Upscaling carbon fluxes over the Great Plains grasslands: Sinks and sources

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[1] Previous studies suggested that the grasslands may be carbon sinks or near equilibrium, and they often shift between carbon sources in drought years and carbon sinks in other years. It is important to understand the responses of net ecosystem production (NEP) to various climatic conditions across the U.S. Great Plains grasslands. Based on 15 grassland flux towers, we developed a piecewise regression model and mapped the grassland NEP at 250 m spatial resolution over the Great Plains from 2000 to 2008. The results showed that the Great Plains was a net sink with an averaged annual NEP of 24 ± 14 g C m^{-2} yr^{-1}, ranging from a low value of 0.3 g C m^{-2} yr^{-1} in 2002 to a high value of 47.7 g C m^{-2} yr^{-1} in 2005. The regional averaged NEP for the entire Great Plains grasslands was estimated to be 336 Tg C yr^{-1} from 2000 to 2008. In the 9 year period including 4 dry years, the annual NEP was very variable in both space and time. It appeared that the carbon gains for the Great Plains were more sensitive to droughts in the west than the east. The droughts in 2000, 2002, 2006, and 2008 resulted in increased carbon losses over drought-affected areas, and the Great Plains grasslands turned into a relatively low sink with NEP values of 15.8, 0.3, 20.1, and 10.2 g C m^{-2} yr^{-1} for the 4 years, respectively.

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1. Introduction

[2] Concerns have grown that global change and associated increasing CO_2 concentrations may influence human, biological, geochemical, and atmospheric processes. These concerns have led to international negotiations on carbon emissions [*Buys et al.*, 2009; *Lipford and Yandle*, 2010], and these negotiations require a better understanding of the carbon fluxes and environmental factors that determine the magnitude of fluxes and the mutual feedback of terrestrial ecosystems and climate [*Gilmanov et al.*, 2005]. Net ecosystem production (NEP) represents the net exchange of carbon between terrestrial ecosystems and the atmosphere. Estimating NEP has been a main goal of carbon research. Numerous models based on remote sensing have been developed to investigate CO_2 exchange between the biosphere and atmosphere at regional, continental, and global scales. These models range in complexity from empirical models [*Hassan et al.*, 2006; *Yang et al.*, 2007; *Wylie et al.*, 2007; *Zhang et al.*, 2007; *Xiao et al.*, 2008; *Phillips and Beeri*, 2008] to biogeochemical models [*Potter et al.*, 1993; *Prince and Goward*, 1995; *Field et al.*, 1995; *Running et al.*, 2004; *Turner et al.*, 2004]. However, the biogeochemical models are often complex because they require numerous assumptions, model parameterization, and abundant accurate data inputs. Recently, diverse empirical upscaling models that integrate flux tower data and remotely sensed environmental variables have been developed for estimating gross primary production (GPP) and NEP at multiple spatiotemporal scales. Types of these models include neural network [*Papale and Valentini*, 2003], piecewise regression tree [*Wylie et al.*, 2007; *Zhang et al.*, 2007; *Xiao et al.*, 2008; *Zhang et al.*, 2010], support vector machine [*Yang et al.*, 2007], stepwise linear regression [*Phillips and Beeri*, 2008], and model tree ensemble [*Jung et al.*, 2009].

[3] Grassland ecosystems cover a vast area comprising about 40% of the Earth's terrestrial land area, excluding areas of permanent ice cover [*World Resources Institute*, 2000]. Grasslands in the U.S. Great Plains occupy about 1.4 million km^2 and constitute the major land cover (61%), with C_3 grassland dominant in the north and C_4 species

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prevalent in the south [*Tieszen et al.*, 1997]. The Great Plains grasslands represent a dry (west) to moist (east) moisture gradient transitioning from shortgrass to mixed-grass and to tallgrass species [*Joyce et al.*, 2001]. These rich grasslands serve as resources for livestock production in North America and are important contributors to climate regulation and global carbon balance because of the relatively high soil carbon stocks in mesic grasslands.

[4] At least 14 flux towers are in operation over the Great Plains grassland for measuring NEP. For the grasslands NEP in the Great Plains, several upscaling models integrating satellite data and flux measurements have been conducted for specific geographic regions. At the national scale, *Xiao et al.* [2008] extrapolated 42 AmeriFlux tower-measured NEP values to the conterminous United States for 2005 at 1 km resolution. At the regional scale, *Phillips and Beeri* [2008] estimated the growing season (1997–2006) NEP from Landsat imagery in the North Dakota grasslands. The northern Great Plains grasslands NEP was estimated by *Wylie et al.* [2007] using the SPOT (Systeme Pour l'Observation de la Terre) VEGETATION normalized difference vegetation index (NDVI) for 1998 to 2001 and by *Zhang et al.* [2010] using the Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI for 2000–2006. At the site level, the interannual variation of NEP was investigated at specific sites based on eddy covariance or Bowen Ratio Energy Balance (BREB) measurements [*Frank and Dugas*, 2001; *Flanagan et al.*, 2002; *Frank*, 2004; *Gilmanov et al.*, 2005; *Heitschmidt et al.*, 2005; *Svejcar et al.*, 2008; *Gilmanov et al.*, 2010]. However, there is a lack of detailed investigations on the long-term interannual variability of carbon exchange for the entire Great Plains grasslands, although the extensive flux towers in the region have been providing temporally continuous flux data.

[5] Previous studies have suggested that grassland ecosystems generally function as potential carbon sinks or are near equilibrium [*Scurlock and Hall*, 1998; *Frank and Dugas*, 2001; *Sims and Bradford*, 2001; *Suyker et al.*, 2003; *Janssens et al.*, 2003; *Xu and Baldocchi*, 2004; *Gilmanov et al.*, 2006; *Svejcar et al.*, 2008]. A large interannual NEP variation was reported for a pasture for 1995–1998 in the southern Great Plains [*Meyers*, 2001] and for the Canadian temperate mixed prairie during 1998 and 2000 [*Flanagan et al.*, 2002]. *Sims and Bradford* [2001] found that a southern Plains mixed-grass prairie was a carbon sink during 1995 and 1997. However, a tallgrass native prairie in 1993 and 1994 in Texas [*Dugas et al.*, 1999], nongrazed mixed-grass prairie for 1996–1999 in North Dakota [*Frank and Dugas*, 2001], and C_4-dominated tallgrass during 1997 and 1999 in Oklahoma [*Suyker et al.*, 2003] were found to be near equilibrium for carbon. Although these studies suggested that grasslands might be carbon sinks or near equilibrium, alternations between carbon sink and source were not unusual.

[6] Droughts significantly influence interannual variation in terrestrial carbon sequestration [*Pereira et al.*, 2007; *Reichstein et al.*, 2007; *Scott et al.*, 2009; *Xiao et al.*, 2009]. Grassland ecosystems shifted between a carbon sink in a normal year to a carbon source in a drought year [*Kim et al.*, 1992; *Meyers*, 2001; *Gilmanov et al.*, 2007; *Granier et al.*, 2007; *Nagy et al.*, 2007; *Pereira et al.*, 2007; *Aires et al.*, 2008; *Arnone et al.*, 2008]. In the past 10 years, severe droughts struck the entire Great Plains in 2002 and 2006 [*NOAA*, 2010] and some subregions in other years. Understanding the carbon dynamics under various climatic conditions (e.g., drought) requires knowledge of interannual and spatial variations in ecosystem carbon exchange with the atmosphere, which is also a prerequisite for global carbon cycle modeling.

[7] Our previous study over the northern Great Plains grasslands found that NEP was highly variable between 2000 and 2006 and that these grasslands were carbon sources during the drought years of 2002, 2004, and 2006 [*Zhang et al.*, 2010]. What are the source/sink dynamics for the entire Great Plains grasslands during the drought and nondrought years? We extended our previous study to the entire Great Plains using the NEP measured from 15 flux tower sites. We developed a rule-based piecewise regression model to map NEP at 7 day intervals and at a spatial resolution of 250 m. Our objectives were to (1) develop a piecewise regression model for estimating NEP with MODIS data and flux tower measurements, (2) quantify the interannual variability of NEP from 2000 to 2008, and (3) identify the drought impacts on carbon sink and source activities in spatiotemporal regions.

2. Data and Methods

2.1. Flux Tower Data

[8] We conducted this study in the U.S. Great Plains (latitudes 25°48′N to 49°00′N and longitudes 90°10′W to 115°00′W), which encompasses 17 ecoregions as defined by Omernik's level III Ecoregions (Figure 1) [*Omernik*, 1987]. The climate in the Great Plains follows a north–south temperature gradient and an east–west precipitation gradient. Annual precipitation ranges from less than 200 mm on the western edge to over 1100 mm on the eastern edge. Average annual temperature is less than 4°C in the northern Great Plains and exceeds 22°C in the southern Great Plains [*Joyce et al.*, 2001]. Grasslands and croplands compose the major land cover over the Great Plains. The cool-season grasslands are mainly distributed in the north and the warm-season grasslands are distributed in the central and southern portions of the region. With the increased precipitation from west to east across the Great Plains, the native vegetation includes more mixed-grass and tallgrass species, and finally tree species [*Joyce et al.*, 2001]. We identified grassland areas with the 2001 National Land Cover Database (NLCD 2001) [*Homer et al.*, 2004], which includes two herbaceous classes: Grassland/Herbaceous and Pasture/Hay. The bulk of grasslands over the Great Plains are relatively static through time, thus the regional assessment of grassland carbon dynamics is assumed to be reliable. NLCD 2001 at 30 m spatial resolution provided a relatively accurate land cover map for the 250 m carbon flux mapping.

[9] Grassland NEP was measured at 14 flux towers that are distributed throughout the Great Plains including the Lethbridge site located in Alberta, Canada (Figure 1 and Table 1). We also included the Batavia site outside the Great Plains in our piecewise regression model to bound the eastern side of the plains and provide additional model robustness. The gap-filled NEP data for these sites, including raw flux data from AmeriFlux [*Baldocchi et al.*, 2001; *Law*, 2007] (eddy covariance measurements) and Rangeflux [*Svejcar et al.*, 1997] (Bowen ratio–energy balance measurements) networks combined with some nonnetwork sites, were acquired

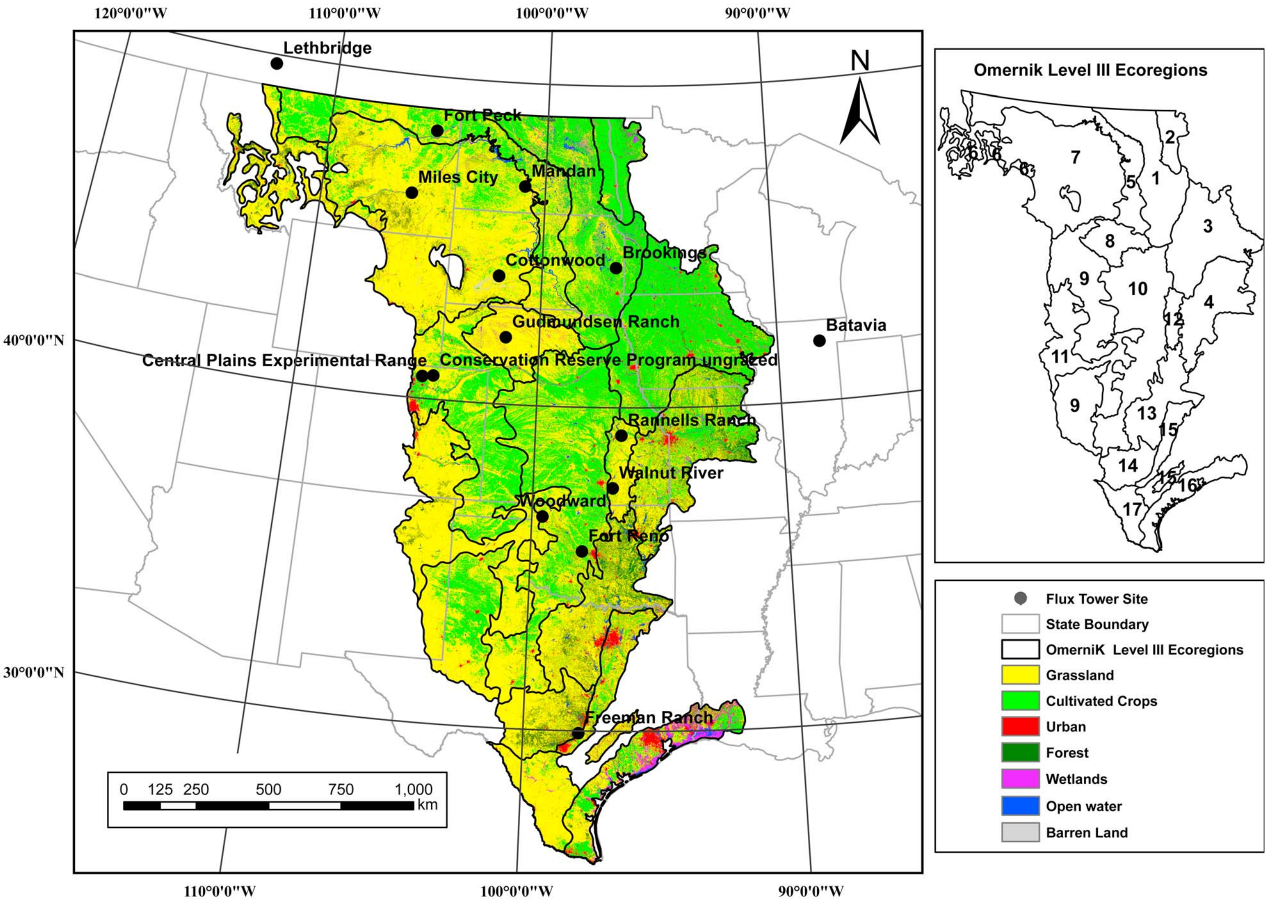

Figure 1. Study area, grassland flux towers, and land cover over the Great Plains. The land cover map was derived from the 2001 National Land Cover Database. The numbers labeled in the Omernik Level III Ecoregions map represent the following: 1, Northern Glaciated Plains; 2, Lake Agassiz Plain; 3, Western Corn Belt Plains; 4, Central Irregular Plains; 5, Northwestern Glaciated Plains; 6, Montana Valley and Foothill; 7, Northwestern Great Plains; 8, Nebraska Sandhills; 9, Western High Plains; 10, Central Great Plains; 11, Southwestern Tablelands; 12, Flint Hills; 13, Central Oklahoma/Texas Plains; 14, Edwards Plateau; 15, Texas Blackland Prairies; 16, Western Gulf Coastal Plain; and 17, Southern Texas Plains.

from the WorldGrassAgriflux database [*Gilmanov et al.*, 2010]. The gap-filling algorithms used the 30 min step data and light response curve analysis as well as relationships with flux tower "slow data" (atmospheric and soil variables) to fill short gaps in the carbon flux estimates [*Gilmanov et al.*, 2005].

[10] These sites represent a wide range of spatial, ecological, and climatic conditions in the region. The flux tower NEP was integrated from hourly to daily time scale, and then averaged over each 7 day period to match the 7 day composite of MODIS NDVI data. We used tower-measured NEP as the training data set for the piecewise regression model and as the testing data set for model validation. At the Lethbridge site, estimates from the piecewise regression model were unavailable because of a lack of gridded meteorological data in Canada. The tower-measured NEP and climate data at the Lethbridge tower were used as the training data for developing the model.

2.2. Model Inputs

[11] The model inputs include remotely sensed vegetation indices and weather data sets, soil data, and the tower-measured NEP. The most important explanatory variables for the final piecewise regression model included NDVI, phenological metrics, weather variables, and soil water holding capacity (WHC) derived from the State Soil Geographic (STATSGO) database. *Sims et al.* [2006] stated that NDVI can be applied to directly estimate carbon exchange at weekly time scales. In this study, we adopted the NDVI derived from the 250 m and 7 day composite eMODIS products. The eMODIS products were developed at the U.S. Geological Survey Earth Resources Observation and Science (EROS) Center and include 7 day composites of NDVI at 250 m, 500 m, and 1 km resolutions [*Jenkerson et al.*, 2010] (see also ftp://emodisftp.cr.usgs.gov/eMODIS/) for the conterminous United States (referred to as "eMODIS CONUS"). The eMODIS CONUS products are processed using the same level 1B swath data as those used by the standard MODIS product, and the level 2 atmospherically corrected surface reflectance data are calculated using the standard MODIS algorithm. The level 2 swath data are directly mapped to the Lambert Azimuthal Equal-area projection and processed for 7 day compositing using an

Table 1. Description of the Grassland Flux Towers Over the Great Plains

Identification Number	Site	Year	Vegetation Type	Latitude, Longitude (°)	Annual Total Precipitation (mm)	Annual Average Temperature (°C)	Method[a]	Network/Principal Investigator
1	Lethbridge, Alberta, Canada	2000–2002	Mixed shortgrass	49.7093, −112.9402	378	6.4	EC	AmeriFlux/L. Flanagan
2	Fort Peck, Montana	2000, 2002–2003	Mixed grass	48.3079, −105.1005	310	7.7	EC	AmeriFlux/T. Meyers
3	Mandan, North Dakota	2000–2002	Mixed grass	46.7667, −100.916	404	5.0	BREB	Rangeflux/A. Frank
4	Miles City, Montana	2000–2001	Mixed grass	46.3, −105.9667	343	7.9	BREB	Rangeflux/M. Haferkamp
5	Brookings, South Dakota	2006–2007	Tallgrass	44.311, −96.798	550	5.8	EC	AmeriFlux/T. Meyers
6	Cottonwood, South Dakota	2005, 2007	Mixed grass	43.95, −101.8466	447	7.7	EC	AmeriFlux/T. Meyers
7	Gudmundsen, Nebraska	2005–2007	Mixed grass	42.069, −101.4074	560	7.9	EC	University of Nebraska, Lincoln/D. Billesbach (personal communication, 2009)
8	Batavia, Illinois	2005	Tallgrass	41.8406, −88.24103	921	10.5	EC	AmeriFlux/R. Matamala
9	Conservation Reserve Program ungrazed, Colorado	2005	Shortgrass	40.7297, −104.3013	332	9.2	EC	Ameriflux/N. Hanan
10	Central Plains Experimental Range, Colorado	2000–2001	Shortgrass	40.6833, −104.75	332	9.2	BREB	Rangeflux/J. Morgan
11	Rannels Flint Hills, Kansas	2000	Tallgrass	39.139, −96.523	840	12.9	CS	Kansas State University/C. Owensby (personal communication, 2009)
12	Walnut River, Kansas	2001–2004	Tallgrass	37.5208, −96.855	1030	13.1	EC	AmeriFlux/R. Coulter
13	Woodward, Oklahoma	2002–2003	Tallgrass	36.6, −99.58333	586	14.3	BREB	Rangeflux/J. Bradford
14	Fort Reno, Oklahoma	2005–2006	Tallgrass	35.557, −98.017	870	14.9	EC	AmeriFlux/D. Billesbach, M. Fischer
15	Freeman Ranch, Texas	2004–2005	Tallgrass	29.93, −98.01	959	19.4	EC	AmeriFlux/J. Heilman

[a]BREB, Bowen ratio–energy balance; EC, eddy covariance; CS, conditional sampling.

enhanced temporal compositing algorithm. The eMODIS products provide significant improvements in image geometric features since the data set avoids the global sinusoidal projection that may cause image distortion resulting from the reprojection-induced resampling [*Jenkerson et al.*, 2010; *Ji et al.*, 2010]. Temporal smoothing of the NDVI time series was done using a moving window regression approach [*Swets et al.*, 1999] to correct short-interval drops associated with residual clouds in some of the 7 day NDVI composites.

[12] The phenological metrics were calculated from the smoothed eMODIS NDVI time series for each year from 2000 to 2008 using the delayed moving average method [*Reed et al.*, 1994; *Reed*, 2006]. The phenological metrics chosen in the piecewise regression model included day of year (DOY), maximum NDVI (MAXN), day of maximum NDVI (MAXT), NDVI value at the start of the growing season (SOSN), day of the start of the growing season (SOST), and seasonally time integrated NDVI (TIN). The weather variables included precipitation (PPT), temperature (TMAX and TMIN), and photosynthetically active radiation (PAR), which were averaged into weekly periods to match the eMODIS NDVI compositing periods. The daily precipitation and temperature data were acquired from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center, and PAR data was obtained from the NOAA National Environmental Satellite, Data and Information Service (NESDIS) (http://www.atmos.umd.edu/~srb/gcip/).

2.3. Modeling Method

[13] In this study, we used the rule-based piecewise regression model with the Cubist software (http://www.rulequest.com/) [*Quinlan*, 1993] to estimate the grassland carbon fluxes over the Great Plains. The piecewise regression model accounts for complicated relationships between predictive and dependent variables and allows both continuous and discrete variables as the input variables. The training samples are recursively partitioned into homogeneous subsets according to a gain ratio criterion, and the subsets are expressed as a series of rules, where each rule defines the conditions under which a multivariate linear regression model is established based on a variant of least squares estimation. The committee model option in Cubist consists of several rule-based models, each model assigning higher weights to the outliers of the previous model. Each member of the committee predicts the target value for a case and the members' predictions are averaged. Committee models allow more complex models and are beneficial for refining a good initial model, but they cannot overcome the deficiencies of a poor initial model.

[14] In this study, we chose the option with five committee members as the program recommended, so the accuracy of the tested model with this setup was higher. The first model is typically the strongest model with the other models trying to focus more on the outliers in the previous models. Using several models from the committee approach helped to make a smoother map by encouraging variations in the regression stratification thresholds between the various models. The first committee member included 31 rules as programmed. The subsequent committee models gave merely higher weights to observations that had higher errors in the previous model. This forced the model to pay more attention

to those particular observations. The final prediction was an average estimate from all five committee models at each pixel.

[15] In Cubist, the accuracy of the constructed piecewise regression model is measured with average absolute error, relative absolute error, and product–moment correlation coefficient. For our model selection, we developed many models with different input variables and model setups (or parameters) in the Cubist software. The final piecewise regression model was determined based on two criteria: the highest model development accuracy and the least number of input variables. We applied the final model using all available training data to estimate and map 7 day and 250 m NEP through time and space. We determined 12 variables (see section 2.2) to train the final model for mapping NEP over the Great Plains. The final model consisted of five committee models with the first model having 31 rule-based condition-constrained piecewise regressions. A few examples of the rules in the first committee model are listed here. Rule 1: if DOY < = 88, PAR > 69, SOST > 88, MAXT > 211, then NEP = −1444 − 1.38 DOY + 3.27 MAXT + 4.07 MAXN. Rule 2: if NDVI < = 121, PAR > 69, SOST > 88, MAXN > 156, MAXT < = 211, then NEP = −21.3 − 9.5 MAXT + 8.66 MAXN + 1.92 SOST − 2.1 TMIN − 0.4 TMAX − 0.05 WHC − 0.13 PPT. Rule 31: if DOY > 153, DOY < = 214, TMIN > 12, MAXN > 156, TIN > 32, TIN < = 36, then NEP = −146.4 + 2.39 PAR + 0.47 MAXT + 0.89 TIN + SOSN − 0.06 DOY − 0.21 NDVI − 0.14 MAXN.

2.4. Accuracy Assessment

[16] We applied leave-one-out cross validation to evaluate the piecewise regression model and the NEP map accuracy. The leave-one-out cross validation in the study consisted of two parts: withholding sites and withholding years. For withholding sites, one data subset from one site was withheld as testing samples for assessing the model and map accuracies, and the remaining 14 sites were used as training samples for the model development. The model based on the 14 sites estimated the NEP values for the withheld site. Each of the 15 sites was successively withheld and the model was developed with the remaining sites. Then the actual NEP value measured at one flux tower site was compared to the model-estimated NEP value using the training data set of all other 14 sites. Similarly, for the year-withheld cross validation, each of the 9 years was withheld successively and then the data from the remaining 8 years were used to develop the model. The actual NEP value measured for a year was compared to the model-estimated NEP value using the training data set of all other 8 years. We used Pearson's correlation coefficient (r) and root mean square error (RMSE) for comparing the measured and estimated samples to quantify the model and map accuracies.

3. Results and Discussion

3.1. Model Accuracy Assessment

[17] We compared the model-estimated NEP with the tower-measured NEP using leave-one-out cross validation by withholding each site (Table 2) or each year (Table 3). The model performances varied among sites and years. The regressions of the tower-measured and model-estimated NEP in the cross validation indicated that r varied between 0.61 and 0.98 and RMSE ranged from 0.30 to 0.52 g C m^{-2} d^{-1} for the NEP estimation by withholding sites, and r varied between 0.81 and 0.92 and RMSE ranged from 0.39 to 0.48 g C m^{-2} d^{-1} for the NEP estimation by withholding years. The mean and standard deviation (SD) values for each pair of the tower-measured and model-estimated NEP are close, which indicates a high precision of the piecewise regression estimation. High estimated accuracies ($r > 0.9$) were obtained at five tower sites (i.e., Lethbridge, Batavia, Rannels Flint Hills, Walnut River, and Fort Reno). Relatively low estimated accuracies occurred at the Mandan, Gudmundsen, ungrazed Central Plains Experimental Range, and Woodward sites with r less than 0.8. The accuracy of NEP estimations was lowest when withholding the Miles City site (r = 0.61) compared to other sites. The lower accuracy was likely caused by the extreme weather or other environmental conditions for the withheld year or site that made the sampled years and sites very influential in the final model. By including the data sets of all the sites and all the years from the 15 flux towers, the final model robustness was maximized for a wide range of geographic, weather, edaphic, and ecological conditions. After assessing model performance with the leave-one-out cross validation, we trained the final model using the complete flux tower data sets. The final piecewise regression model accuracy for NEP estimates was reasonably high with r = 0.88 and RMSE = 0.45 g C m^{-2} d^{-1}. In future assessments, additional flux tower information for extreme weather years and geographic gaps (southern and west central Great Plains) could provide additional model robustness.

[18] We compared the model-estimated NEP with the tower-measured NEP for each site at the 7 day interval (Figure 2), which showed that our estimated NEP captured most of the seasonal NEP variations. For some sites or years, the model did not capture the extreme high and low NEP values. The piecewise regression model underestimated NEP at some sites such as Lethbridge (2002), Fort Peck (spring 2003), Gudmundsen (2005), and Rannels Flint Hills (2000), but overestimated NEP at other sites such as Fort Peck (2002, summer 2003) and Brookings (2006).

[19] The leave-one-out cross validation results indicated that our piecewise regression model is robust and stable. The current tower sites are distributed fairly well throughout the Great Plains, representing a wide range of spatial, ecological, and climatic conditions. We will continue to add new flux tower sites and extreme weather years to our data set in order to improve model robustness.

3.2. Source/Sink Activity of the Great Plains Grasslands

[20] We calculated annual NEP for each year during 2000–2008 from the 7 day NEP estimates. During this period, the annual carbon fluxes ranged from a low value of 0.3 g C m^{-2} yr^{-1} in 2002 to a high value of 47.7 g C m^{-2} yr^{-1} in 2005 with the years of 2005, 2001, and 2003 having the largest carbon sinks, and the years 2002, 2008, and 2000 having the lowest carbon sinks (Table 4). The average annual NEP over the Great Plains grasslands was 24 ± 14 g C m^{-2} yr^{-1} and the cumulative flux during the 9 years was 214 g C m^{-2}. These results indicate that the entire Great Plains was a carbon sink with an averaged annual estimate of 336 Tg C yr^{-1} from 2000 to 2008.

Table 2. Leave-One-Out Cross Validation of Model-Estimated NEP by Withholding Each Site[a]

Identification Number	Site	n	Mean of Tower NEP ($\overline{T}_{nep}$)	SD of Tower NEP	Mean of Model NEP ($\overline{P}_{nep}$)	SD of Model NEP	Difference of Mean Between Model and Tower NEP ($\overline{P_{nep}} - \overline{T_{nep}}$)	Difference of SD Between PWR and Tower NEP	Pearson's Correlation Coefficient (r)	RMSE
1	Lethbridge	156	0.30	1.36	0.28	1.07	−0.02	−0.29	0.93	0.40
2	Fort Peck	102	−0.21	1.12	−0.15	0.64	0.06	−0.49	0.82	0.37
3	Mandan	111	0.25	0.89	0.27	0.73	0.02	−0.16	0.77	0.47
4	Miles City	78	−0.21	0.77	−0.17	0.39	0.04	−0.38	0.61	0.31
5	Brookings	87	0.08	1.31	0.03	0.85	−0.06	−0.46	0.84	0.46
6	Cottonwood	103	−0.08	0.91	−0.12	0.75	−0.05	−0.17	0.83	0.42
7	Gudmundsen	155	−0.07	0.99	−0.04	0.51	0.04	−0.48	0.78	0.32
8	Batavia	52	0.70	2.35	0.78	2.00	0.08	−0.35	0.98	0.40
9	Conservation Reserve Program ungrazed, Colorado	51	−0.43	0.82	−0.37	0.44	0.06	−0.38	0.73	0.30
10	Central Plains Experimental Range, Colorado	86	0.18	1.14	0.26	0.79	0.08	−0.35	0.84	0.43
11	Rannels Flint Hills	52	0.45	1.89	0.40	1.23	−0.05	−0.66	0.92	0.50
12	Walnut River	162	0.14	1.15	0.13	0.91	−0.01	−0.24	0.90	0.40
13	Woodward	104	0.24	1.15	0.22	0.84	−0.03	−0.31	0.79	0.52
14	Fort Reno	94	0.16	1.64	0.31	1.28	0.15	−0.36	0.95	0.41
15	Freeman Ranch	52	0.14	0.94	0.11	0.75	−0.03	−0.19	0.83	0.42

[a]The unit of the NEP is g C m^{-2} d^{-1}, with positive values indicating a carbon sink. Here n, number of observations.

[21] Spring (March–May) and summer (June–August) precipitation and the seasonal sink strength contributes to the total sink activity. Carbon fluxes over the Great Plains were higher in summer (43 ± 11 g C m^{-2} $season^{-1}$) than in spring (28 ± 5 g C m^{-2} $season^{-1}$). For the dry years of 2000, 2002, 2006, and 2008, both the spring fluxes and the summer fluxes were relatively low. For 2007, the high summer fluxes compensated for the low spring fluxes resulting in a medium-high annual NEP. By contrast, the high spring flux compensated for the relatively low summer flux in 2003 causing a high 2003 flux.

[22] Figure 3 illustrates the spatial distribution of annual NEP over the Great Plains grasslands and shows the strong influence of precipitation on NEP. Considerable spatial heterogeneity resulted in carbon sources in the western region (especially southwest) and carbon sinks in the eastern region, generally following a west–east precipitation gradient across this region. The mean annual NEP at 250 m pixel size for the Great Plains grasslands ranged from −409 to 434 g C m^{-2} yr^{-1} (Figure 3), which represented the extreme values for the entire region. Our modeled results were similar to the results from a site level analysis by T. G. Gilmanov et al. (manuscript in preparation, 2010), who found that the Great Plains grasslands displayed a wide range of source-sink behavior from –382 to 491 g C m^{-2} yr^{-1}. The highest variability of annual NEP was detected in the southern Great Plains, particularly in the Southern Texas Plains, the southern part of the Central Great Plains, and the Western High Plains. Carbon sources over the northern Great Plains in 2002, 2004, and 2006 were relatively intensive and extensive compared to the other years. Droughts in the western part of the Great Plains in 2002 caused decreased NEP, resulting in a lower carbon sink for the entire Great Plains. Overall, it appeared that the carbon gains for the Great Plains were more sensitive to the droughts in the western regions such as the Northwestern Great Plains, the Western High Plains, and the Southwestern Tablelands than in the east.

[23] Fourteen of the 17 Great Plains ecoregions were sinks during the study period (Figure 4). The southern Great Plains, including the Western Gulf Coastal Plain (ecoregion 16), the Edwards Plateau (14), the Texas Blackland Prairies (15), and the Southern Texas Plains (17), had high annual NEP (144, 129, 103, 99 g C m^{-2} yr^{-1}, respectively). The Western Corn Belt Plains (3) and the Flint Hills (12) had intermediate NEP values of 58 and 65 g C m^{-2} yr^{-1}, respectively. Most ecoregions in the western Great Plains, including the Southwestern Tablelands (11), the Western High Plains (9), and the Northwestern Great Plains (7), had

Table 3. Leave-One-Out Cross Validation of Model-Estimated NEP by Withholding Each Year[a]

Year	n	Mean of Tower NEP ($\overline{T}_{nep}$)	SD of Tower NEP	Mean of Model NEP ($\overline{P}_{nep}$)	SD of Model NEP	Difference of Mean Between Model and Tower NEP ($\overline{P_{nep}} - \overline{T_{nep}}$)	Difference of SD Between Model and Tower NEP	r	RMSE
2000	225	0.12	1.19	0.21	0.80	0.09	−0.39	0.85	0.42
2001	203	0.13	0.96	0.10	0.71	−0.03	−0.25	0.84	0.39
2002	228	0.07	1.29	0.09	1.00	0.02	−0.29	0.89	0.46
2003	156	0.25	1.39	0.18	0.99	−0.07	−0.40	0.88	0.48
2004	86	0.03	1.05	0.09	0.80	0.06	−0.25	0.85	0.42
2005	252	0.26	1.53	0.29	1.20	0.04	−0.33	0.92	0.46
2006	139	0.04	1.30	0.08	0.92	0.04	−0.38	0.87	0.46
2007	156	−0.22	0.93	−0.21	0.66	0.01	−0.27	0.81	0.39

[a]The unit of the NEP is g C m^{-2} d^{-1}, with positive values indicating a carbon sink. Here n, number of observations.

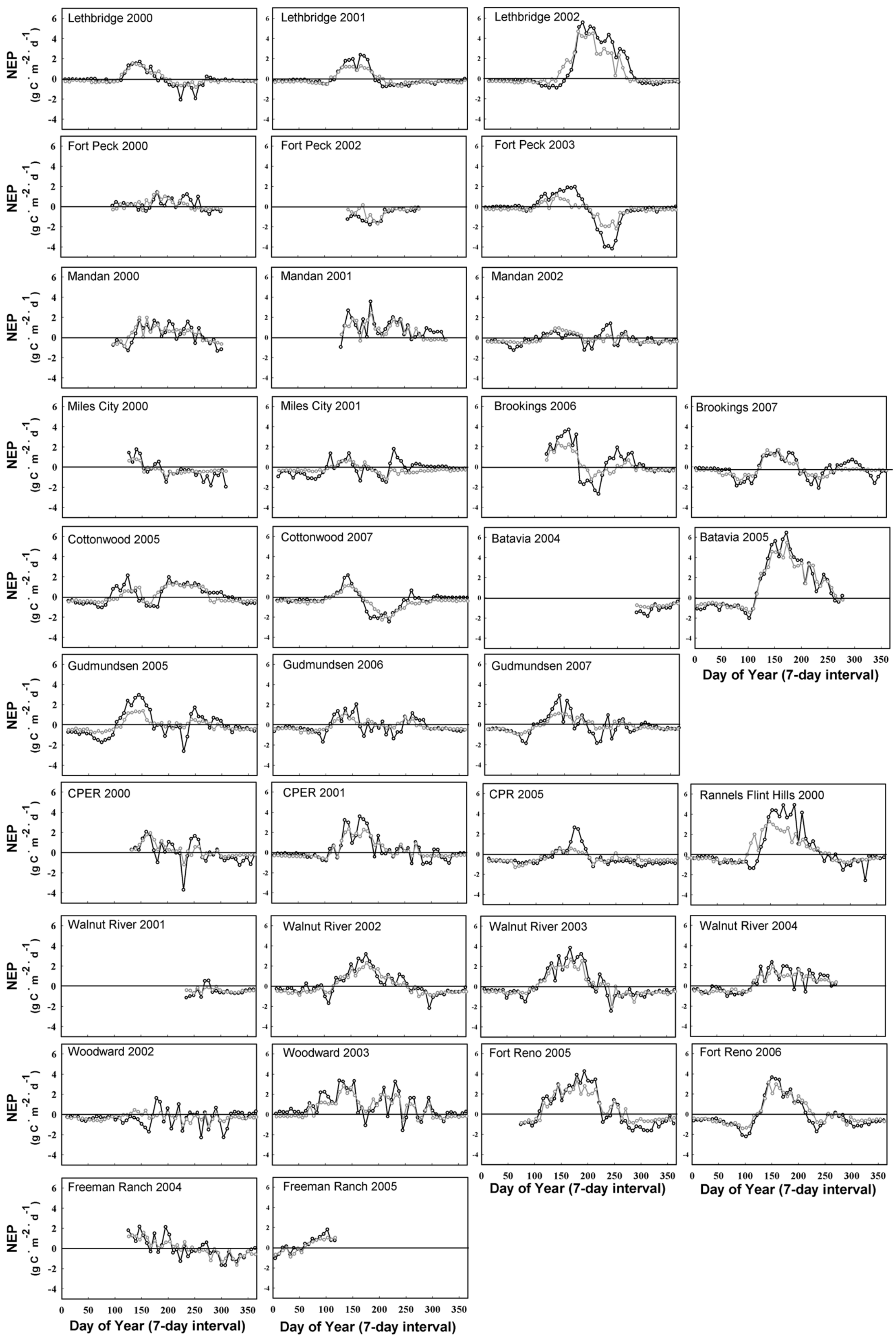

Figure 2. The agreement of seasonal dynamics of measured and estimated NEP (g C m^{-2} d^{-1}) at the 15 flux towers at 7 day intervals. Black lines represent the measured NEP. Gray lines represent the estimated NEP.

Table 4. Annual NEP for the Great Plains Grasslands

	NEP (g C m^{-2} yr^{-1})	Spring (Mar–May) NEP (g C m^{-2} Season^{-1})	Summer (June–Aug) NEP (g C m^{-2} Season^{-1})	Total Precipitation (Mar–Aug) (mm)	Annual Precipitation (mm)
2000	15.8	26.81	36.95	371	650
2001	36.1	28.69	46.80	400	680
2002	0.30	22.73	25.84	392	650
2003	31.7	34.36	40.82	364	590
2004	27.3	32.11	46.78	477	770
2005	47.7	34.49	60.30	396	600
2006	20.1	28.55	33.55	337	570
2007	24.9	20.71	58.34	582	810
2008	10.2	20.99	40.91	442	670
Mean ± SD	24 ± 14	28 ± 5	43 ± 11	418 ± 74	666 ± 80

negative NEP values of −77, −49, and −1 g C m^{-2} yr^{-1}, respectively. Of the 17 ecoregions, precipitation deficits affected 15 ecoregions, especially in the southern Great Plains in 2000. Droughts affected 12 ecoregions mainly in the central western Great Plains in 2002, the entire Great Plains in 2006, and to a smaller extent in 2008. The droughts resulted the lower NEP values of 15.8, 0.3, 20.1, and 10.2 g C m^{-2} yr^{-1} for 2000, 2002, 2006, and 2008, respectively, which were below the 9 year average of 24 g C m^{-2} yr^{-1}.

[24] For the entire Great Plains grasslands, areas of carbon sinks (from 0 to 150 g C m^{-2} yr^{-1}) were noticeably larger in 2001, 2005, and 2007, and areas of carbon sources (from 0 to 150 g C m^{-2} yr^{-1}) were noticeably larger in 2002 and 2006 (Figure 5). The largest values for the areas in 2001 and 2005 were carbon sinks with about 100 g C m^{-2} yr^{-1}. At the other extreme, the largest values for the areas in 2002 and 2006 were carbon sources with about −150 g C m^{-2} yr^{-1}.

[25] For the entire Great Plains, the peak NEP during the 9 years occurred from mid-May to late June (Figure 6). Temporally, the average period for CO_2 uptake was from mid-April to late August and then it gradually changed to a carbon source. The entire Great Plains exhibited a rapid CO_2 uptake for a short period (4 months) and a longer period of low CO_2 loss. The trajectory of the 7 day mean NEP for

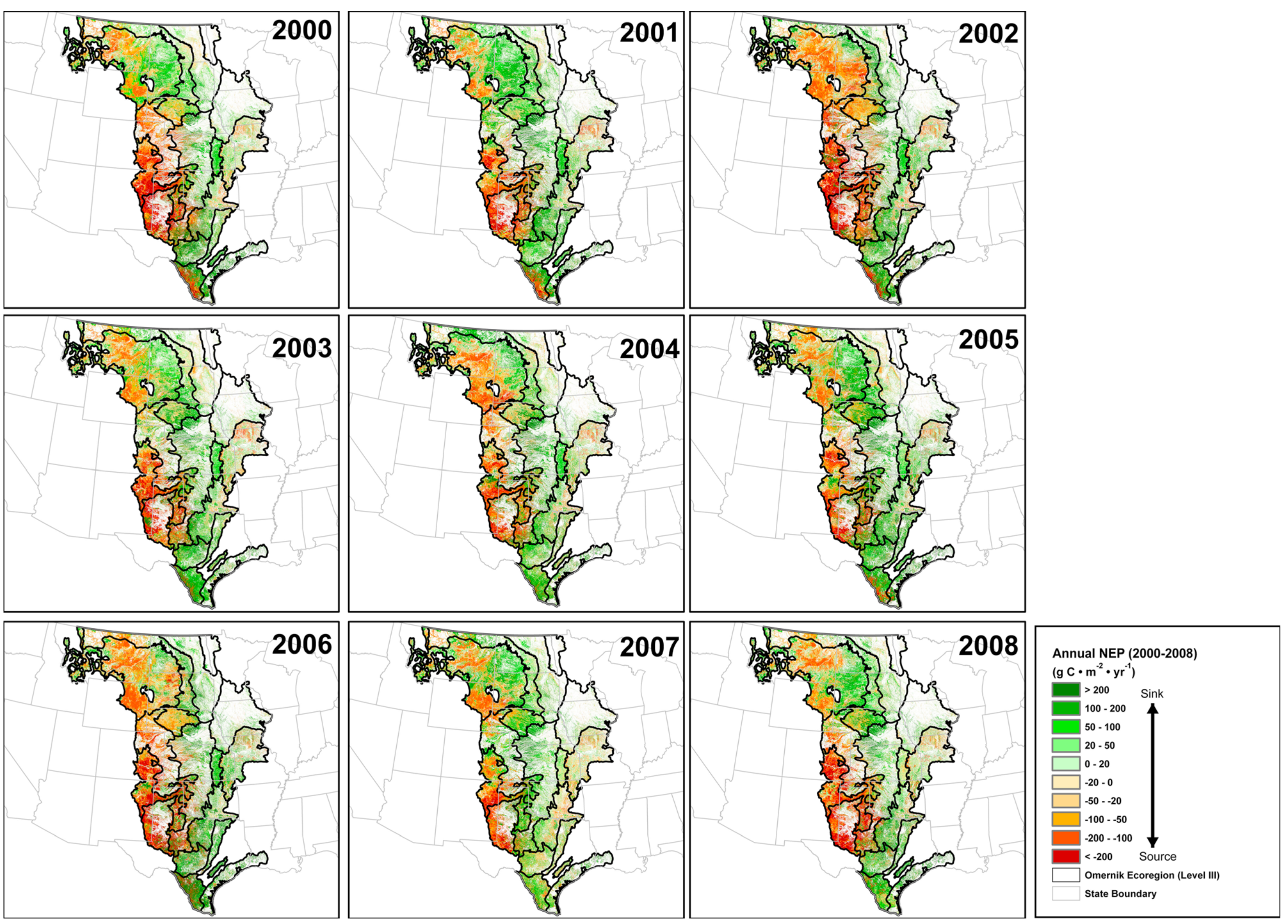

Figure 3. Maps of annual NEP over the Great Plains grasslands during 2000–2008.

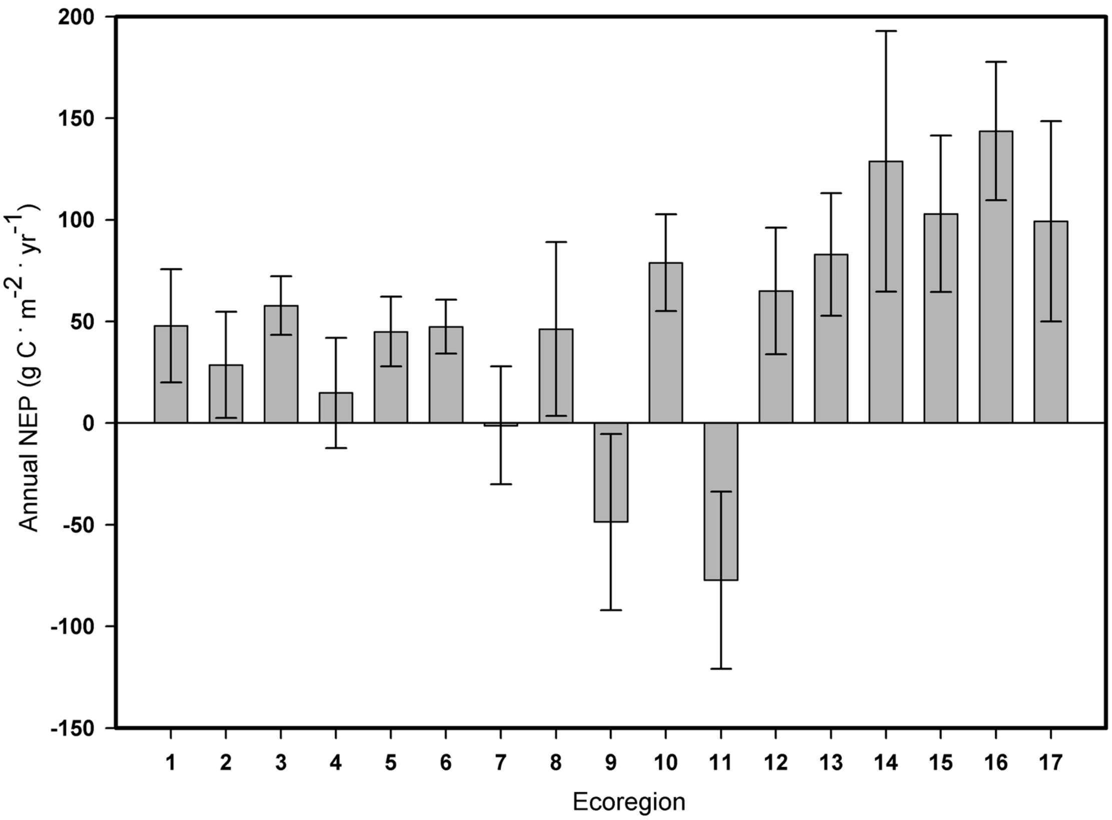

Figure 4. Nine year average annual NEP from 2000 to 2008 in 17 ecoregions. The error bar shows 1 standard deviation of the estimated annual NEP for the 9 years. The numbers on the *x* axis represent the ecoregion numbers as shown in Figure 1.

each year over the entire Great Plains grassland showed the summer NEP values were lowest in 2002 and highest in 2005. Drought reduced the duration and magnitude of positive NEP for the dry years of 2002, 2006, and 2008 and the carbon sinks turned to carbon sources 20 days earlier in these 3 years.

[26] We divided the 7 day NEP into four seasons: spring (March–May), summer (June–August), fall (September–November), and winter (December–February). Figure 7 illustrates the spatial distribution of seasonal NEP over the Great Plains grasslands for 2002 (the smallest carbon sink) and 2005 (the largest carbon sink). The seasonal NEP patterns reflected the controlling effects of climatic conditions and showed different spatial distributions in 2002 and 2005. Spring and summer are the two seasons when the largest coverage contributed as a carbon sink. In the spring, the southern Great Plains, dominated by tallgrass prairies, assimilated carbon with NEP values greater than 60 g C m^{-2} yr^{-1}.

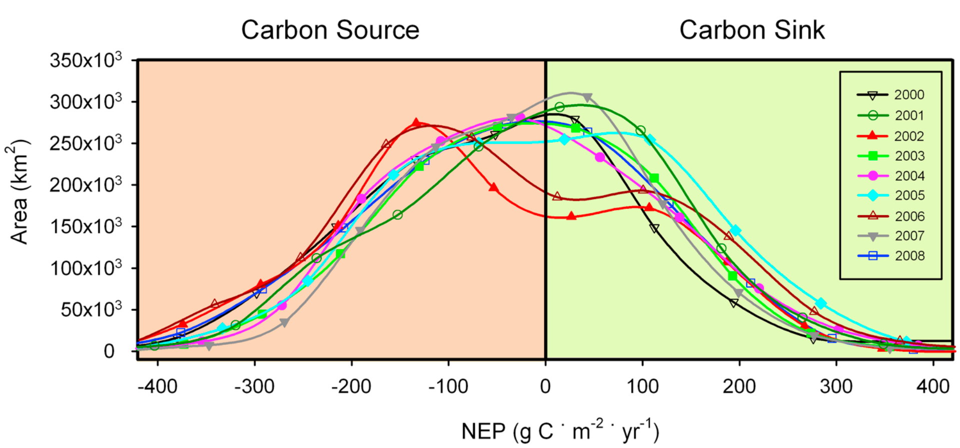

Figure 5. Areal distribution of annual NEP in the Great Plains grasslands during 2000–2008.

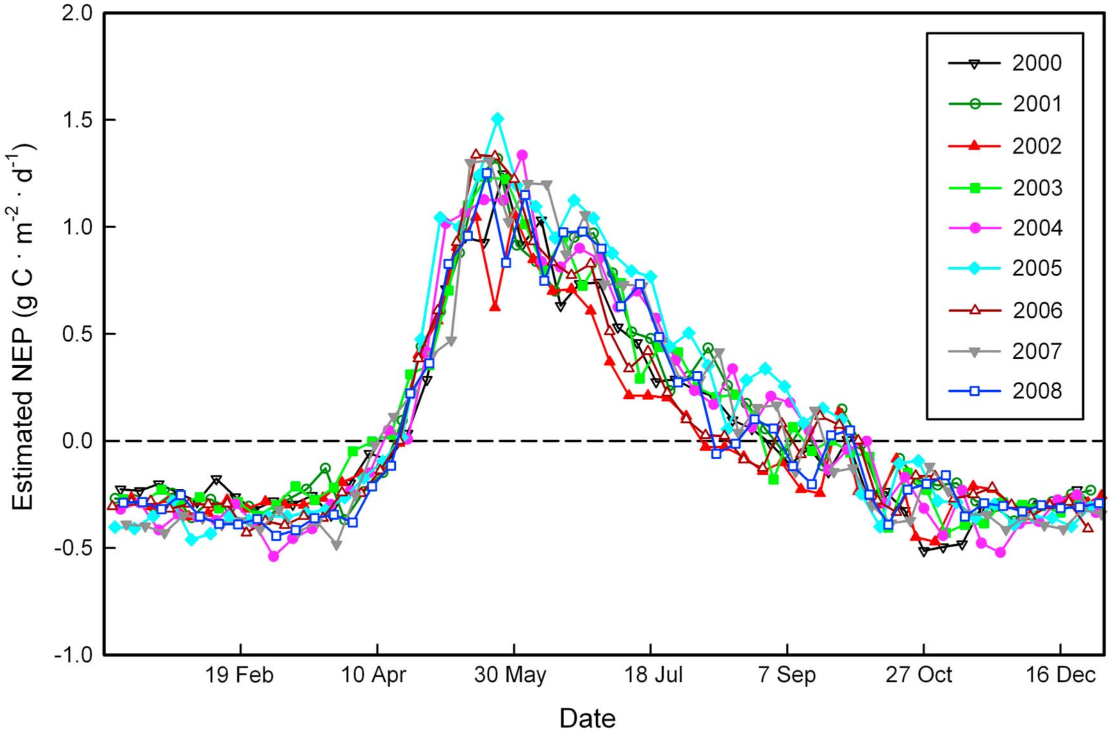

Figure 6. Model-estimated mean 7 day NEP for the Great Plains grasslands from 2000 to 2008.

By contrast, the northern Great Plains, dominated by shortgrass or mixed prairies, had a smaller carbon sink. In summer, NEP was characterized by negative values (sources) in the west and positive values (sinks) in the east of the Great Plains. Compared with 2005, 2002 had more extensive and intensive carbon sources in the western Great Plains, especially in the Northwestern Great Plains, due to the drought effects that resulted in a lower carbon budget for the entire Great Plains in 2002 than in 2005. In the fall and winter, most areas of the Great Plains released carbon because the grasses were either senescent or dormant.

3.3. Drought Impacts on Carbon Sinks and Sources

[27] Precipitation plays a critical role for grassland production in the Great Plains [*Sala et al.*, 1988; *Smart et al.*, 2005]. During the 20th century, the annual precipitation

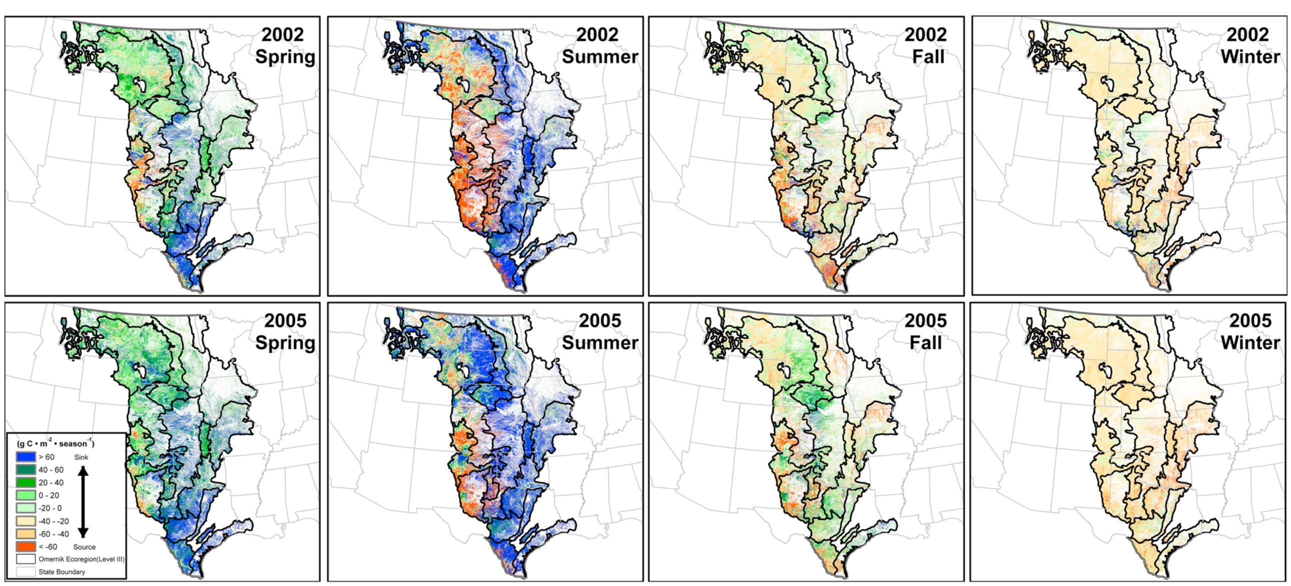

Figure 7. The spatial distribution of model-estimated NEP in 2002 and 2005 for spring (March–May), summer (June–August), fall (September–November), and winter (December–February).

decreased by 10% in eastern Montana, North Dakota, eastern Wyoming, and Colorado [*Joyce et al.*, 2001]. Droughts struck parts or the entire Great Plains during 2000–2008 [*NOAA*, 2010]. Although previous studies suggested that grasslands are generally carbon sinks or near equilibrium, it was not unusual for the grasslands to switch between carbon sink and source, especially when influenced by extreme climatic conditions (e.g., drought) [*Ciais et al.*, 2005; *Gilmanov et al.*, 2007]. The magnitude of the terrestrial carbon sink estimated for a short period could be substantially overestimated if extreme climate events are not considered [*Xiao et al.*, 2009].

[28] The carbon sources depend not only on drought severity or duration but also on the timing of drought event in relation to the growth stage of the grasses [*Kim et al.*, 1992]. In the study area, the growing season droughts caused increased carbon losses over the drought-affected areas, which resulted in a great annual net carbon loss over the Great Plains and changed the region to a relatively low sink from a substantial sink during nondrought years. In 2000, 2002, and 2006, the growing season precipitation (Table 4) was below the 9 year average, which generated a lower sink of CO_2 for the region. Geographically (Figure 3) low NEP was more widespread in 2000, 2002, and 2006 than 2008, especially over the northern Great Plains. However, the dry winter in the south (ecoregions 13, 14, 15, 17) and dry spring in the southwest (ecoregions 9, 11, 14, 16, 17) in 2008 caused a low NEP for the southern Great Plains in winter and spring. Especially in mid-April, the 2008 NEP was the lowest of all years (Figure 6), which hampered the exponential growth phase of grasses. Further, an early drop occurred in late summer of 2008 NEP (Figure 6). Year 2008 over the Flint Hills (ecoregion 12) was characterized by cool wet springs and had their lowest NEP (13 g C m^{-2} yr^{-1}) in 2008 compared with the annual average of 65 g C m^{-2} yr^{-1} during 2000–2008. Therefore, the low seasonal precipitation in winter and spring in the southern Great Plains and a cool wet spring in the Flint Hills caused a weak sink in 2008 for the entire Great Plains. In 2005, the wet summer led to a high summer NEP value (60.3 g C m^{-2} $season^{-1}$) and thus the high annual NEP, but the spring NEP value (34.49 g C m^{-2} $season^{-1}$) was not significantly high.

[29] The NEP values varied greatly among ecoregions impacted by precipitation (Figure 4). The northern Great Plains (including the Northwestern Great Plains and the Western High Plains) and the Southwestern Tablelands had the lowest mean growing season (March–August) precipitation (less than 300 mm) during the 9 year period compared to the mean growing season precipitation for the entire Great Plains (418 mm). Lower growing season precipitation caused different responses with respect to carbon fluxes. The Western High Plains and the Southwestern Tablelands were all carbon sources during the study period. The Northwestern Great Plains was a carbon source in 2002, 2004, and 2006 with an average annual NEP of −1 g C m^{-2} yr^{-1}. The decreased precipitation generally caused a net carbon release from the grasslands. For example, the growing season precipitation decreased by 2%, 36%, 14%, and 10% in the Southwestern Tablelands for the dry years of 2000, 2002, 2006, and 2008, respectively, which resulted in considerable carbon losses (−124, −132, −95, and −124 g C m^{-2} yr^{-1}, respectively). The Northwestern Great Plains released a relatively small amount of carbon (−51 and −36 g C m^{-2} yr^{-1}) in 2002 and 2006 with the decreased precipitation of 21% and 27%.

[30] In our analysis, we found positive annual NEP for the entire Great Plains for all 9 years. However, in our previous study [*Zhang et al.*, 2010], we found that in 3 (2002, 2004, 2006) of 7 years (2000 to 2006), carbon was released in the northern Great Plains, which implied that the northern Great Plains were affected by drought more severely than the entire Great Plains. The large sink activities in the southern Great Plains offset the source activities for some years (e.g., 2002, 2004, and 2006) over the northern Great Plains, which caused a sink for carbon in the entire Great Plains grasslands for the 3 years. Whether the region was considered a sink or source depended on the spatial extent and time frame.

4. Conclusions

[31] We integrated 9 years of remotely sensed NDVI and weather data sets with NEP data from 15 flux tower sites to develop a NEP model using a piecewise regression tree approach. The model accuracy for NEP estimates was reasonably high with $r = 0.88$.

[32] From this study, we concluded that the entire Great Plains grasslands acted as a net sink for carbon with a mean estimate of 336 Tg C yr^{-1} during 2000–2008. The Great Plains have the potential to sequester carbon for an extended period. The annual CO_2 fluxes ranged from a low value of 0.3 g C m^{-2} yr^{-1} in 2002 to a high value of 47.7 g C m^{-2} yr^{-1} in 2005. The largest carbon sinks occurred in 2005, 2001, and 2003 and the lowest carbon sinks occurred in 2002, 2008, and 2000.

[33] Drought greatly influenced the carbon budget and altered the long-term carbon balances across the Plains. Over the 9 year period, which included several dry years (2000, 2002, 2006, and 2008), the annual NEP showed large spatial and temporal variability. Some ecoregions were heavily impacted by drought events. The Western High Plains and Southwestern Tablelands were consistently carbon sources during the 9 years. The Northwestern Great Plains was a carbon source in 2002, 2004, and 2006 and a carbon sink in other years. Droughts in the western portion of the Great Plains in 2002 decreased the aggregated NEP sink and resulted in a weak carbon sink for the entire Great Plains. It appeared that the carbon gains for the Great Plains were more sensitive to droughts in the west than in the east. As a consequence, droughts resulted in increased carbon losses over the impacted areas, which led to the greatest annual net carbon loss over these regions and finally changed the Great Plains from acting as a carbon sink during nondrought years to a weak sink during drought years.

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