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Net ecosystem productivity of temperate grasslands in northern China: An upscaling study

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ABSTRACT

Grassland is one of the widespread biome types globally, and plays an important role in the terrestrial carbon cycle. We examined net ecosystem production (NEP) for the temperate grasslands in northern China from 2000 to 2010. We combined flux observations, satellite data, and climate data to develop a piecewise regression model for NEP, and then used the model to map NEP for grasslands in northern China. Over the growing season, the northern China's grassland had a net carbon uptake of 158 ± 25 g C m^{-2} during 2000–2010 with the mean regional NEP estimate of 126 Tg C. Our results showed generally higher grassland NEP at high latitudes (northeast) than at low latitudes (central and west) because of different grassland types and environmental conditions. In the northeast, which is dominated by meadow steppes, the growing season NEP generally reached 200–300 g C m^{-2}. In the southwest corner of the region, which is partially occupied by alpine meadow systems, the growing season NEP also reached 200–300 g C m^{-2}. In the central part, which is dominated by typical steppe systems, the growing season NEP generally varied in the range of 100–200 g C m^{-2}. The NEP of the northern China's grasslands was highly variable through years, ranging from 129 (2001) to 217 g C m^{-2} growing season^{-1} (2010). The large interannual variations of NEP could be attributed to the sensitivity of temperate grasslands to climate changes and extreme climatic events. The droughts in 2000, 2001, and 2006 reduced the carbon uptake over the growing season by 11%, 29%, and 16% relative to the long-term (2000–2010) mean. Over the study period (2000–2010), precipitation was significantly correlated with NEP for the growing season ($R^2 = 0.35$, p-value < 0.1), indicating that water availability is an important stressor for the productivity of the temperate grasslands in semi-arid and arid regions in northern China. We conclude that northern temperate grasslands have the potential to sequester carbon, but the capacity of carbon sequestration depends on grassland types and environmental conditions. Extreme climate events like drought can significantly reduce the net carbon uptake of grasslands.

1. Introduction

Grasslands are one of the most widespread vegetation types comprising about 40% of the Earth's terrestrial land area, excluding areas of permanent ice cover (World Resources Institute, 2000). Grassland ecosystems play an important role in the global carbon

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cycle (Adams et al., 1990; Parton et al., 1995) and in livestock development (Reynolds et al., 2005). It was reported that grasslands (including tundra) store one fifth of the global total carbon (485 Pg C) in both vegetation and soil (Adams et al., 1990). Many studies have suggested that grassland ecosystems function as potential carbon sinks or are near equilibrium with respect to carbon exchange (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). For example, a southern Great Plains mixed-grass prairie has been identified as a carbon sink (Sims and Bradford, 2001); however, a native tallgrass prairie in Texas (Dugas et al., 1999), non-grazed mixed-grass prairie in North Dakota (Frank and Dugas, 2001), and tallgrass in Oklahoma (Suyker et al., 2003) were found to be near equilibrium in terms of carbon. Although these studies suggested that grasslands might be carbon sinks or near equilibrium, alternation between acting as a carbon sink or source frequently occurs (Novick et al., 2004; Gilmanov et al., 2007). For example, a switch from sink to source was observed in a pasture in the southern Great Plains (Meyers, 2001), in a Canadian temperate mixed prairie during drought (Flanagan et al., 2002), and in a warm temperate grassland in southeastern U.S. after harvesting (Novick et al., 2004).

Soil water stress was found to be the main factor regulating the annual net ecosystem production (NEP) in the northern temperate grasslands (Flanagan et al., 2002; Suyker et al., 2003; Hunt et al., 2004; Fu et al., 2006). Therefore, extreme events, such as droughts, can significantly influence interannual variation in terrestrial carbon sequestration in grassland ecosystems, and even switch ecosystems from 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; Kwon et al., 2008; Zhang et al., 2011). Identifying the effects of climate change and extreme events on grassland carbon dynamics is critical for predicting the response of grassland production to future climate change (Parton et al., 1995). However, large uncertainties exist with respect to the role of grasslands in the global carbon budget and their response to climate change under various climatic scenarios and management regimes (Jones and Donnelly, 2004; Verburg et al., 2004; Piao et al., 2007). For example, Scurlock and Hall (1998) suggested that carbon storage in tropical grasslands and savannas may have been underestimated, and Fu et al. (2006) and Ma et al. (2010) showed that different grassland ecosystems might respond differently to climate change in the future.

China's grasslands make up ~10% of total world grassland area and they have been estimated to store 9–16% (Ni, 2002) or 4.4–11.9% (Fan et al., 2008) of the total world grassland carbon. The extensive grasslands in China provide an opportunity to enhance terrestrial carbon sinks, which could have significant effects on carbon cycles both globally and in arid lands (Ni, 2002). Grasslands are the dominant ecosystem type in China and account for 40% of the national land area (Kang et al., 2007; Xu et al., 2008). The grasslands in northern China account for about 78% of the grasslands in China (Sun, 2005), and are an important component of the Eurasian temperate steppes (Bai et al., 2008). The temperate grasslands of northern China are located in the arid and semi-arid climate zones (Bai et al., 2008) and are strongly influenced by the East Asian monsoon. Grasslands in arid and semi-arid regions are ecologically fragile and sensitive to climate change and human disturbances (Gao and Reynolds, 2003; Li et al., 2005), especially to changes in precipitation (Sala et al., 1988; Knapp and Smith, 2001; Ma et al., 2007; Guo et al., 2012).

It is predicted that heat waves and droughts will become more frequent in the 21st century (IPCC, 2007). Moreover, climate change is predicted to cause variations and trends in extreme weather events such as extreme precipitation that will not only affect annual precipitation but will also be manifested in seasonal variations (Easterling et al., 2000). Precipitation and droughts are usually limiting factors in controlling primary production in the arid and semi-arid grassland ecosystems (Kang et al., 2007). The northern China steppe frequently suffers from drought and water stress (Fu et al., 2006). The precipitation in arid and semi-arid regions is highly variable both temporally and spatially. Fluctuations in vegetation production have been found to be closely associated with interannual and intra-annual variations in precipitation in arid and semi-arid ecosystems (Bai et al., 2004; Niu et al., 2008; Shen et al., 2008; Du et al., 2012), and widespread and persistent droughts have caused a general decrease in vegetation productivity in the grassland systems of northern China (Xiao et al., 2009).

Previous studies have presented carbon storage estimates for grasslands of China at a national level using global databases and statistical data, field surveys or investigations, and satellite-based statistical models (Ni, 2001, 2002, 2004; Piao et al., 2007; Fan et al., 2008). However, our knowledge of carbon dynamics and their feedbacks to climate change in the grasslands of northern China remains limited, owing, in part, to a lack of in situ measurements and the spatial heterogeneity in grassland biomass (Ma et al., 2010). Therefore, studies of the impact of climatic conditions on productivity in this area are of significance to understanding both the carbon cycling processes of the grassland ecosystems and the role of grasslands in the national and global carbon budgets.

The NEP is a useful indicator for ecosystem carbon budgets; it represents the net exchange of carbon between terrestrial ecosystems and the atmosphere and is determined by both photosynthetic processes and autotrophic and heterotrophic respiration. The growing network of eddy covariance flux towers provides a synoptic record of the exchange of carbon, water, and energy between the ecosystem and the atmosphere (Baldocchi et al., 2001). These tower sites provide valuable measurements for ecosystem carbon and water exchange worldwide (Yu et al., 2006; Law, 2007). Recently, data-driven upscaling models that integrate flux tower data and remotely sensed environmental variables have been developed for estimating and quantifying terrestrial CO_2 exchange on multiple spatiotemporal scales (Turner et al., 2003; Yang et al., 2007; Wylie et al., 2007; Xiao et al., 2008; Sims et al., 2008; Jung et al., 2009; Zhang et al., 2007, 2010, 2011). Their results showed that the upscaling method is effective for providing highly accurate spatial estimates of vegetation productivity. However, there have been relatively few studies focusing on temperate grassland ecosystems in the northern hemisphere at the regional scale (Wylie et al., 2006; Zhang et al., 2011).

In this study, we used a piecewise regression tree approach (PWR) driven by the long-term satellite and meteorology datasets to upscale eddy flux NEP to the entire grasslands of northern China. The objectives of our study were to: (1) develop a rule-based piecewise regression model to map NEP with Moderate Resolution Imaging Spectroradiometer (MODIS) data and flux tower measurements; (2) map NEP for grasslands in northern China for the period 2000–2010; and (3) quantify the interannual variability of NEP from 2000 to 2010. Our study will provide a better understanding of the magnitude of carbon fluxes and the mutual feedback of terrestrial ecosystems over northern temperate grasslands.

2. Materials and methods

2.1. Study area and flux tower data

This study was conducted in the temperate grasslands of northern China across three provinces: Inner Mongolia, Gansu, and Ningxia (Fig. 1). The study region is characterized by arid and semi-arid conditions and is strongly influenced by the East Asian

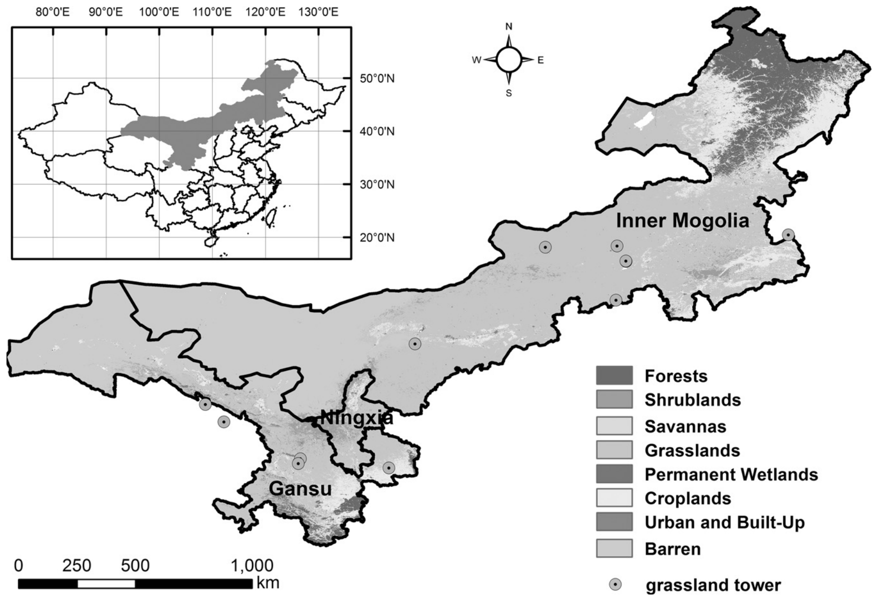

Fig. 1. Land-cover types and the grassland flux towers in northern China. The land-cover data was simplified from the 500-m MODIS data (MCD12Q1).

monsoon, where the rainfall season and the highest temperatures occur in summer (June–August). The mean annual temperature ranges from −3 °C to 9 °C and is higher in the more arid western part than in the eastern part (Hu et al., 2007). The annual precipitation varies from about 450 mm in the northeast to 350 mm in the center and to 150 mm in the southwest (Sun, 2005). Following the east-to-west precipitation gradient, the temperate grasslands in northern China change longitudinally from meadow steppes in the northeast, through typical steppes in the middle, and to desert steppes in the dry southwest (Sun, 2005). The growing season usually starts in May and ends in late September with the maximum aboveground biomass occurring in July and August (Kato et al., 2004; Chen et al., 2009a). These grasslands serve as important resources for livestock production (Kang et al., 2007) and are significant contributors to global carbon balance because of the relatively high soil carbon stocks in the arid and semi-arid region (Feng et al., 2001).

We complied data from twelve grassland flux tower sites (Fig. 1 and Table 1), six of which (ID 1–6 in Table 1) are part of the Coordinated Observation and Synthesis in Arid and Semi-arid China (COSAS). These sites are evenly distributed throughout the northern China's grasslands, representing a wide range of spatial, ecological, and climatic conditions in the region. Data has been collected over these sites for seven years. For the eddy covariance sites from the COSAS in the arid and semi-arid areas of China, a linear interpolation method was applied to fill small gaps (less than two hours) of missing or bad data and larger gaps were filled with values derived from mean diurnal ensemble values (Wang et al., 2010). More details on data treatments can be found in Liu et al. (2008) and Wang et al. (2010). The other six sites (ID 7–12 in Table 1) include steppe and meadow sites and their vegetation greenness varied among sites. For examples, the leaf area index (LAI) during growing season (May–September) for sites Xi1 (typical fenced steppe), Xi2 (degraded steppe), and Du2 (typical steppe) were 0.26, 0.25, 0.47, respectively, (Chen et al., 2009b). The annual maximum LAI was around 1.0 during 2004 and 2006 for site Xfs (short grass steppe) (Wang et al., 2008). For the alpine meadow HaM site, the annual maximum LAI was 3.1 in August, 2001 and 3.8 in July, 2002 (Kato et al., 2004). More detailed ecological and climate information can be found in Chen et al. (2009a,b) for sites of Xi1, Xi2, Du2, and Ku2, in Wang et al. (2008) and Wang and Zhou (2012) for site Xfs, and in Kato et al. (2004, 2006) for site HaM.

In our study, the half-hourly NEP data provided by flux-tower measurements were integrated to the daily time scale, and then averaged over each 8-day period to match the 8-day composite of the MODIS normalized difference vegetation index (NDVI) data. We adopted ecological sign convention assuming that positive NEP values describe uptake of carbon from the atmosphere to the ecosystem. We used 8-day NEP series from 12 tower sites as the dependent variable in a piecewise regression model with independent variables including spatial NDVI and weather parameters. We included two sites (Arou and HaM) in the western edge of our study area in our piecewise regression model to constrain the

Table 1
Description of the grassland flux towers in northern China.

ID	Site name	Location (°N, °E)	Site years	Elevation (m)	Precipitation (mm/yr)
1	Arou	38.04, 100.46	2008–2009	3033	396
2	Yuzhong	35.95, 104.13	2008–2009	1968	382
3	Xinglongshan	35.77, 104.05	2008–2009	2481	480–622
4	Qingyang	35.59, 107.54	2009	1298	561
5	Tongyu	44.57, 122.93	2008–2009	151	404
6	Dongsu	44.09, 113.57	2008–2009	990	287
7	Du2	42.04, 116.29	2006	1350	399
8	HaM	37.37, 101.18	2002–2004	3250	567
9	Xfs	44.13, 116.33	2004–2006	1030	290
10	Xi1	43.55, 116.68	2006	1250	360
11	Xi2	43.55, 116.67	2006	1250	360
12	Ku2	40.38, 108.55	2006	1160	300

western side and provide additional model robustness. The 8-day NEP data were used both to assess model accuracy and for model development.

2.2. Model development

We developed a rule-based piecewise regression model to estimate the grassland NEP over northern China. The PWR model accounts for multivariate nonlinear relationship of the dependent variable (NEP) and a set of predictors and allows the use of both continuous and discrete variables as input variables. Model development samples are recursively partitioned into homogeneous subsets according to a gain ratio criterion, and the subsets are characterized by a series of rules, where each rule defines a set of conditions under which a multivariate least squares-type linear regression model is established (Zhang et al., 2010, 2011). The accuracy of the constructed PWR model was assessed with average error, relative error, and product–moment correlation coefficient that were also used to identify the most important predictive variables for estimating NEP (Zhang et al., 2010).

In this study, the PWR model was applied to derive the empirical relationship between the independent variables and the tower-based NEP at the 12 flux towers over multiple years at 8-day intervals. We first developed several models with different input variables and model parameters. The flux tower NEP data was used for model training and validation, and the remotely sensed and climatic data sets were used as explanatory or predictive variables. A preliminary analysis of the frequency of use and relevance in the PWR models decided the most important predictive variable in the final PWR model. The final PWR model was selected as having the highest accuracy and lowest number of input variables. Eight independent spatial variables (see Section 2.3) were selected to train the final model for mapping NEP over the northern China's grasslands. Then the model was applied to data through space and time to estimate the 8-day and 500-m NEP across the study area.

The final model composed of five committee models. Each committee model consists of several rule-based models and each model assigning higher weights to the outliers of the previous model (Xiao et al., 2008; Zhang et al., 2011). Committee models allow more complicated models and are beneficial for refining a good initial model (Zhang et al., 2011). The first model is generally the strongest model with other models focusing more on the outliers from the previous models. The PWR model composed of several committee models helps make a smooth map by encouraging variations in the regression stratification thresholds among various models. The final prediction was an average estimate from all five committee models at pixel level.

2.3. Model inputs and prediction

The identified model inputs include remotely sensed NDVI, phenological metrics, climate data sets, and the tower-measured NEP. The phenological metrics chosen in the PWR model included day of year, NDVI value at the start of the growing season, day of the start of the growing season, and annual maximum NDVI. The 8-day weather variables included precipitation, temperature, and photosynthetically active radiation (PAR).

In this study, we adopted the NDVI data derived from the 500-m and 8-day composite MODIS products (MOD09A1, collection 5). Temporal smoothing of the NDVI time series was performed using a moving window regression approach (Swets et al., 1999) to correct short-interval drops in NDVI associated with residual clouds in some of the 8-day NDVI composites. The phenological metrics were calculated from the smoothed MODIS NDVI time series for each year from 2000 to 2010 using the delayed moving average method (Reed et al., 1994). The daily gridded precipitation, temperature, and PAR data were acquired from the global Modern Era Retrospective-Analysis for Research and Applications (MERRA) reanalysis data set. The MERRA reanalysis data set developed by NASA's Global Modeling and Assimilation Office (GMAO) provides meteorological data with a spatial resolution of $0.5^\circ \times 0.67^\circ$. MERRA makes use of observations from NASA's Earth Observing System satellites and reduces the uncertainty in precipitation and interannual variability by improving the representation of the water cycle in the reanalysis (Rienecker et al., 2011). The three daily climatic variables were averaged into 8-day composites to match the MODIS NDVI compositing periods. All selected model inputs were resampled to 500-m resolution to match the MODIS NDVI resolution. We then applied the final PWR model using all available training data to estimate and map 8-day and 500-m NEP throughout the growing season (May–September) for grasslands of northern China.

2.4. Accuracy assessment

We applied leave-one-out cross-validation (i.e., withholding sites and years) to evaluate the PWR model. For withheld sites, one data subset from one site was withheld as a testing sample to assess the accuracy of the model, and the remaining 11 sites were used as training samples for model development. The model based on the 11 sites estimated the NEP values for the withheld site. Each of the 12 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 for all other 11 sites. Similarly, for the year-withheld cross-validation, each of the 7 years was withheld successively and then the data from the remaining 6 years were used to develop the model. The actual NEP value measured for a given year was compared to the model-estimated NEP value using the training data set for all other 6 years. We used Pearson's correlation coefficient (r) and root mean square error (RMSE) to compare the measured and estimated NEP to quantify the model and map accuracies.

3. Results

3.1. Model accuracy

We compared the model-estimated NEP with the tower-measured NEP. For all sites, the regressions of the tower-measured and model-estimated NEP in the cross-validation yielded values of $r = 0.97$ and RMSE = 0.31 g C m^{-2} d^{-1} for the NEP estimation by withholding site (Fig. 2). For all years, the regression of the tower-measured and model-estimated NEP in the cross-validation indicated that $r = 0.97$ and RMSE = 0.33 g C m^{-2} d^{-1} for the NEP estimation by withholding year (scatter plot was similar to Fig. 2). The tower-measured and model-estimated NEP regression is close to the 1:1 line, indicating a high precision of the piecewise regression model estimation. The model performance slightly varied by site and year (Table 2). The regressions of the tower-measured and model-estimated NEP in the cross-validation indicated that r varied between 0.80 and 0.98 and the RMSE ranged from 0.13 to 0.75 g C m^{-2} d^{-1} for the NEP estimation by withholding sites, and r varied between 0.85 and 0.98 and RMSE ranged from 0.12 to 0.55 g C m^{-2} d^{-1} for the NEP estimation by withholding years. After assessing the model performance with the leave-one-out cross-validation, we trained the final model using the complete flux tower data sets. The final model estimated the NEP reasonably well ($r = 0.97$, RMSE = 0.33 g C m^{-2} d^{-1}, p-value < 0.01). By including the data sets of all 12 sites and all seven years, maximum robustness in the final model was ensured over a wide range of geographic, weather, and ecological conditions.

Table 2
Accuracy of model-estimated NEP for each site and year assessed through leave-one-out cross-validation by withholding site and year.

ID	Site name	*r*	RMSE ($g\,C\,m^{-2}\,d^{-1}$)	ID	Year	*r*	RMSE ($g\,C\,m^{-2}\,d^{-1}$)
1	Arou	0.95	0.70	1	2002	0.94	0.31
2	Yuzhong	0.94	0.45	2	2003	0.98	0.19
3	Xinglongshan	0.98	0.40	3	2004	0.97	0.24
4	Qingyang	0.82	0.26	4	2005	0.92	0.12
5	Tongyu	0.96	0.75	5	2006	0.85	0.19
6	Dongsu	0.94	0.38	6	2008	0.97	0.51
7	Du2	0.80	0.22	7	2009	0.97	0.55
8	HaM	0.97	0.26				
9	Xfs	0.89	0.19				
10	Xi1	0.90	0.19				
11	Xi2	0.87	0.20				
12	Ku2	0.87	0.13				

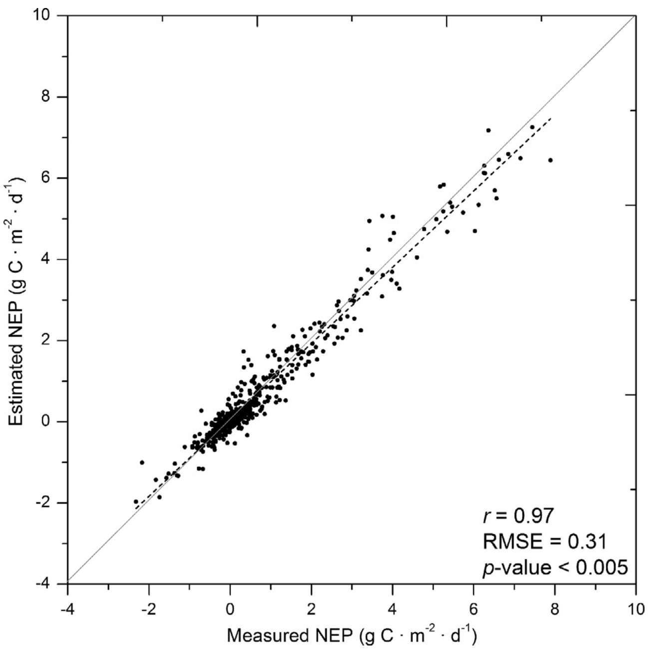

Fig. 2. Leave-one-out cross-validation of model-estimated NEP by withholding site.

3.2. Source/sink activity of grasslands in northern China

We mapped carbon fluxes for grasslands in northern China using our PWR model. In this study, we focused on flux modeling in the growing season (May–September). We calculated the spatial distribution of the growing-season NEP for each year during 2000–2010 from the 8-day NEP estimates and the results are shown in Fig. 3. Our results showed generally higher grassland NEP at high latitudes (northeast) than at low latitudes (central and west) because of different grassland types and environmental conditions. In the northeast, which is dominated by meadow steppes, the growing season NEP generally reached 200–300 $g\,C\,m^{-2}$. In the southwest corner of the region, which is partially occupied by alpine meadow systems, the growing season NEP also reached 200–300 $g\,C\,m^{-2}$. In the central part dominated by typical steppe communities, the NEP generally varied in the range 100–200 $g\,C\,m^{-2}$ over the growing season. It can be seen that carbon uptake in 2004 and 2010 had uniformly high NEP magnitudes relative to other years. Carbon release during the growing season was identified in parts of the northeastern and central regions in some other years.

During the study period, NEP over the growing season ranged from 129 (2001) to 217 $g\,C\,m^{-2}$ (2010) (Table 3). The multiple year average growing season NEP over the northern China's grasslands was $158 \pm 25\,g\,C\,m^{-2}$ during the period 2000–2010. During this period, the entire northern China's grassland had the mean carbon uptake of 126 Tg C over the growing season. Fig. 4 illustrates the areal distribution of the growing-season NEP during 2000–2010 for the entire grassland area of northern China. Areas of carbon uptake (from 0 to 300 $g\,C\,m^{-2}$ growing season^{-1}) were larger in 2004 and 2010 with most pixels concentrated at around 200. Areas of carbon releases (from 0 to $-100\,g\,C\,m^{-2}$ growing season^{-1}) were noticeably larger in 2001 and most pixels were centered around $-120\,g\,C\,m^{-2}$ growing season^{-1}. For the years of 2003 and 2006, despite high frequencies of carbon release pixels, the large areas of carbon uptake offset these and resulted in the entire region having intermediate carbon uptake in both years. The pixels for 2005, 2008, and 2009 were mostly concentrated in carbon uptakes around 120 $g\,C\,m^{-2}$ growing season^{-1}.

Temporally, most carbon uptake occurred between April and September with a gradual transition to carbon release presumably after September or October (Fig. 5). Higher NEP occurred

Table 3
Growing-season (May–September) NEP for the northern China grasslands.

Year	Growing-season NEP ($g\,C\,m^{-2}$ growing season^{-1})	Annual precipitation (mm)	Growing-season precipitation (mm)
2000	147	262	194
2001	129	278	211
2002	148	331	244
2003	146	408	312
2004	196	328	263
2005	156	281	227
2006	142	278	227
2007	148	287	212
2008	156	308	235
2009	157	253	190
2010	217	295	214
Mean ± SD	158 ± 25	300 ± 43	230 ± 34

Note: Positive values indicate carbon uptake and negative values indicate carbon release.

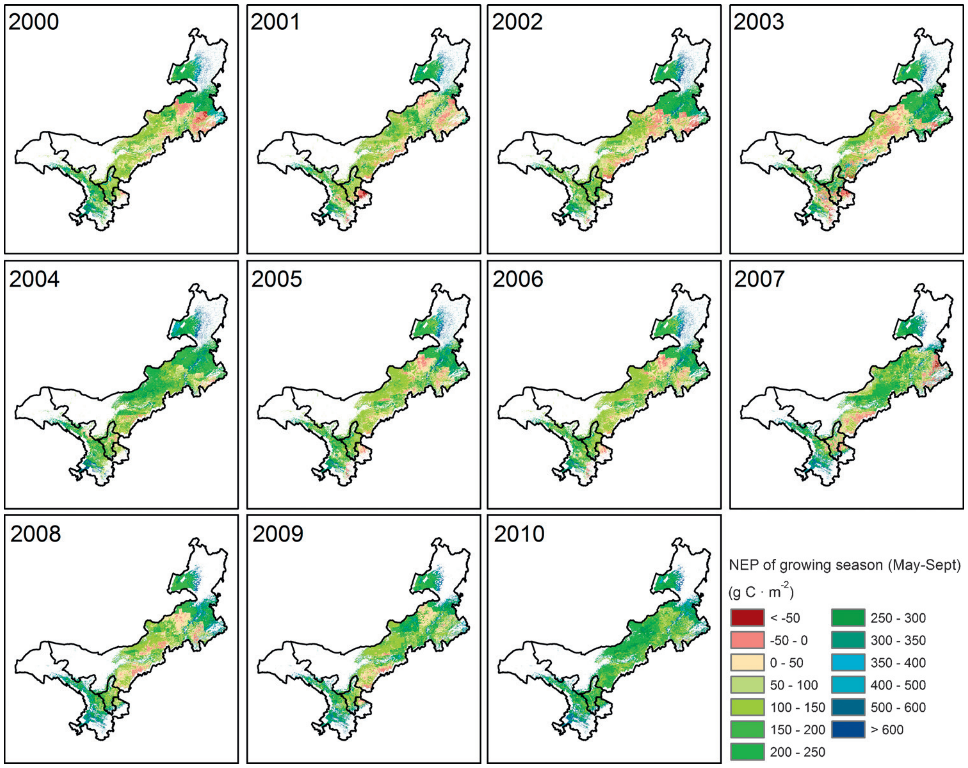

Fig. 3. Maps of the growing-season NEP over the northern China's grasslands during 2000–2010. Positive values indicate carbon uptake and negative values indicate carbon release.

throughout the growing seasons of 2004 and 2010, while lower NEP occurred throughout the growing season in 2001. The growing seasons in 2004 and 2010 were longer and with a higher NEP in August and September than those in other years. In the northern China's grasslands, the peak NEP usually occurred in June during 2000–2010. The trajectory of the 8-day NEP for each year showed that the June NEP was lowest in 2001 and 2007 (1.20 g C m^{-2} d^{-1}), while it was highest in 2010 (2.17 g C m^{-2} d^{-1}). Although the June NEP was lower in 2006 and 2007, higher values in July and August compensated for the low carbon uptake in June, resulting in intermediate carbon uptake in both years.

Fig. 6 indicates the mean and standard deviation (SD) of the growing-season NEP over the grasslands of northern China. Spatially, NEP does not show a distinct gradient in northern China (Fig. 6a). The mean growing season NEP over northern China ranged from −86 to 672 g C m^{-2} over an area that represents the extreme values for the entire region in space. The carbon uptake is notably higher for northeast of the study area and many pixels there showed relatively high carbon uptakes.

4. Discussion

4.1. Carbon uptake of grasslands in northern China

The entire northern China's grassland was an area of net carbon uptake for atmospheric CO_2 during the growing seasons of 2000–2010 with an average estimated NEP of 158 ± 25 g C m^{-2} (126 Tg C) (Table 3). Our regional estimate was similar to that from a study by Ma et al. (2010) who reported a sink of 135 Tg C yr^{-1} in typical steppes of northern China's grasslands. The inter-annual NEP

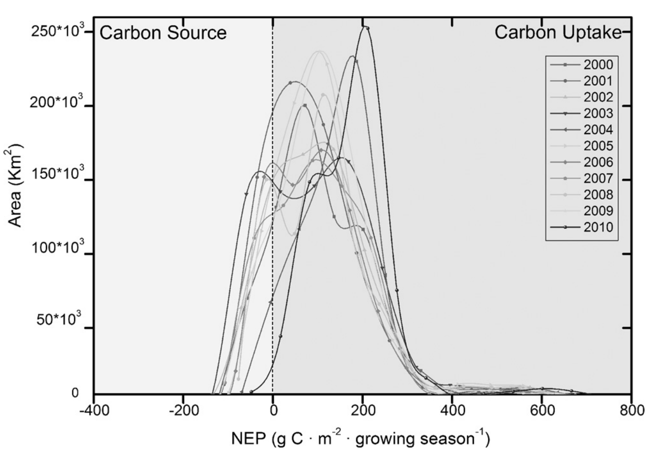

Fig. 4. Areal distribution of the growing-season NEP in the northern China's grasslands during 2000–2010.

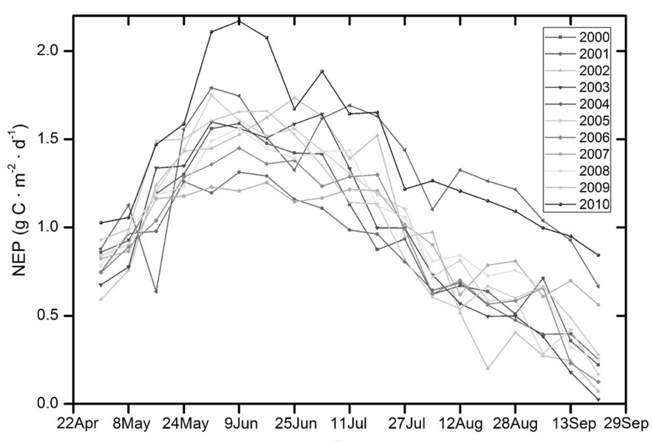

Fig. 5. Model-estimated regional mean 8-day NEP for the northern China's grasslands during the growing seasons of 2000–2010.

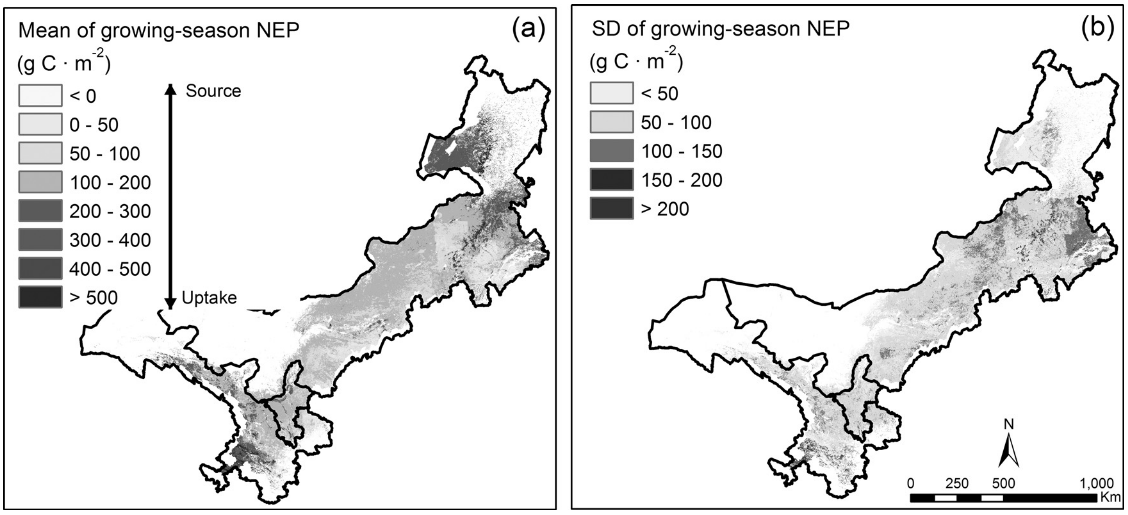

Fig. 6. Maps of (a) mean and (b) standard deviation of growing-season NEP over the grasslands of the northern China (2000–2010).

was extremely variable and the growing-season NEP was above the long-term mean in only 2 of 11 years (18%). Our estimated NEP ranged from 129 g C m^{-2} growing season^{-1} in 2001 to 217 in 2010 (range of 88 g C m^{-2} growing season^{-1}). In 2004 and 2010, grasslands showed higher carbon uptake. Our study of the entire northern China's grasslands showed a similar trend to an alpine meadow on the Qinghai–Tibetan Plateau, where a high NEP value of 192.5 g C m^{-2} yr^{-1} in 2004 almost doubled that in 2002 and 2003 (Kato et al., 2006). The large interannual variations are probably attributable to the sensitivity of grasslands to variation of climatic conditions and management practices. The higher NEP in 2004 was possibly related to higher precipitation and lower temperatures in 2004 that stimulated gross primary production and inhibited ecosystem respiration during the growing season (Kato et al., 2006). The length of the growing season may also play an important role in seasonal NEP (Kato et al., 2006). The late senescence in 2004 and 2010 increased the growing-season NEP. From our model estimates (Fig. 5), the growing season length was found to be longer in 2004 than in other years, except 2010, and this finding was consistent with site observations (Kato et al., 2006). In 2001, however, the total carbon uptake was low, as low precipitation in 2001 reduced the duration and magnitude of NEP. The seasonal maximum NEP in June 2001 was among the lowest (1.31 g C m^{-2} d^{-1}) of the eleven years, and the NEP rates remained at extremely low levels throughout the remainder of July.

Carbon uptake in the northern China's grasslands was higher in northeast dominated by meadow steppes and southwest corner dominated partially by alpine meadows. In the southwest corner, the NEP was higher largely because of more favorable moisture conditions at higher elevations (Wang et al., 2010). In 2004 and 2010, most of the southwest corner showed positive NEP with most areas having growing season NEP values around 200 g C m^{-2}. Carbon release was more frequent in the 2000–2003 growing seasons, especially in the central region. In 2001, a dry year, many areas released carbon over the growing season with NEP values between −20 and −30 g C m^{-2}. Although the year 2003 had large areas of carbon release, they were offset by large areas of carbon uptake in other parts of the region, primarily in the northeast, resulting in intermediate region-wide carbon uptake in 2003.

Similar to other temperate grasslands, the CO_2 uptake in northern China's grasslands occurred during April to September. June was the most active month for carbon uptake in the region, which is similar to the observations on the Great Plains, where the peak NEP typically occurred from mid-May to late June (Zhang et al., 2011). The growing-season NEP in the northern China's grasslands was lowest in 2001 and highest in 2010. In the dry year of 2001, the magnitude of NEP was maintained at low levels and the seasonal maximum NEP was only 1.31 g C m^{-2} d^{-1}. In 2010, however, the NEP was maintained at high levels throughout the growing season, reaching its peak of 2.17 g C m^{-2} d^{-1} in June. Although the June NEP was low in both 2006 and 2007, this was partially compensated by higher NEP in July and August, yielding an intermediate growing-season NEP. In contrast, the high spring carbon flux in 2009 compensated more for the relatively low summer flux in July and August, resulting in a higher 2009 growing-season uptake.

World grassland flux-tower synthesis estimated the mean grassland net uptake to be 191 g C m^{-2} yr^{-1} for intensively managed grasslands and 70 g C m^{-2} yr^{-1} for extensively managed grasslands (Gilmanov et al., 2010). Considering the winter carbon sources, our regional estimate of 158 ± 25 g C m^{-2} growing season^{-1} (from May to September) indicates that the carbon uptake capacity of the northern China's grasslands was intermediate between intensively managed grasslands and extensively managed grasslands. We also compared our results to other grasslands with similar vegetation or climatic conditions. Because of its arid and semi-arid climate, the NEP of our region was relatively low when compared to European temperate grasslands. European temperate grasslands (most sites had annual precipitation greater than 700 mm) have been shown to have highly variable NEP from significant net uptake (>655 g C m^{-2} yr^{-1}) to significant release (< −164 g C m^{-2} yr^{-1}) (Gilmanov et al., 2007). Compared with North America, our NEP estimate was very similar to that of grasslands in the U.S. Northern Great Plains (from −146 to 166 g C m^{-2} yr^{-1}, Gilmanov et al., 2005), but higher than that for two sagebrush steppes in the Intermountain West (22 and 69 g C m^{-2} yr^{-1}, Gilmanov et al., 2006), and much lower than for North Dakota grasslands under Conservation Reserve Program (from −366 to 692 g C m^{-2} growing season^{-1}, Phillips and Beeri, 2008) and for a warm temperate grassland in the southeastern United States (from −400 to 800 g C m^{-2} yr^{-1}, Novick et al., 2004). For temperate steppe sites in northern China, grasslands showed source activities with annual NEP values varying from −37 to −68 g C m^{-2} yr^{-1} (Wang et al., 2008) and from −107 to −140 g C m^{-2} yr^{-1} (Fu et al., 2009), while a weak sink of 41 g C m^{-2} yr^{-1} was reported for central Mongolia (Li et al., 2005). For three meadow sites in northeast of the Qinghai–Tibetan Plateau, the average NEP values were estimated to be carbon sinks of 76.9, 149.4, and 147.6 g C m^{-2} yr^{-1} (Zhang et al., 2009). Our regional estimate fell within the range of

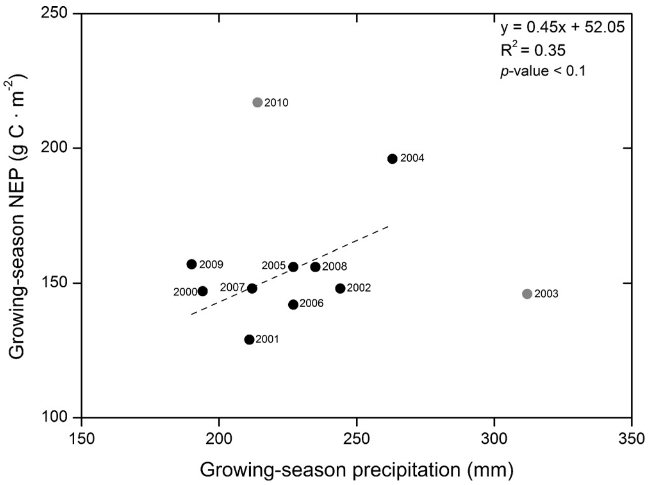

Fig. 7. The relationships between growing season precipitation and NEP over the grasslands of northern China. The years with a gray circle (●) in the graphs are those years that were excluded from the regression analysis due to their extreme values.

the carbon uptakes of the northern Eurasia temperate grasslands (Gilmanov et al., 2010), but was higher than most of the sites in the above studies, probably as a result of our growing-season estimate not including the annual source budget in winter and of a large diverse study region that includes significant areas of productive grasslands.

4.2. Sensitivity of northern China's grasslands to precipitation and drought

Precipitation is the dominant variable controlling grassland productivity (Sala et al., 1988; Knapp and Smith, 2001; Suyker et al., 2003; Flanagan and Adkinson, 2011), especially in the semi-arid steppe ecosystems (Fu et al., 2006; Knapp et al., 2008; Chen et al., 2009a). Site-level studies have shown that the annual amount and timing of precipitation is the major factor affecting gross primary productivity and respiration (Xu and Baldocchi, 2004; Jacobs et al., 2007; Craine et al., 2012), and thus, the NEP in the arid and semi-arid ecosystems. In our study, we found the northern China's grasslands were sensitive to precipitation. The low precipitation during the growing season in 2000 and 2001 (15.3% and 7.8% lower than the long-term mean, respectively) caused a reduction in carbon uptake in 2000 and 2001 (7.2% and 18.5% lower than the long-term mean, respectively), and higher precipitation in 2003 and 2004 (36.2% and 14.8% higher, respectively) caused a higher NEP in 2004 (23.8% higher) (Table 3). Although the precipitation was sufficient in 2003, the grasslands did not fully recover from drought in the previous two years.

The relationship between precipitation and NEP reflected direct effect of soil water availability on plant production in grasslands (Ma et al., 2010). However, the responses of grassland to climatic conditions differed by grassland type (Ma et al., 2010) and the shape of the relationship between precipitation and productivity varied by region (Hu et al., 2007; Guo et al., 2012). To identify the influence of precipitation on NEP, we calculated the regional means of growing season precipitation and NEP for each year and then examined their statistical relationship (Fig. 7). We observed that the growing-season precipitation had significant influence on the NEP for northern China's grasslands ($R^2 = 0.35$, p-value < 0.1). The northern China is strongly influenced by the East Asian summer monsoon, and therefore, most of the annual precipitation falls in the summer months, especially in July (Wittmer et al., 2010), which are the critical periods for plant growth. The steep slope implies that the water use efficiency (NEP/precipitation) could be highly achieved by plants in northern China's grasslands.

Droughts contribute to most of the interannual variability in terrestrial carbon sequestration (Xu and Baldocchi, 2004) and reduce the period and magnitude of positive NEP (Svejcar et al., 2008). The droughts in 2000, 2001, and 2006 caused the carbon release in the northern China's grasslands. In 2000, it reduced carbon uptake by 11%, and in 2001, the continuing drought from the previous year reduced carbon uptake by 29%. The 2000–2001 droughts continued to affect the ecosystems in 2002 and 2003 (10% and 12% lower than the long-term mean) and the grasslands did not fully recover from the previous droughts, although precipitation levels in 2002 and 2003 were both higher than the long-term mean. The 2006 drought combined with the slight drought in 2005 caused a reduction of carbon uptake of 16% in 2006. Our study further confirmed that the effect of a drought year may spread into the following year due to root turnover (Suyker et al., 2003) or the stimulation of heterotrophic respiration of soil biota (Arnone et al., 2008). In addition, seasonal precipitation may have some impact on this ecosystem. It was reported that serious drought struck the Inner Mongolian steppe from mid-June to August in 2003 (Ma et al., 2010). We found that the NEP in 2003 changed to a lower uptake during the dry periods in July and August (Fig. 5), which was similar to the findings of Ma et al. (2010). Therefore, the lower uptake in July and August contributed to the intermediate region-wide carbon uptake in 2003, although the uptake prior to June was relatively high.

Although previous studies suggested that grasslands were generally carbon sinks or near equilibrium, our studies indicated that it is common for the northern temperate grasslands to switch between carbon uptake and release, especially when influenced by extreme climatic conditions (e.g., drought). The magnitude of the carbon budget variation over a short period could be substantially overestimated if extreme climatic events are not considered (Xiao et al., 2009). Our results suggested that productivity reduction in northern China's grasslands can be explained by rainfall deficit or droughts and implied the critical role of precipitation and water availability in regulating grassland carbon budgets.

4.3. Potential effects of grassland functional types on carbon uptake

The variation of C_3 and C_4 components in grasslands is possibly another potential factor leading to the variability of NEP in the northern China's grasslands. Diversity of the plant functional types increases the ability of grassland to take the advantage of weather conditions. For example, the C_4 species can better tolerate environmental stress and are better able to maintain intense photosynthesis during the growing season (Tieszen et al., 1997; Wang, 2002). The C_4 species will predominate where moisture is more limited and nutrients are less available (Tieszen et al., 1997). Therefore, the water use efficiency of C_4 plants is higher than that of C_3 plants.

The geographical distribution of C_3/C_4 grasses in China is not as distinct as that in the U.S. Great Plains (Yin and Li, 1997). In China, the C_3 plants are the dominant plants in the northern China grasslands and the C_4 plants are relatively scarce compared to the C_3 plants (Han et al., 2006; Su et al., 2011). The C_4 grasses are mostly observed in the low-latitude region of the northern China (Wang et al., 1997) and the deserts of the northwestern China (Han et al., 2006; Su et al., 2011), where the C_4 plants can tolerate severe environment stress (Wang, 2002). The C_3/C_4 proportion affects the magnitude and seasonal distribution of biomass production (Wittmer et al., 2010). C_3 and C_4 grasslands were not explicitly distinguished in our study because C_3/C_4 grassland distribution map is not available yet for northern China. The intensity and capacity of the carbon cycle in grasslands may be different due to different

grass functional types. Climate change (rising temperature, precipitation, and CO_2 concentration) would change the proportion of C_3/C_4 plants, and thus, their ability to act as a carbon sink.

5. Conclusions

In this study, we integrated eleven years of MODIS NDVI and weather data sets with NEP data from twelve flux tower sites to develop a piecewise regression tree model for estimating NEP in the grasslands of northern China. The estimated NEP maps describe the spatio-temporal variations of NEP and carbon uptake activities in this area. Compared with previous estimates from global databases and statistical data, field surveys, and satellite-based statistical models, our NEP estimates provide an alternative and new dataset at higher spatial (500-m) and temporal (8-day) resolutions and can capture changes in NEP induced by extreme events because the MODIS NDVI dataset provides real-time (8-day) information for grassland biomass estimations.

The northern China's grasslands have the potential to sequester carbon for an extended period. The northern China's grasslands showed a net carbon uptake of $158 \pm 25\,\mathrm{g\,C\,m^{-2}}$ over the growing season during 2000–2010 with regional average estimates of 126 Tg C. The NEP was highly variable through the study period and ranged from 129 (2001) to $217\,\mathrm{g\,C\,m^{-2}}$ (2010), with higher carbon uptake in 2004 and 2010 and lower uptake during 2000–2003 and 2006–2007. The large interannual variations are probably attributable to the sensitivity of temperate grasslands to climate change and extreme climatic events. We observed that the interannual variations of the net growing season carbon uptake in the northern China's grasslands were very sensitive to precipitation and droughts. Low levels of precipitation reduced carbon uptake and higher levels induced higher NEP. Droughts in 2000, 2001, and 2006 caused carbon release for the grasslands of northern China. Although northern temperate grasslands have the potential to sequester carbon, droughts strongly influenced the carbon budget and altered the long-term carbon balances across the grasslands. If droughts become more frequent, carbon uptake in arid and semi-arid grasslands will decrease. This study provides insight into the response of a typical northern temperate grassland ecosystem to climate change.

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References

Adams, J., Faure, H., Faure-Denard, L., McGlade, J., Woodward, F., 1990. Increases in terrestrial carbon storage from the Last Glacial Maximum to the present. Nature 348, 711–714.

Aires, L.M.I., Pio, C.A., Pereira, J.S., 2008. Carbon dioxide exchange above a Mediterranean C_3/C_4 grassland during two climatologically contrasting years. Global Change Biol. 14, 539–555.

Arnone III, J.A., Verburg, P.S.J., Johnson, D.W., Larsen, J.D., Jasoni, R.L., Lucchesi, A.J., Batts, C.M., von Nagy, C., Coulombe, W.G., Schorran, D.E., Buck, P.E., Braswell, B.H., Coleman, J.S., Sherry, R.A., Wallace, L.L., Luo, Y., Schimel, D.S., 2008. Prolonged suppression of ecosystem carbon dioxide uptake after an anomalously warm year. Nature 455, 383–386.

Bai, Y., Han, X., Wu, J., Chen, Z., Li, L., 2004. Ecosystem stability and compensatory effects in the Inner Mongolia grassland. Nature 431, 181–184.

Bai, Y., Wu, J., Xing, Q., Pan, Q., Huang, J., Yang, D., Han, X., 2008. Primary production and rain use efficiency across a precipitation gradient on the Mongolia plateau. Ecology 89, 2140–2153.

Baldocchi, D., Falge, E., Gu, L., 2001. FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. Bull. Am. Meteorol. Soc. 82, 2415–2434.

Chen, S., Lin, G., Huang, J., Jenerette, G.D., 2009a. Dependence of carbon sequestration on the differential responses of ecosystem photosynthesis and respiration to rain pulses in a semiarid steppe. Glob. Change Biol. 15, 2450–2461.

Chen, S., Chen, J., Lin, G., Zhang, W., Miao, H., Wei, L., Huang, J., Han, X., 2009b. Energy balance and partition in Inner Mongolia steppe ecosystems with different land use types. Agric. For. Meteorol. 149, 1800–1809.

Craine, J.M., Nippert, J.B., Elmore, A.J., Skibbe, A.M., Hutghinson, S.L., Brunsell, N.A., 2012. Timing of climate variability and grassland productivity. Proc. Natl. Acad. Sci. U.S.A. 109, 3401–3405.

Du, Q., Liu, H.Z., Feng, J.W., Huang, J.P., Zhang, W., Bernhofer, C., 2012. Carbon dioxide exchange processes over the grassland ecosystems in semiarid areas of China. Sci China Earth Sci. 55, 644–655.

Dugas, W., Heuer, M., Mayeux, H., 1999. Carbon dioxide fluxes over bermudagrass, native prairie, and sorghum. Agric. For. Meteorol. 93, 121–139.

Easterling, D.R., Meehl, G.A., Parmesan, C., Changnon, S.A., Karl, T.R., Mearns, L.O., 2000. Climate extremes: observations, modeling, and impacts. Science 289, 2068–2074.

Fan, J., Zhong, H., Harris, W., Yu, G., Wang, S., Hu, Z., Yue, Y., 2008. Carbon storage in the grasslands of China based on field measurements of above-and below-ground biomass. Clim. Change 86, 375–396.

Feng, Q., Cheng, G., Mikami, M., 2001. The carbon cycle of sandy lands in China and its global significance. Clim. Change 48, 535–549.

Flanagan, L.B., Wever, L.A., Carlson, P.J., 2002. Seasonal and interannual variation in carbon dioxide exchange and carbon balance in a northern temperate grassland. Global Change Biol. 8, 599–615.

Flanagan, L.B., Adkinson, A.C., 2011. Interacting controls on productivity in a northern Great Plains grassland and implications for response to ENSO events. Global Change Biol. 17, 3293–3311.

Frank, A., Dugas, W., 2001. Carbon dioxide fluxes over a northern, semiarid, mixed-grass prairie. Agric. For. Meteorol. 108, 317–326.

Fu, Y., Yu, G., Sun, X., Li, Y., Wen, X., Zhang, L., Li, Z., Zhao, L., Hao, Y., 2006. Depression of net ecosystem CO_2 exchange in semi-arid *Leymus chinensis* steppe and alpine shrub. Agric. For. Meteorol. 137, 234–244.

Fu, Y., Zheng, Z., Yu, G., Hu, Z., Sun, X., Shi, P., Wang, Y., Zhao, X., 2009. Environmental influences on carbon dioxide fluxes over three grassland ecosystems in China. Biogeosciences 6, 2879–2893.

Gao, Q., Reynolds, J.F., 2003. Historical shrub–grass transitions in the northern Chihuahuan Desert: modeling the effects of shifting rainfall seasonality and event size over a landscape gradient. Global Change Biol. 9, 1475–1493.

Gilmanov, T.G., Tieszen, L.L., Wylie, B.K., Flanagan, L.B., Frank, A.B., Haferkamap, M.R., Meyers, T.P., Morgan, J.A., 2005. Integration of CO_2 flux and remotely-sensed data for primary production and ecosystem respiration analyses in the Northern Great Plains: potential for quantitative spatial extrapolation. Global Ecol. Biogeogr. 14, 271–292.

Gilmanov, T.G., Svejcar, T.J., Johnson, D.A., Angell, R.F., Saliendra, N.Z., Wylie, B.K., 2006. Long-term dynamics of production, respiration, and net CO_2 exchange in two sagebrush-steppe ecosystems. Rangeland Ecol. Manage. 59, 585–599.

Gilmanov, T.G., Soussana, J.F., Aires, L., Allard, V., Ammann, C., Balzarolo, M., Barcza, Z., Bernhofer, C., Campbell, C.L., Cernusca, A., Cescatti, A., Clifton-Brown, J., Dirks, B.O.M., Dore, S., Eugster, W., Fuhrer, J., Gimeno, C., Gruenwald, T., Haszpra, L., Hensen, A., Ibrom, A., Jacobs, A.F.G., Jones, M.B., Lanigan, G., Laurila, T., Lohila, A., Manca, G., Marcolla, B., Nagy, Z., Pilegaard, K., Pinter, K., Pio, C., Raschi, A., Rogiers, N., Sanz, M.J., Stefani, P., Sutton, M., Tuba, Z., Valentini, R., Williams, M.L., Wohlfahrt, G., 2007. Partitioning European grassland net ecosystem CO_2 exchange into gross primary productivity and ecosystem respiration using light response function analysis. Agric. Ecosyst. Environ. 121, 93–120.

Gilmanov, T.G., Aires, L., Barcza, Z., Baron, V.S., Belelli, L., Beringer, J., Billesbach, D., Bonal, D., Bradford, J., Ceschia, E., Cook, D., Corradi, C., Frank, A., Gianelle, D., Gimeno, C., Gruenwald, T., Guo, H., Hanan, N., Haszpra, L., Heilman, J., Jacobs, A., Jones, M.B., Johnson, D.A., Kiely, G., Li, S., Magliulo, V., Moors, E., Nagy, Z., Nasyrov, M., Owensby, C., Pinter, K., Pio, C., Reichstein, M., Sanz, M.J., Scott, R., Soussana, J.F., Stoy, P.C., Svejcar, T., Tuba, Z., Zhou, G., 2010. Productivity, respiration, and light-response parameters of world grassland and agroecosystems derived from flux-tower measurements. Rangeland Ecol. Manage. 63, 16–39.

Granier, A., Reichstein, M., Bre'da, N., Janssens, I.A., Falge, E., Ciais, P., Grünwald, T., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Facini, O., Grassi, G., Heinesch, B., Ilvesniemi, H., Keronen, P., Knohl, A., Köstner, B., Lagergren, F., Lindroth, A., Longdoz, B., Loustau, D., Mateus, J., Montagnani, L., Nys, C., Moors, E., Papale, D., Peiffer, M., Pilegaard, K., Pita, G., Pumpanen, J., Rambal, S., Rebmann, C., Rodrigues, A., Seufert, G., Tenhunen, J., Vesala, T., Wang, Q., 2007. Evidence

for soil water control on carbon and water dynamics in European forests during the extremely dry year: 2003. Agric. For. Meteorol. 143, 123–145.
Guo, Q., Hu, Z., Li, S., Li, X., Sun, X., Yu, G., 2012. Spatial variations in aboveground net primary productivity along a climate gradient in Eurasian temperate grassland: effects of mean annual precipitation and its seasonal distribution. Global Change Biol. 18, 3624–3631.
Han, M., Yang, L., Zhang, Y., Zhou, G., 2006. The biomass of C_3 and C_4 plant function groups in *Leymus chinensis* communities and theirs response to environmental change along Northeast China transect. Acta Ecol. Sin. 26, 1825–1832 (in Chinese).
Hu, Z., Fan, J., Zhong, H., Yu, G., 2007. Spatiotemporal dynamics of aboveground primary productivity along a precipitation gradient in Chinese temperate grassland. Sci. China Ser. D: Earth Sci. 50, 754–764.
Hunt, J.E., Kelliher, F.M., McSeveny, T.M., Ross, D.J., Whitehead, D., 2004. Long-term carbon exchange in a sparse, seasonally dry tussock grassland. Global Change Biol. 10, 1785–1800.
IPCC, 2007. Climate change 2007: impacts, adaptation, and vulnerability. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Contribution of Working Group II to the Fourth Assessment Report of the Intergovernment Panel on Climate Change. Cambridge University Press, Cambridge, p. 976.
Jacobs, A.F., Heusinkveld, B.G., Holtslag, A.A., 2007. Seasonal and interannual variability of carbon dioxide and water balances of a grassland. Clim. Change 82, 163–177.
Janssens, I.A., Freibauer, A., Ciais, P., Smith, P., Nabuurs, G., Folberth, G., Schlamadinger, B., Hutjes, R.W.A., Ceulemans, R., Schulze, E.D., Valentini, R., Dolman, A.J., 2003. Europe's terrestrial biosphere absorbs 7–12% of European anthropogenic CO_2 emissions. Science 300, 1538–1542.
Jones, M., Donnelly, A., 2004. Carbon sequestration in temperate grassland ecosystems and the influence of management, climate and elevated CO_2. New Phytol. 164, 423–439.
Jung, M., Reichstein, M., Bondeau, A., 2009. Towards global empirical upscaling of FLUXNET eddy covariance observations: validation of a model tree ensemble approach using a biosphere model. Biogeosciences 6, 2001–2013.
Kang, L., Han, X., Zhang, Z., Sun, O.J., 2007. Grassland ecosystems in China: review of current knowledge and research advancement. Philos. Trans. R. Soc. B: Biol. Sci. 362, 997–1008.
Kato, T., Tang, Y., Gu, S., Cui, X., Hirota, M., Du, M., Li, Y., Zhao, X., Oikawa, T., 2004. Carbon dioxide exchange between the atmosphere and an alpine meadow ecosystem on the Qinghai–Tibetan Plateau, China. Agric. For. Meteorol. 124, 121–134.
Kato, T., Tang, Y., Gu, S., Hirota, M., Du, M., Li, Y., Zhao, X., 2006. Temperature and biomass influences on interannual changes in CO_2 exchange in an alpine meadow on the Qinghai–Tibetan Plateau. Global Change Biol. 12, 1285–1298.
Kim, J., Verma, S.B., Clement, R.J., 1992. Carbon dioxide budget in a temperate grassland ecosystem. J. Geophys. Res.: Atmospheres 97, 6057–6063.
Knapp, A.K., Smith, M.D., 2001. Variation among biomes in temporal dynamics of aboveground primary production. Science 291, 481–484.
Knapp, A.K., Briggs, J.M., Collins, S.L., Archer, S.R., Bret-Harte, M.S., Ewers, B.E., Peters, D.P., Young, D.R., Shaver, G.R., Pendall, E., Cleary, M.B., 2008. Shrub encroachment in North American grasslands: shifts in growth form dominance rapidly alters control of ecosystem carbon inputs. Global Change Biol. 14, 615–623.
Kwon, H., Pendall, E., Ewers, B.E., Cleary, M., Naithani, K., 2008. Spring drought regulates summer net ecosystem CO_2 exchange in a sagebrush-steppe ecosystem. Agric. For. Meteorol. 148, 381–391.
Law, B., 2007. AmeriFlux network aids global synthesis. Eos, Trans. Am. Geophys. Union 88, 286.
Li, S., Asanuma, J., Eugster, W., Kotani, A., Liu, J., Urano, T., Oikawa, T., Davaa, G., Oyunbaatar, D., Sugita, M., 2005. Net ecosystem carbon dioxide exchange over grazed steppe in central Mongolia. Global Change Biol. 11, 1941–1955.
Liu, H., Tu, G., Fu, C., Shi, L., 2008. Three-year variations of water, energy and fluxes of cropland and degraded grassland surfaces in a semi-arid area of northeastern China. Adv. Atmos. Sci. 25, 1009–1020.
Ma, S., Baldocchi, D.D., Xu, L., Hehn, T., 2007. Inter-annual variability in carbon dioxide exchange of an oak/grass savanna and open grassland in California. Agric. For. Meteorol. 147, 157–171.
Ma, W., Fang, J., Yang, Y., Mohammat, A., 2010. Biomass carbon stocks and their changes in northern China's grasslands during 1982–2006. Sci. China Life Sci. 53, 841–850.
Meyers, T.P., 2001. A comparison of summertime water and CO_2 fluxes over rangeland for well watered and drought conditions. Agric. For. Meteorol. 106, 205–214.
Nagy, Z., Pintér, K., Czóbel, Sz., Balogh, J., Horváth, L., Fóti, Sz., Barcza, Z., Weidinfer, T., Csintalan, Zs., Dinh, N., Grosz, B., Tuba, Z., 2007. The carbon budget of semi-arid grassland in a wet and a dry year in Hungary. Agric. Ecosyst. Environ. 121, 21–29.
Ni, J., 2001. Carbon storage in terrestrial ecosystems of China: estimates at different spatial resolutions and their responses to climate change. Clim. Change 49, 339–358.
Ni, J., 2002. Carbon storage in grasslands of China. J. Arid Environ. 50, 205–218.
Ni, J., 2004. Forage yield-based carbon storage in grasslands of China. Clim. Change 67, 237–246.
Niu, S., Wu, M., Han, Y., Xia, J., Li, L., Wan, S., 2008. Water-mediated responses of ecosystem carbon fluxes to climate change in a temperate steppe. New Phytol. 177, 209–219.
Novick, K.A., Stoy, P.C., Katul, G.G., Ellsworth, D.S., Siqueira, M.B.S., Juang, J., Oren, R., 2004. Carbon dioxide and water vapor exchange in a warm temperate grassland. Oecologia 138, 259–274.
Parton, W., Scurlock, J., Ojima, D., Schimel, D., Hall, D., 1995. Impact of climate change on grassland production and soil carbon worldwide. Global Change Biol. 1, 13–22.
Pereira, J.S., Mateus, J.A., Aires, L.M., Pita, G., Pio, C., David, J.S., Andrase, V., Banza, J., David, T.S., Paco, T.A., Rodrigues, A., 2007. Net ecosystem carbon exchange in three contrasting Mediterranean ecosystems – the effect of drought. Biogeosciences 4, 791–802.
Phillips, R.L., Beeri, O., 2008. Scaling-up knowledge of growing-season net ecosystem exchange for long-term assessment of North Dakota grasslands under the Conservation Reserve Program. Global Change Biol. 14, 1008–1017.
Piao, S., Fang, J., Zhou, L., Tan, K., Tao, S., 2007. Changes in biomass carbon stocks in China's grasslands between 1982 and 1999. Global Biogeochem. Cycles 21, 1–10.
Reed, B.C., Brown, J.F., Vanderzee, D., Loveland, T.R., Merchant, J.W., Ohlen, D.O., 1994. Measuring phenological variability from satellite imagery. J. Veg. Sci. 5, 703–714.
Reynolds, S., Batello, C., Baas, S., Mack, S., 2005. Grassland and forage to improve livelihoods and reduce poverty. In: McGilloway, D.A. (Ed.), Grassland: A Global Resource. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 323–338.
Rienecker, M.M., Suarez, M.J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M.G., Schubert, S.D., Takacs, L., Kim, G., Bloom, S., Chen, J., Collins, D., Conaty, A., da Silva, A., Gu, W., Joiner, J., Koster, R.D., Lucchesi, R., Molod, A., Owens, T., Pawson, S., Pegion, P., Redder, C.R., Reichle, R., Robertson, F.R., Ruddick, A.G., Sienkiewicz, M., Woollen, J., 2011. MERRA: NASA's modern-era retrospective analysis for research and applications. J. Clim. 24, 3624–3648.
Sala, O.E., Parton, W., Joyce, L., Lauenroth, W., 1988. Primary production of the central grassland region of the United States. Ecology 69, 40–45.
Scurlock, J., Hall, D., 1998. The global carbon sink: a grassland perspective. Global Change Biol. 4, 229–233.
Shen, W., Jenerette, G.D., Hui, D., Phillips, R.P., Ren, H., 2008. Effects of changing precipitation regimes on dryland soil respiration and C pool dynamics at rainfall event, seasonal and interannual scales. J. Geophys. Res.: Biogeosci. 113, G03024.
Sims, P.L., Bradford, J., 2001. Carbon dioxide fluxes in a southern plains prairie. Agric. For. Meteorol. 109, 117–134.
Sims, D.A., Rahman, A.F., Cordova, V.D., El-Masri, B.Z., Baldocchi, D.D., Bolstad, P.V., Flanagan, L.B., Goldstein, A.H., Hollinger, D.Y., Misson, L., Monson, R.K., Oechel, W.C., Schmid, H.P., Wofsy, S.C., Xu, L., 2008. A new model of gross primary productivity for North American ecosystems based solely on the enhanced vegetation index and land surface temperature from MODIS. Remote Sens. Environ. 112, 1633–1646.
Su, P., Xie, T., Zhou, Z., 2011. Geographical distribution of C_4 plant species in desert regions of China and its relation with climate factors. J. Desert Res. 31, 267–276 (in Chinese).
Sun, H., 2005. Ecosystems of China. Science Press, Beijing (in Chinese).
Suyker, A.E., Verma, S.B., Burba, G.G., 2003. Interannual variability in net CO_2 exchange of a native tallgrass prairie. Global Change Biol. 9, 255–265.
Svejcar, T., Angell, R., Bradford, J.A., Dugas, W., Emmerich, W., Frank, A.B., Gilmanov, T., Haferkamp, M., Johnson, D.A., Mayeux, H., Mielnick, P., Morgan, J., Saliendra, N.Z., Schuman, G.E., Sims, P.L., Snyder, K., 2008. Carbon fluxes on North American rangelands. Rangeland Ecol. Manage. 61, 465–474.
Swets, D., Reed, B., Rowland, J., Marko, S., 1999. A weighted least-squares approach to temporal smoothing of NDVI. In: Proceedings: Bethesda, Maryland, American Society for Photogrammetry and Remote Sensing, CD-ROM, p. 1.
Tieszen, L.L., Reed, B.C., Bliss, N.B., Wylie, B.K., DeJong, D.D., 1997. NDVI, C_3 and C_4 production, and distributions in Great Plains grassland land cover classes. Ecol. Appl. 7, 59–78.
Turner, D.P., Ritts, W.D., Cohen, W.B., Gower, S.T., Zhao, M., Running, S.W., Wofsy, S.C., Urbanski, S., Dunn, A.L., Munger, J.W., 2003. Scaling gross primary production (GPP) over boreal and deciduous forest landscapes in support of MODIS GPP product validation. Remote Sens. Environ. 88, 256–270.
Verburg, P.S., Arnone III, J.A., Obrist, D., Schorran, D.E., Evans, R.D., Leroux-Swarthout, D., Johnson, D.W., Luo, Y., Coleman, J.S., 2004. Net ecosystem carbon exchange in two experimental grassland ecosystems. Global Change Biol. 10, 498–508.
Wang, H., Jia, G., Feng, J., Zhao, T., Ma, Z., 2010. Modeling gross primary production by integrating satellite data and coordinated flux measurements in arid and semi-arid China. Atmos. Oceanic Sci. Lett. 3, 7–13.
Wang, P., Yin, L., Li, J., 1997. Ecological distribution and physiological adaptation to saline-alkali environment of C_3 and C_4 plants in Northeastern China prairie area. Chin. J. Appl. Ecol. 8, 407–411 (in Chinese).
Wang, R., 2002. The C_4 photosynthetic pathway and life forms in grassland species from North China. Photosynthetica 40, 97–102.
Wang, Y., Zhou, G., Wang, Y., 2008. Environmental effects on net ecosystem CO_2 exchange at half-hour and month scales over *Stipa krylovii* steppe in northern China. Agric. For. Meteorol. 148, 714–722.
Wang, Y., Zhou, G., 2012. Light use efficiency over two temperate steppes in Inner Mongolia, China. PLoS ONE 7, e43614.
Wittmer, M.H., Auerswald, K., Bai, Y., SchÄufele, R., Schnyder, H., 2010. Changes in the abundance of C_3/C_4 species of Inner Mongolia grassland: evidence from isotopic composition of soil and vegetation. Global Change Biol. 16, 605–616.
World Resources Institute, 2000. Taking stock of ecosystems-grassland ecosystems. In: World Resources 2000–2001: People and Ecosystems—The Fraying Web of Life. World Resour. Inst., Washington, D.C., pp. 119–131.

Wylie, B.K., Gilmanov, T.G., Johnson, D.A., Saliendra, N.Z., Tieszen, L.L., Doyle, A.F., Laca, E.A., 2006. Scaling-up of CO_2 fuxes to assess carbon sequestration in rangelands of Central Asia. In: USDA Forest Service Proceedings RMRS, pp. 111–119.

Wylie, B.K., Fosnight, E.A., Gilmanov, T.G., Frank, A.B., Morgan, J.A., Haferkamp, M.R., Meyers, T.P., 2007. Adaptive data-driven models for estimating carbon fluxes in the Northern Great Plains. Remote Sens. Environ. 106, 399–413.

Xiao, J., Zhuang, Q., Baldocchi, D.D., Law, B.E., Richardson, A.D., Chen, J., Oren, R., Starr, G., Noormets, A., Ma, S., Verma, S.B., Wharton, S., Wofsy, S.C., Bolstad, P.V., Burns, S.P., Cook, D.R., Curtis, P.S., Drake, B.G., Falk, M., Fischer, M.L., Foster, D.R., Gu, L., Hadley, J.L., Hollinger, D.Y., Katul, G.G., Litvak, M., Martin, T.A., Matamala, R., McNulty, S., Meyers, T.P., Monson, R.K., Munger, J.W., Oechel, W.C., Tha Paw, U.K., Schmid, H.P., Scott, R.L., Sun, G., Suyker, A.E., Torn, M.S., 2008. Estimation of net ecosystem carbon exchange for the conterminous United States by combining MODIS and AmeriFlux data. Agric. For. Meteorol. 148, 1827–1847.

Xiao, J., Zhuang, Q., Liang, E., McGuire, A.D., Moody, A., Kicklighter, D.W., Shao, X., Melillo, J.M., 2009. Twentieth-century droughts and their impacts on terrestrial carbon cycling in China. Earth Interact. 13, 1–31.

Xu, B., Yang, X., Tao, W., Qin, Z., Liu, H., Miao, J., Bi, Y., 2008. MODIS-based remote sensing monitoring of grass production in China. Int. J. Remote Sens. 29, 5313–5327.

Xu, L., Baldocchi, D.D., 2004. Seasonal variation in carbon dioxide exchange over a Mediterranean annual grassland in California. Agric. For. Meteorol. 123, 79–96.

Yang, F., Ichii, K., White, M.A., Hashimoto, H., Michaelis, A.R., Votava, P., Zhu, A., Huete, A., Running, S.W., Nemani, R.R., 2007. Developing a continental-scale measure of gross primary production by combining MODIS and AmeriFlux data through Support Vector Machine approach. Remote Sens. Environ. 110, 109–122.

Yin, L., Li, M., 1997. A study on the geographic distribution and ecology of C_4 plants in China. Acta Ecol. Sin. 17, 350–363 (in Chinese).

Yu, G., Wen, X.F., Sun, X.M., Tanner, B.D., Lee, X.H., Chen, J.Y., 2006. Overview of ChinaFLUX and evaluation of its eddy covariance measurement. Agric. For. Meteorol. 137, 125–137.

Zhang, L., Wylie, B.K., Loveland, T., Fosnight, E.A., Tieszen, L.L., Ji, L., 2007. Evaluation and comparison of gross primary production estimates for the Northern Great Plains grasslands. Remote Sens. Environ. 106, 173–189.

Zhang, L., Wylie, B.K., Ji, L., Gilmanov, T.G., Tieszen, L.L., 2010. Climate-driven interannual variability in net ecosystem exchange in the northern Great Plains grasslands. Rangeland Ecol. Manage. 63, 40–50.

Zhang, L., Wylie, B.K., Ji, L., Gilmanov, T.G., Tieszen, L.L., Howard, D.M., 2011. Upscaling carbon fluxes over the Great Plains grasslands: sinks and sources. J. Geophys. Res.: Biogeosci. 116, G00J03.

Zhang, P., Hirota, M., Shen, H., Yamamoto, A., Mariko, S., Tang, Y.H., 2009. Characterization of CO_2 flux in three Kobresia meadows differing in dominant species. J. Plant Ecol. 2, 187–196.