)

5.1 Inter-annual NEE variability (2000–2006)

The annual NEE varied from -35 (source) in 2006 to 32 gCm^{-2} year^{-1} (sink) in 2001 in the NGP grassland, with sources in drier years of 2002, 2004, and 2006, and sinks in other years (Fig. 4). On average, the annual NEE amounts to –2±24 gCm^{-2} year^{-1}, which means that averaged over the 7 years, the NGP grassland was a weak source for atmospheric CO_2, with a relatively large standard deviation (STD).

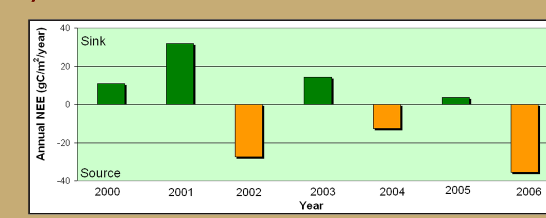


Figure 4. Annual NEE variation during 2000–2006.

The 2000–2006 NEE maps (Fig. 5) show extensive carbon sources in drier western regions and carbon sinks in wetter eastern regions, which follows the pattern of the east-west gradient of annual precipitation across this region and higher drought probability in the western parts.

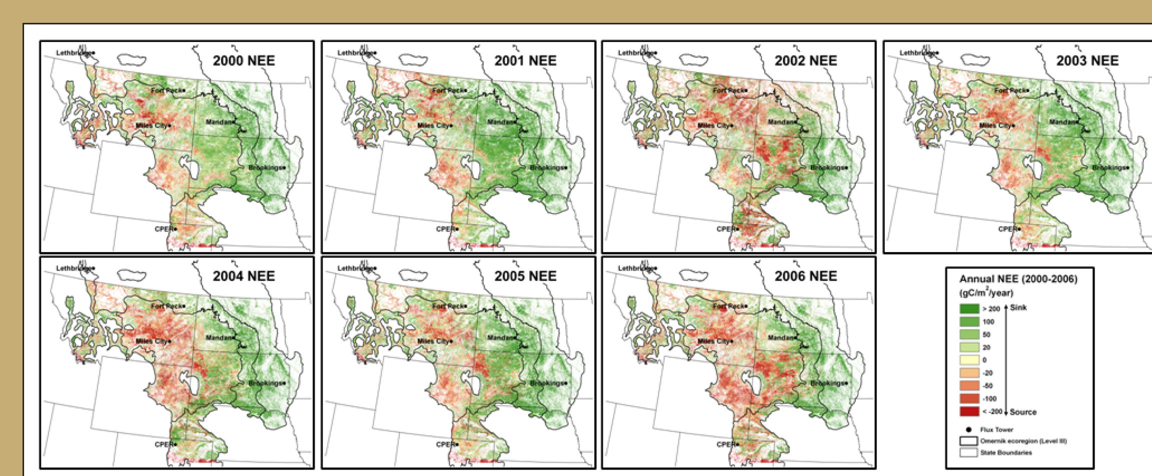


Figure 5. Spatial distribution of NEE over the NGP for 2000–2006.

5.2 Intra-annual NEE variability

The grasslands are a sink for carbon in May and June and become a carbon source in July and August (Fig. 6). The monthly NEE maps show different spatial distributions, especially in July and August. In July of the wet year 2001, NEE indicates carbon sources in the west but sinks in the east. However, NEE shows a carbon source in the entire NGP area in July of the dry year 2002.

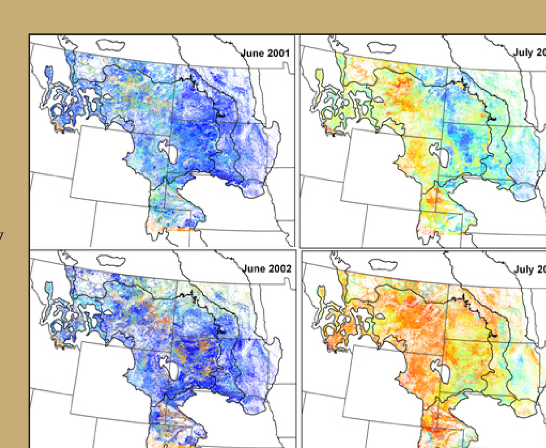
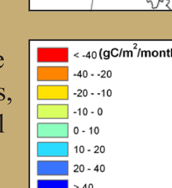


Figure 6. Monthly NEE during 2001 and 2002.



5.3 Carbon sink and source by ecoregion

In the entire NGP, all ecoregions are different with respect to the carbon fluxes. The Northern Glaciated Plains and Northwestern Glaciated Plains always were strong carbon sinks, but the Northwestern Great Plains, Western High Plains, and Montana Valley and Foothill Prairies had a net release of carbon for the 7 years (Fig. 7). The Northwestern Great Plains shows the largest carbon source average of –32 gCm^{-2} year^{-1} for the 7 years. During 2000–2006, the Northwestern Great Plains was a carbon sink in the wet year 2001 but released large amounts of carbon (–65, –56, –79 gCm^{-2} year^{-1}) for the drought years 2002, 2004, and 2006, and released small amounts of carbon for 2000, 2003, and 2005 following the drought years.

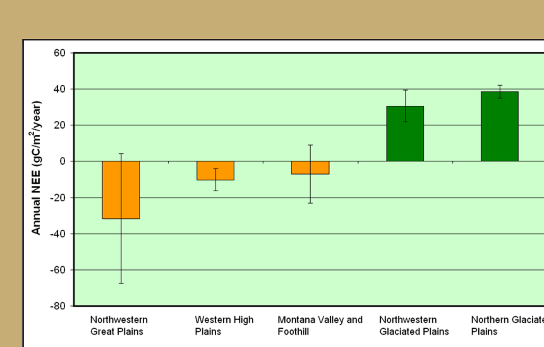


Figure 7. Average annual NEE (2000–2006) by ecoregion (Error bar: standard deviation of 7-year estimate NEE).

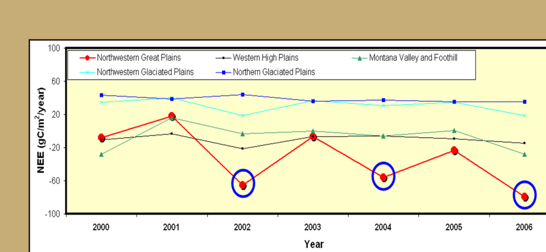


Figure 8. Annual NEE variation by ecoregion.

The NEE in the Northwestern Great Plains showed the largest variation through the 7 years because of larger climate variation in this ecoregion. NEE in the Northwestern Great Plains fluctuated around zero during the normal years 2000, 2001, 2003, and 2005, but in the drier years 2002, 2004, and 2006, the drought drove the grassland to release carbon (shown by the blue circle in Fig. 8). The Northern Glaciated Plains and western High Plains have relatively higher GPP of 636 and 564 gCm^{-2} growing season^{-1} (Fig. 11), but Montana Valley and Foothill Prairies has the lowest GPP of 336 gCm^{-2} growing-season^{-1}. The GPP shows large inter-annual variation in the western High Plains, but less variation in the northern Glaciated Plains and Montana Valley and Foothill Prairies.

6. Gross primary production (GPP)

6.1 Inter-annual GPP variability (2000–2006)

The average GPP was 455±20 gCm^{-2} in the growing season. GPP was relatively stable, with the greatest GPP (488 gCm^{-2} growing-season^{-1}) in the wet year 2001 and the lowest GPP (433 gCm^{-2} growing-season^{-1}) in 2003 following the dry year 2002. This suggests that there was a lagged drought effect on GPP, although these grasslands became a carbon sink in 2003.

We estimated a 4 percent reduction of GPP in the dry year 2002 compared to the average GPP for the years 2000–2006 and an 11 percent reduction relative to the wet year 2001, which resulted in an anomalous net source of carbon (–27 gCm^{-2} year^{-1}) in this region in 2002. Especially in the Western High Plains, the 2002 GPP was 16 percent below the 7-year average GPP and was 21 percent below the 2001 level.

6.2 Intra-annual GPP variability

The 2002 drought significantly reduced the GPP in June and July compared to 2001 (Fig. 9).

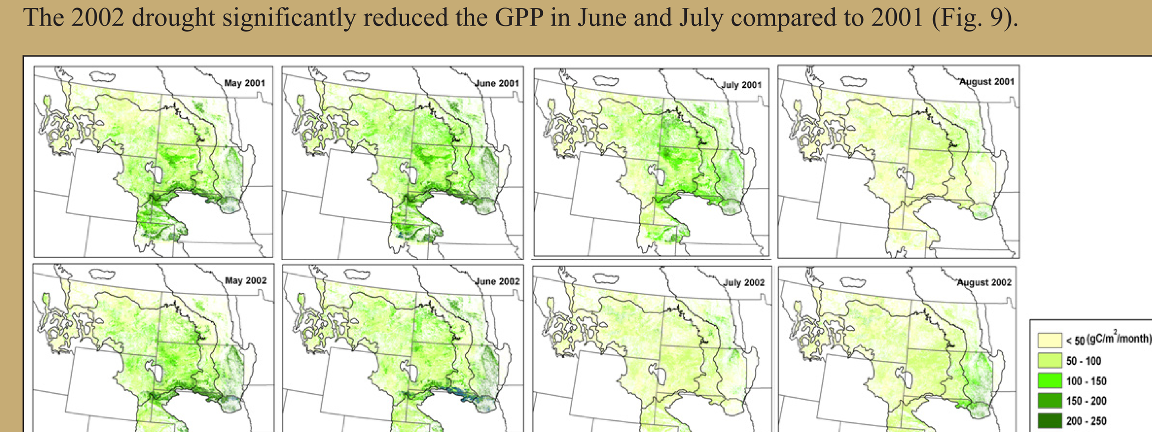


Figure 9. Monthly GPP during 2001 and 2002.

6.3 Gross primary production by ecoregion

The 7-year average GPP map (Fig. 10) shows that the GPP is higher in the Northern Glaciated Plains and Western High Plains, which are characterized by higher percentages of C_4 grasses (Fig. 11).

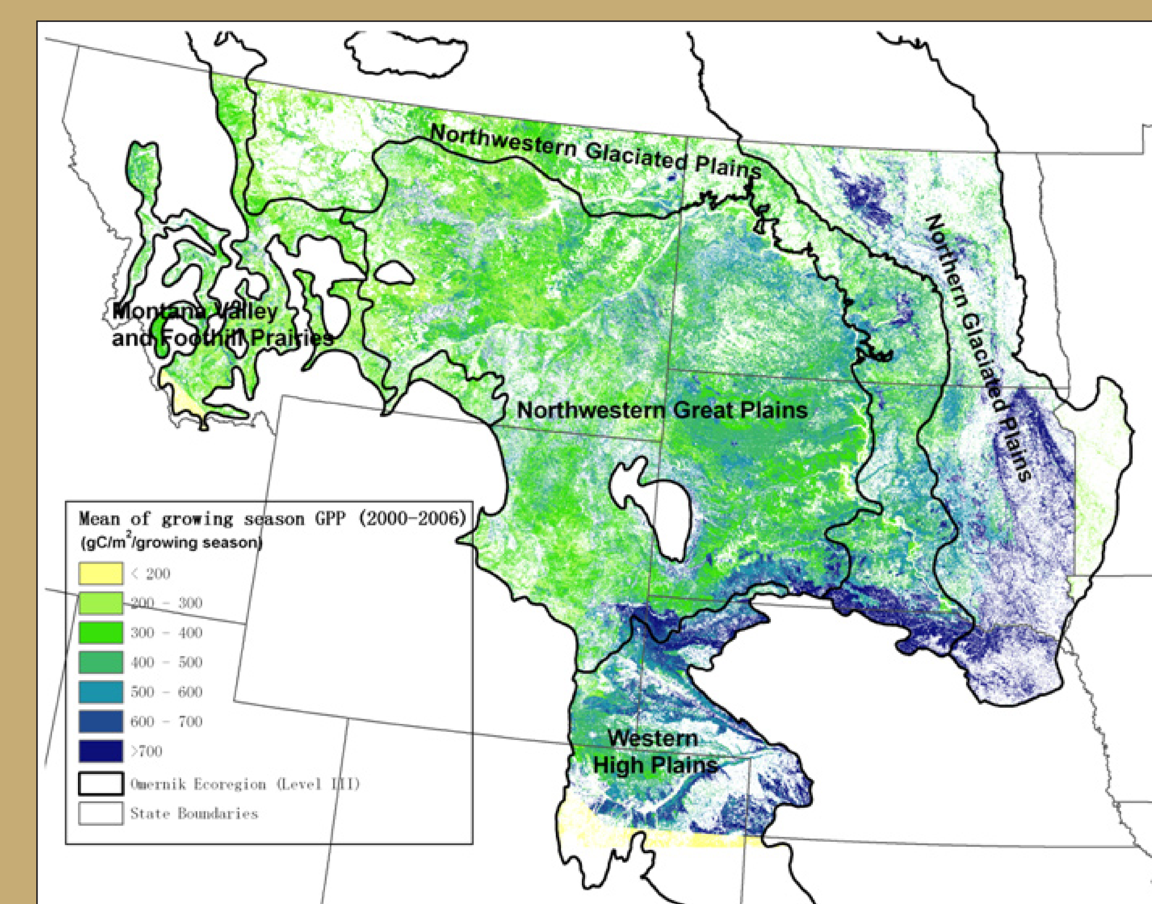


Figure 10. Average GPP for the 2000–2006 growing season.

The Northern Glaciated Plains and Western High Plains have relatively higher GPP of 636 and 538 gCm^{-2} growing-season^{-1} (Fig. 11), but the Montana Valley and Foothill Prairies region has the lowest GPP with 330 gCm^{-2} growing-season^{-1}. The GPP shows large inter-annual variation in the Western High Plains, but less variation in the Northern Glaciated Plains and Montana Valley and Foothill Prairies.

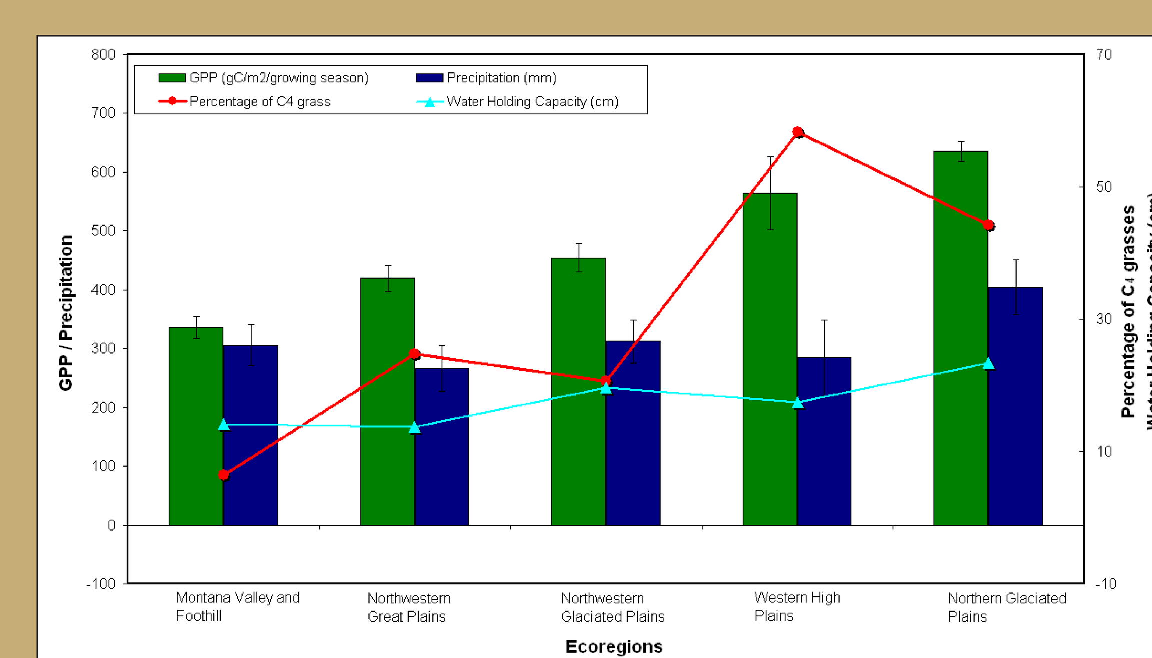


Figure 11. Average GPP (2000–2006) and percentage of C_4 grasses by ecoregion (Error bar: standard deviation of 7-year estimate GPP).

7. Drought Impact on Grassland Ecosystems

The carbon budget and grassland gross primary production, to a great extent, are dependent upon the amount and distribution of precipitation in this region. For example, the precipitation in the Western High Plains decreased by 34%, 6%, and 14% for the years 2002, 2004, and 2006, respectively, which caused decreases of GPP in this ecoregion of 16%, 4%, and 7%. As a result, the grassland released a large amount of carbon to the atmosphere in the 3 years in the Northwestern Great Plains (Fig. 8).
The percentage area of drought in the NGP (http://www.drought.unl.edu/dm/dmtabs_archive.htm), and the GPP and NEE estimated by the PWR model, have a strong linear correlation, with $R^2 = 0.71$ and $R^2 = 0.56$ for GPP and NEE, respectively (Fig. 13, left and right).

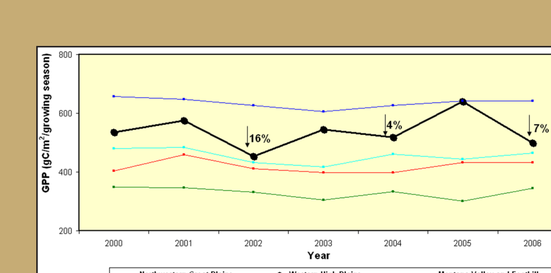


Figure 12. The growing season GPP variation by ecoregion.

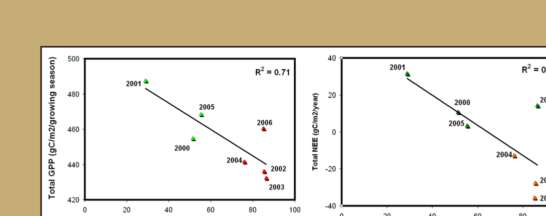


Figure 13. Drought impact on GPP and NEE in NGP.

8. Conclusions

1. Though previous studies have shown that a grassland ecosystem is a potential carbon sink, NEE in the study area was consistently low (–35 to 32 gCm^{-2}year^{-1}) and fluctuated around zero, with a small carbon source of –2 gCm^{2}year (7-year average).
2. The annual NEE transitioned from sinks to sources in the dry years of 2002, 2004, and 2006, and the region was an extensive carbon source in July and August in the dry years. If drought events increase in the future, the ecosystems may change to larger carbon sources.
3. NEE shows strong spatial variation, with carbon sources in the drier west and carbon sinks in the wetter east.
4. The Northwestern Great Plains was the largest carbon source area during the 7 years and showed the largest variation of carbon budget from –79 gCm^{-2}year^{-1} in 2006 to 17 gCm^{-2}year^{-1} in 2001.
5. The average GPP in the NGP was 455±20 gCm^{-2} in the growing season. The drought significantly reduced the GPP in June and July.
6. The Northern Glaciated Plains had the largest GPP of 636 gCm^{-2} growing-season^{-1}, with a higher percentage of C_4 grasses (44%) compared to other areas in the NGP.
7. By estimating GPP and NEE over a 7-year period, we show that drought has a strong impact on the NGP grassland ecosystems, especially in the Western High Plains and the Northwestern Great Plains.

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