SCIENCE CHINA
Life Sciences

July 2010 Vol.53 No.7: 841–850
doi: 10.1007/s11427-010-4020-6

Biomass carbon stocks and their changes in northern China's grasslands during 1982–2006

MA WenHong[1,2], FANG JingYun[1*], YANG YuanHe[1] & Anwar MOHAMMAT [3]

[1]*Department of Ecology, and Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing 100871, China;*
[2]*College of Life Science, Inner Mongolia University, Hohhot 010021, China;*
[3]*Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China*

Received February 9, 2010; accepted May 2, 2010

Grassland covers approximately one-third of the area of China and plays an important role in the global terrestrial carbon (C) cycle. However, little is known about biomass C stocks and dynamics in these grasslands. During 2001–2005, we conducted five consecutive field sampling campaigns to investigate above-and below-ground biomass for northern China's grasslands. Using measurements obtained from 341 sampling sites, together with a NDVI (normalized difference vegetation index) time series dataset over 1982–2006, we examined changes in biomass C stock during the past 25 years. Our results showed that biomass C stock in northern China's grasslands was estimated at 557.5 Tg C (1 Tg=10^{12} g), with a mean density of 39.5 g C m^{-2} for above-ground biomass and 244.6 g C m^{-2} for below-ground biomass. An increasing rate of 0.2 Tg C yr^{-1} has been observed over the past 25 years, but grassland biomass has not experienced a significant change since the late 1980s. Seasonal rainfall (January–July) was the dominant factor driving temporal dynamics in biomass C stock; however, the responses of grassland biomass to climate variables differed among various grassland types. Biomass in arid grasslands (i.e., desert steppe and typical steppe) was significantly associated with precipitation, while biomass in humid grasslands (i.e., alpine meadow) was positively correlated with mean January–July temperatures. These results suggest that different grassland ecosystems in China may show diverse responses to future climate changes.

above-ground biomass, alpine grasslands, below-ground biomass, carbon stock, NDVI, temperate grasslands

Citation: Ma W H, Fang J Y, Yang Y H, *et al*. Biomass carbon stocks and their changes in northern China's grasslands during 1982–2006. Sci China Life Sci, 2010, 53: 841−850, doi: 10.1007/s11427-010-4020-6

Above-and below-ground vegetation biomass are important components of terrestrial ecosystem carbon (C) stocks [1]. Estimating the size and dynamics of biomass C stocks has been one of the key issues in global terrestrial C cycling [2–5]. Grassland ecosystems play an important role in the global terrestrial C cycle due to their large area and high proportion of below-ground C stock [6]. They likely contribute as much as 20% of the total terrestrial production and provide an annual sink of ~0.5 Pg C [7]. A quantitative assessment of biomass C stock and its temporal dynamics in grassland ecosystems is thus the basis to accurately evaluate C sinks or sources in global terrestrial C cycling [8,9]. Moreover, identifying the effects of climate change on biomass C dynamics in grassland ecosystems is critical to predicting the response of grassland ecosystems to future climate change [10]. However, large uncertainties still exist in estimates of grassland biomass C stock and its response to climate change [11,12].

China's grasslands cover nearly one-third of the country's area [13]. As an important component of northern China's grasslands, temperate grasslands are distributed in arid and semi-arid regions [14], while alpine grasslands are

*Corresponding author (email: jyfang@urban.pku.edu.cn)

located on the Tibetan Plateau. Plant production in these grassland ecosystems potentially plays an important role in the regional C balance. However, our knowledge of biomass C dynamics and its feedback to climate change in northern China's grasslands remains limited, partly because of a lack of direct measurements and large spatial heterogeneity in grassland biomass. Thus, it is necessary to examine the size and dynamics of vegetation C stock in northern China's grasslands to understand its potential role in China's terrestrial C cycle.

Biomass C stock in China's grasslands has been evaluated based on global biomass databases [15,16], resource inventories [17], field investigations [18,19], and satellite-based statistical models [11]. However, few studies have analyzed the interannual variability in biomass C stock and its response to climate change. Moreover, large uncertainties still exist due to the lack of field measurements based on a standard sampling method, particularly for below-ground biomass (BGB) [20,21]. In addition, previous estimates have been mainly based on field surveys from the 1960s to 1980s, which limits our understanding of the current C stock in grassland biomes. Also, few studies have analyzed the interannual variation of biomass C stocks and their relationships with climatic factors. Thus, it is necessary to obtain current data on vegetation biomass and then use long-term satellite information to assess biomass C dynamics at the regional scale.

In this study, we conducted five consecutive field sampling campaigns during the summers (June–August) of 2001–2005 across the northern part of China (including Qinghai, Tibet, Inner Mongolia, Ningxia, Gansu, and Xinjiang). Using biomass measurements obtained from 341 sites (a total of 1075 plots) and a remote sensing dataset called normalized difference vegetation index (NDVI) covering 1982–2006, we estimated biomass C stock and its dynamics over the past 25 years in northern China's grasslands and also analyzed its relationships with climatic variables.

1 Materials and methods

1.1 Study area

This study was conducted in China's temperate and alpine grasslands. The distribution of grassland types was extracted from a vegetation map of China at a scale of 1: 1000000 [22]. Based on China's vegetation classification system, we divided northern China grasslands into six types: alpine steppe, alpine meadow, desert steppe, typical steppe, meadow steppe, and mountain meadow (Figure 1).

1.2 Field biomass survey

We sampled 341 sites across northern China during the summers (June to August) of 2001–2005 (Figure 1). At each site (10 m×10 m), all plants in five plots (1 m×1 m) were harvested to determine above-ground biomass (AGB). To determine BGB, either three 50 cm×50 cm soil pits or nine

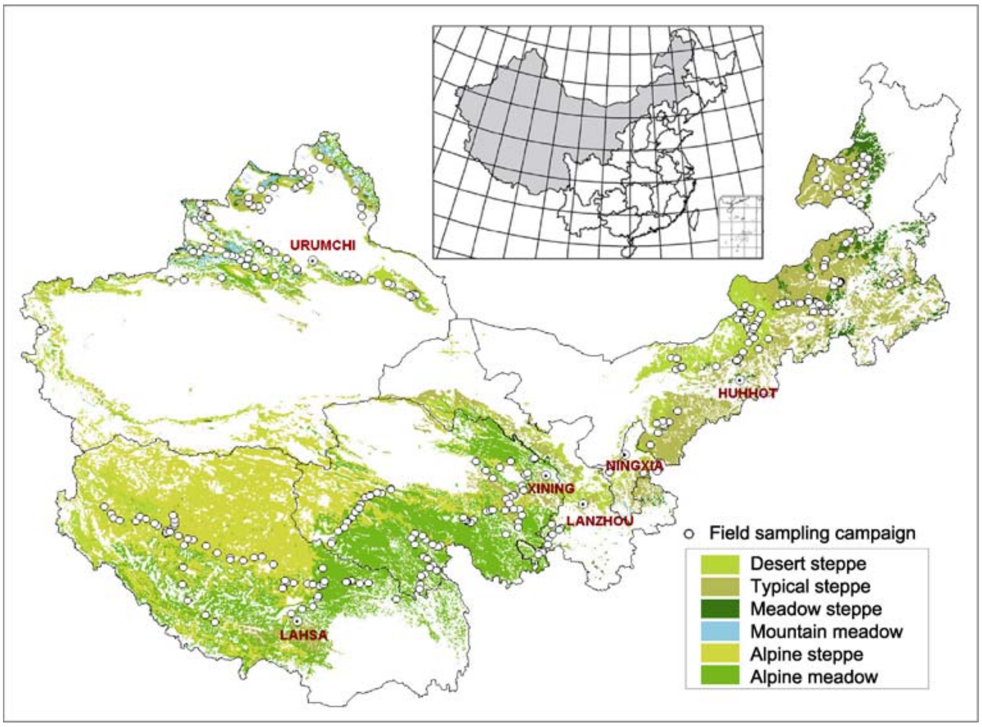

Figure 1 Locations of the 341 sampling sites across northern China grasslands on the back-ground of China's vegetation map at a scale of 1:1000000. The sampling campaigns were conducted during the summers (June–August) of 2001–2005.

soil cores (8-cm diameter) were used to collect samples at 10-cm intervals. Root samples were immediately placed in a cooler and then transported to the laboratory. In the laboratory, root samples were soaked in deionized water and cleaned from soil residue through a sieve with a mesh size of 0.5 mm. Live roots were distinguished by their color, resilience, and attached fine roots [23]. Biomass samples were oven-dried at 65°C to a constant mass and weighed to the nearest 0.1 g. Biomass was converted to C content using a conversion factor of 0.45.

1.3 Remote sensing and climate data

NDVI of growing seasons (May–September) during 1982–2006 was used to estimate biomass. The data were obtained from the Global Inventory Monitoring and Modeling Studies (GIMMS) group derived from the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer (NOAA/AVHRR) dataset at a spatial resolution of 8 km×8 km and a 15-day interval [24,25]. Monthly maximum NDVI values were used to reduce atmospheric and bidirectional effect [26]. Given that NDVI data in sparsely vegetated areas are largely influenced by the spectral characteristics of the soil, we analyzed grassland areas with mean growing season NDVI>0.1 [27].

Monthly mean air temperature and precipitation data during 1982–2006 were derived from 833 meteorological stations across northern China. Considering the lag response of biomass to climate change in grassland ecosystems [28,29], seasonal mean temperature and precipitation from January to July were spatially interpolated at a resolution of 0.1×0.1 degrees using Kriging techniques [30]. Climate data for each grassland type were obtained by overlaying the climate dataset over the vegetation map of China [21].

1.4 Biomass estimation

In this study, biomass in northern China's grasslands was estimated using the following four steps. First, biomass measurements obtained from the 341 biomass sites were combined to 60 communities based on species composition and the vegetation map of China at a scale of 1:1000000. The relationship between AGB and mean growing season NDVI during 2001–2005 is shown in Figure 2A for these communities. We then used the regression model (equation (1)) to estimate AGB for each pixel across the grassland region and obtained the spatial distribution of AGB. Second, based on field measurements, we developed an allometric relationship (Figure 2B) and used equation (2) to estimate BGB for each pixel. Third, biomass data for each grassland type were obtained by overlaying the above- and below-ground datasets over the vegetation map of China. Finally, we calculated biomass at five different time periods (1982–1986, 1987–1991, 1992–1996, 1997–1001, and 2002–2006) and then analyzed the trend of AGB over the past 25 years.

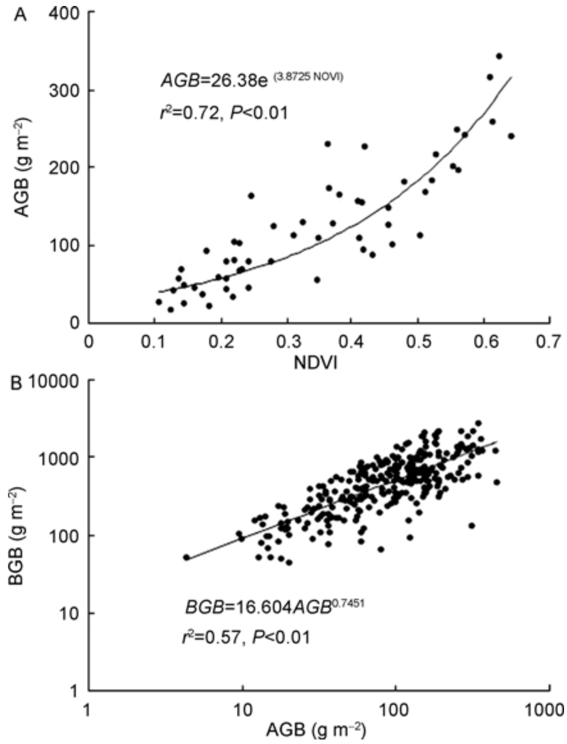

Figure 2 Relationships between above-ground biomass (AGB) and NDVI (A) and below-ground biomass (BGB) and NDVI (B) for grasslands in northern China. The relationship in (A) is based on mean AGB for 60 communities and their mean NDVI during the growing season. The relationship in (B) is based on mean AGB and BGB from 341 sampling sites.

$$AGB = 26.38\exp(3.8725\times NDVI)\ (r^2=0.70, P<0.01), \quad (1)$$

$$BGB=16.604\times AGB^{0.7451}\ (r^2=0.57, P<0.01). \quad (2)$$

1.5 Statistical analysis

To analyze the effects of climatic factors on seasonal AGB, correlations between AGB and climatic factors (temperature and precipitation) were determined for various grassland types and total grasslands in northern China. Because positive trends in both biomass and temperature may lead to a higher correlation between these two variables, we used the detrended method [25] to establish the relationship between AGB and the detrended temperature. In addition, we examined the relationships between the biomass anomaly index (BAI) and the mean January–July temperature anomaly index (TAI) or the January–July rain anomaly index (RAI) based on their mean values over the past 25 years. In this study, we defined BAI as the difference between individual-year AGB over 1982–2006 and the mean AGB for the 25 years.

2 Results

2.1 Spatial distributions of above- and below-ground biomass

AGB and BGB exhibited large variations across all 341 sites, ranging from 4.2 to 203.4 g C m^{-2} for AGB and 20.1 to 1253.1 g C m^{-2} for BGB. Mean values were estimated at 49.0 and 271.5 g C m^{-2} for AGB and BGB, respectively (Figure 3A and B). The spatial distribution of biomass also exhibited large differences among different regions (Figure 3C and D). Relatively low biomass was observed in southwestern Inner Mongolia, western Tibet, and southern Xinjiang (AGB and BGB were less than 25 and 150 g C m^{-2}, respectively), while relatively high values occurred in northeastern Inner Mongolia, eastern Tibet, and northern Xinjiang (AGB and BGB were more than 50 and 300 g C m^{-2}, respectively).

2.2 Interannual changes in biomass C density and C stock

AGB and BGB C densities and stocks during the five different periods are listed in Table 1. Specifically, biomass C stock (2002–2006) across northern China's grasslands was estimated at 557.5 Tg C, with 77.4 and 480.1 Tg C occurring in above- and below-ground, respectively. Over 58% of the total biomass C stock was distributed in alpine steppe and alpine meadow. With an area of 38.52 million ha, typical steppe accounted for 24.2% (135.0 Tg C) of the total biomass C stock in northern China's grasslands.

Across the entire grassland area, total biomass C stock increased from 531.6 Tg C in the early 1980s (1982–1986) to 557.5 Tg C in the early 2000s (2002–2006), with increases of 4.8 and 21.1 Tg C in above- and below-ground C stocks, respectively. AGB and BGB C density increased by 6.6% and 4.6%, respectively, from 37.0 and 233.8 g C m^{-2} (in the early 1980s) to 39.5 and 244.6 g C m^{-2} (in the early 2000s). The largest increase occurred in the late 1980s (1987–1991) with a total increase in biomass C stock of 22.1 Tg C, but there have been no large increases since the late 1980s (Table 1). Biomass C differed greatly among different grassland types. Biomass C in temperate typical steppe and alpine meadow showed the largest increase (AGB increased by 9.1% and 8.8%, respectively; BGB increased by 6.8% and 6.2%, respectively) since the early 1980s, while biomass C in mountain meadow only exhibited a slight difference between the early 1980s and the early 2000s (14.9 Tg C in the early 1980s and 14.7 Tg C in the early 2000s).

To assess spatial patterns of biomass dynamics during 1982–2006, the slope of the relationship between AGB C density and year was calculated for each grid across grassland areas. The temporal dynamics of AGB showed large spatial heterogeneity across the study area (Figure 4). At the center of Inner Mongolia grasslands and the eastern part of the Tibetan Plateau, trends in biomass change were positive but statistically insignificant, while slightly decreasing

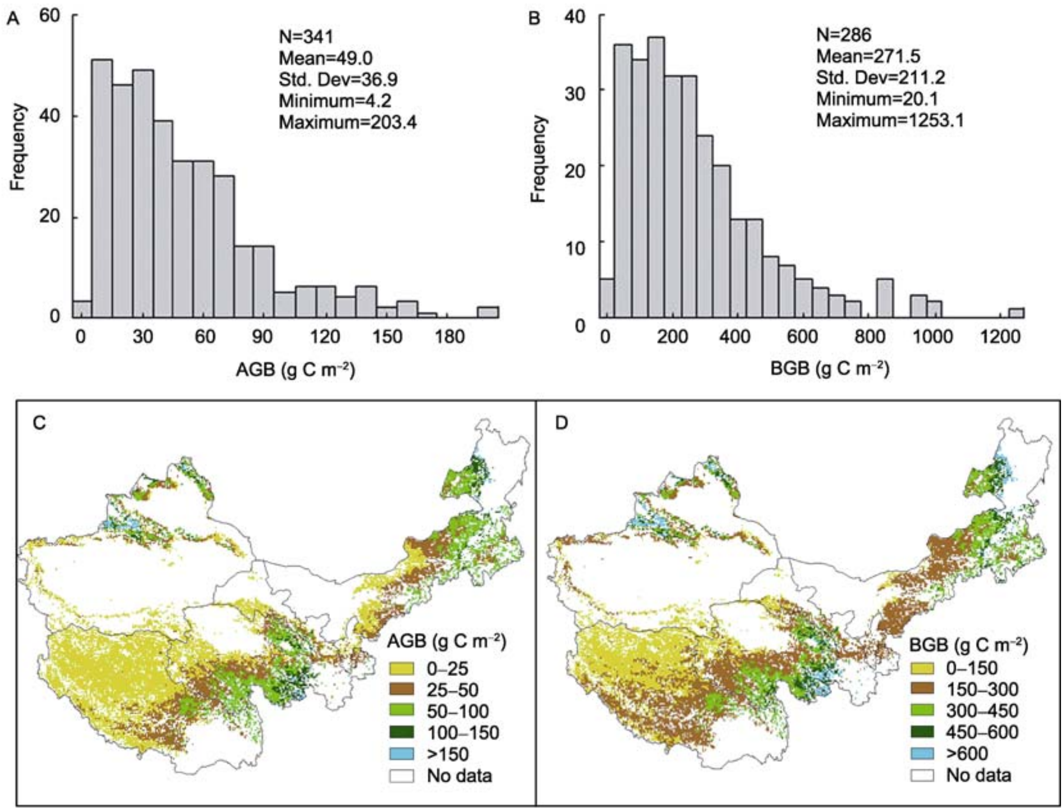

Figure 3 Frequency distributions of (A) above-ground biomass (AGB) and (B) below-ground biomass (BGB) based on field measurements during 2001–2005, and spatial distributions of AGB (C) and BGB (D) based on remote sensing data during the 2000s.

Table 1 Biomass densities and C stocks in northern China's grasslands for different time periods[a)]

Grassland type	Area (10^4 km^2)	AGB (g C m^{-2})					AGB stock (Tg C)				
		1982–1986	1987–1991	1992–1996	1997–2001	2002–2006	1982–1986	1987–1991	1992–1996	1997–2001	2002–2006
Ds	18.31	25.2	26.3	27.2	26.7	26.4	4.6	4.8	5.0	4.9	4.8
Ts	38.52	46.1	49.8	50.7	48.8	50.4	17.8	19.2	19.5	18.8	19.4
Ms	7.64	93.6	100.7	101.2	98.7	97.6	7.2	7.7	7.7	7.5	7.5
Mm	2.29	111.6	123.2	122.6	119.6	110.6	2.6	2.8	2.8	2.7	2.5
As	70.81	20.1	20.7	20.8	21.4	20.6	14.2	14.7	14.7	15.1	14.6
Am	58.73	44.8	46.9	47.3	48.5	48.7	26.3	27.5	27.8	28.5	28.6
Total	196.30	37.0	39.1	39.5	39.5	39.5	72.7	76.7	77.5	77.6	77.4
		BGB (g C m^{-2})					BGB stock (Tg C)				
Ds	18.31	180.2	185.3	187.6	187.6	185.9	33.0	33.9	34.4	34.4	34.0
Ts	38.52	281.0	297.0	297.0	293.3	300.2	108.2	114.4	114.4	113.0	115.6
Ms	7.64	479.2	506.3	500.7	498.4	495.9	36.6	38.7	38.3	38.1	37.9
Mm	2.29	538.3	581.0	568.8	568.1	530.1	12.3	13.3	13.0	13.0	12.1
As	70.81	153.4	156.7	155.1	160.3	155.7	108.6	111.0	109.9	113.5	110.3
Am	58.73	272.7	282.0	279.4	289.1	289.6	160.2	165.6	164.1	169.8	170.1
Total	196.30	233.8	243.0	241.5	245.4	244.6	458.9	476.9	474.0	481.7	480.1
		TB (g C m^{-2})					TB stock (Tg C)				
Ds	18.31	205.4	211.6	214.8	214.4	212.3	37.6	38.7	39.3	39.3	38.9
Ts	38.52	327.2	346.8	347.7	342.1	350.6	126.0	133.6	133.9	131.8	135.0
Ms	7.64	572.8	607.0	601.9	597.1	593.5	43.8	46.4	46.0	45.6	45.3
Mm	2.29	650.0	704.2	691.4	687.7	640.7	14.9	16.1	15.8	15.7	14.7
As	70.81	173.5	177.5	175.9	181.7	176.4	122.8	125.7	124.6	128.6	124.9
Am	58.73	317.5	328.9	326.7	337.6	338.3	186.5	193.2	191.9	198.2	198.7
Total	196.30	270.8	282.0	280.9	284.9	284.0	531.6	553.7	551.5	559.3	557.5

a) AGB, above-ground biomass; BGB, below-ground biomass; TB, total biomass; Ds, desert steppe; Ts, temperate steppe; Ms, mountain steppe; Mm, mountain meadow; As, alpine steppe; Am, alpine meadow.

trends occurred in the northern parts of the Tibetan Plateau, Inner Mongolia, and Xinjiang. Overall, biomass increased significantly across nearly 20.5% of the study area and significantly declined across 3.7% of the study area. Biomass did not change significantly during 1982–2006 in 75.8% of the study area (Figure 4A).

The AGB in northern China's grasslands exhibited a weak increasing trend (r^2=0.17, P=0.042, n=25) (Figure 4B), and AGB C stock increased from 72.4 Tg C in 1982 to 78.2 Tg C in 2006, with a mean annual increase of 0.2 Tg C. This increase was mainly driven by low biomass C density during 1982–1987. However, biomass C density from 1988–2006 had large interannual fluctuations, and the changing slope was not significantly different from zero (r^2=0.02, P=0.593, n=19). Biomass C density in four temperate grasslands (i.e., desert steppe, typical steppe, meadow steppe, and mountain meadow) also did not exhibit significant changing patterns (Figure 5A–D). By contrast, biomass C density in alpine meadow showed a significant increasing trend (r^2=0.36, P=0.002, Figure 5F).

2.3 Effects of climatic variables on biomass C

To understand the responses of biomass C to climate change, we analyzed changes in seasonal climatic variables and their relationships with AGB during 1982–2006 (Figure 6, Table 2). During the 25 years, mean January–July temperature significantly increased by 0.06°C yr^{-1} ($r^{2=}$0.75, P<0.01, Figure 6A). There was large interannual variation ($r^{2=}$0.02, P>0.05), alternating between drought and wet years, in average January–July precipitation for the entire grassland region (Figure 6B). Coupled with interannual variations of temperature and precipitation, AGB showed a similar changing trend (except biomass in 1989 and 1994). In other words, low biomass occurred in cooler and drier years and high biomass occurred in warmer and wetter years (Figure 6B).

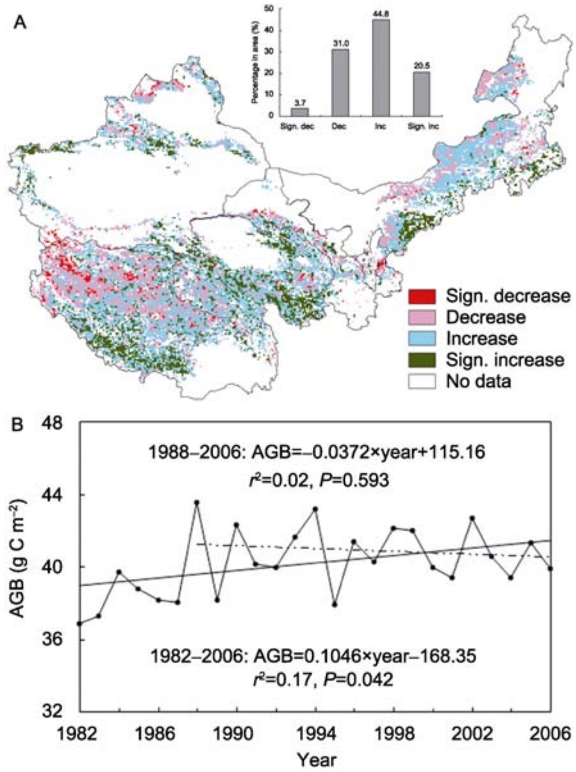

Figure 4 Spatial distribution of the significance of changing trends in above-ground biomass (AGB) over a period of 25 years (1982–2006) (A), and a time series of AGB for 1982–2006 (B) (Dashed line: 1988–2006; Solid line: 1982–2006). The legend in A shows the proportion of grassland in the total study area that significantly decreased, decreased but not significantly, increased but not significantly, and significantly increased.

Ordinary least squares (OLS) regression analysis indicated that AGB was positively correlated with January–July precipitation (r^2=0.22, P=0.016) and mean January–July temperature (r^2=0.24, P=0.012) (Table 2). However, caution is needed when interpreting these results because of the assumption of stationary data in the OLS regression model and the stochastic trends in the NDVI and temperature datasets [25]. Because the positive trends in both air temperature and biomass are likely to strengthen the correlation between them, we used a detrending method [25] to reanalyze the relationship between biomass and temperature for the 25-year time series. The weaker correlation (r^2=0.10, P=0.145) between biomass data and detrended climate supports the assumption that positive trends in these two datasets caused a higher correlation between them.

Moreover, the influence of precipitation on biomass differed among grassland types, with significantly positive correlations occurring in arid and semi-arid temperate grasslands (P<0.05) and insignificant biomass-precipitation relationships occurring in other grassland types (P>0.05). In most grassland regions, biomass did not increase during the 25-year period. Although AGB in alpine meadow was significantly correlated with mean January–July temperature (r^2=0.31, P=0.004, Table 2), the detrended analysis indicated a weaker correlation between these two variables (r^2=0.04, P=0.319).

3 Discussion

3.1 Quantifying biomass C in northern China's grasslands

Remote sensing data have been widely used to evaluate vegetation activity at large spatial scales [5,31,32], particularly for grassland biomes [33]. Compared with previous estimations based on mean biomass values of different vegetation types [15,16,18,19], remote sensing data could be used to describe the spatial distribution of biomass and thus provide more accurate estimations for C stock [34]. In this study, we obtained ground-based AGB and BGB data at a large scale and estimated biomass C stock across northern China grasslands based on an empirical relationship between community-level biomass and an NDVI dataset. This estimate would reduce uncertainty due to the spatial disparity between ground-based measurements and remote sensing observations [3]. Moreover, satellite-based measurements of northern China's grasslands provide a comprehensive picture of the temporal dynamics of biomass C over the 25-year period.

Quantifying below-ground C stocks is critical for C estimation at the regional scale. This is particularly essential for addressing biomass partitioning patterns in grassland ecosystems because of the large proportion of root biomass [35,36]. As shown by this study, more than 85% of biomass occurred below-ground. Thus, reliable BGB data are urgently needed to precisely evaluate the role of grassland biomes in the regional C balance [7]. However, limited BGB data may constrain our understanding of the role of potential C sequestration in grasslands. The *R/S* ratios that have been widely used to estimate BGB may be unreliable due to the difficulties in sampling roots and the low numbers of reported data [11,35]. A recent analysis of global *R/S* ratios by Mokany *et al*. [35] indicated that 62% of 786 reported datasets were unreliable, and estimates of root biomass across global grasslands declined after the unreliable observations were excluded from analysis. In contrast, a recent study by Wang *et al*. [37] showed that at the individual level more biomass was distributed above-ground than below-ground [37], and fewer *R/S* ratios were reported at the community level. Therefore, reliable data on R/S ratios, or the relationship between AGB and BGB [36, 38], based on large field investigations are necessary to precisely estimate biomass C stock in grasslands. By this study, the relationship between AGB and BGB could be well fitted by a power function. Using this partitioning relationship and the relationship between AGB and NDVI, we calculated biomass C stock across northern China's grasslands, which could potentially reduce the uncertainty in below-ground C stock estimation.

3.2 Size of biomass C stock in China's grasslands

The biomass C stocks estimated in this study are largely different from earlier estimates (Table 3). We attribute these differences to the different data sources used among the studies. For example, the grassland area used by Fang *et al.* [17] (430.7×10^8 ha including savannas and grasslands in desert areas) derived from land use resources was larger than that used in this study (196.3×10^8 ha). Thus, their estimate of biomass C stock was approximately double our estimate. Also, Ni [15,16] used averaged C density data from global ecosystems [39] to estimate biomass C stock, which might lead to an overestimate because the vegetation classification systems used may not be suitable for China' s grasslands [18]. Large differences among various studies could also be derived from unreliable BGB data. Fan *et al.* [18] gathered 146 published records and sampled 78 field sites in China's grasslands, which resulted in an estimated biomass C stock that was nearly four times the value in our study (2435 vs. 558 Tg C). BGB C density in their study was particularly higher than that in the current study (1209.7 vs. 244.6 g C m^{-2}). *R/S* ratios reported in previous studies may contain large errors and render root biomass estimates highly unreliable due to methodological limitations in root sampling. Thus, compared with previous studies, our assessment of grassland biomass C stock using the allometric relationship between AGB and BGB and a statistical model between AGB and satellite data can potentially provide a more reliable regional C estimate.

3.3 Effects of climatic factors on biomass change

Using an NDVI dataset from 1982 to 1999, several studies have indicated that terrestrial ecosystems in middle and high latitudes of the Northern Hemisphere have functioned as C sinks for atmospheric CO_2 [4,5,11]. For example, Piao *et al.* [11] observed that AGB C stock in China's grasslands increased by 1.01 Tg C yr^{-1} during 1982–1999. However,

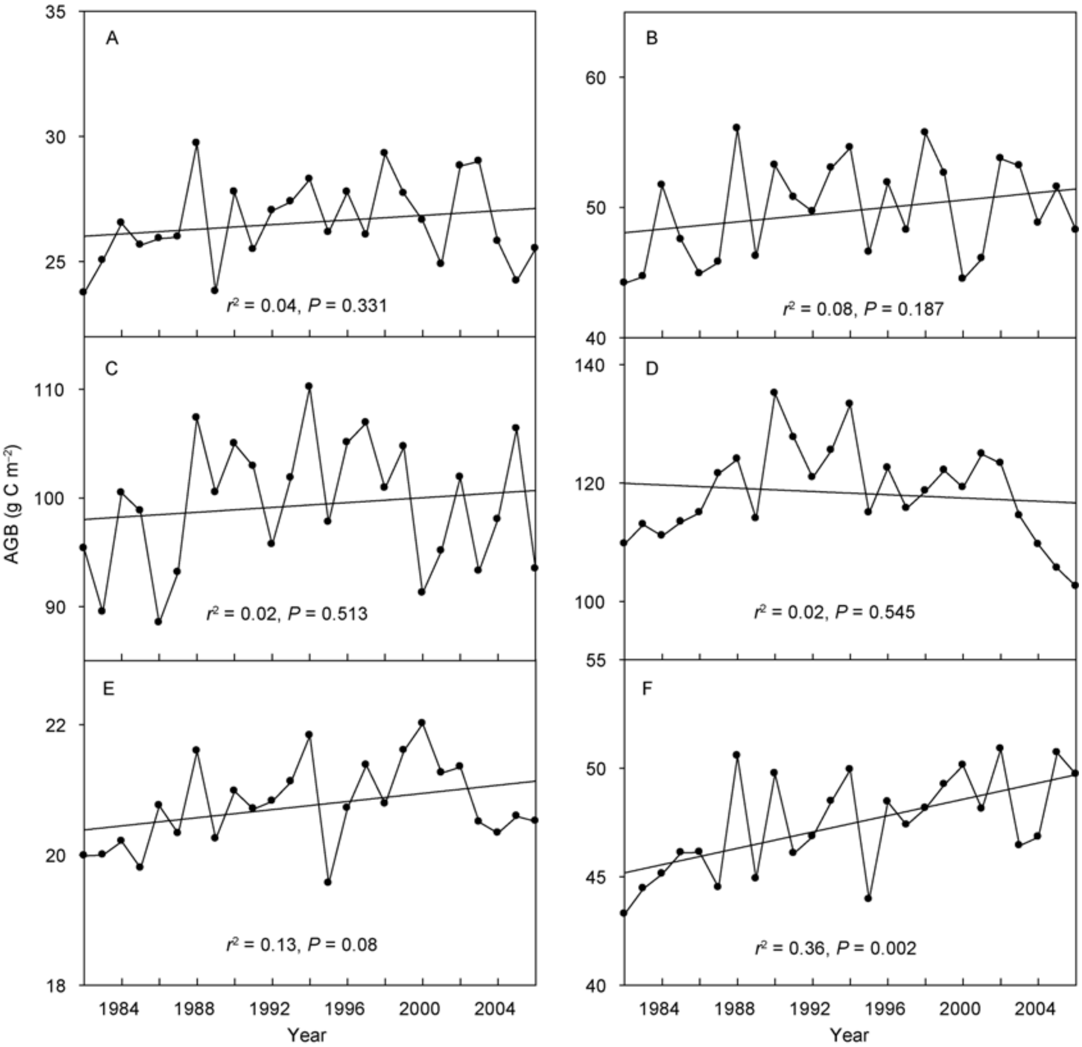

Figure 5 Trends in above-ground biomass (AGB) from 1982–2006 for different grassland types in northern China. A, desert steppe; B, typical steppe; C, meadow steppe; D, mountain meadow; E alpine steppe; F, alpine meadow.

using a longer period of NDVI data from 1982–2006, our results show a slight increase of 0.2 Tg C yr^{-1} over the past 25 years. The AGB time series covering large grassland regions also showed insignificant variation patterns during the 25-year period. Long-term records from recent studies in temperate *Leymus chinensis* steppe in Inner Mongolia

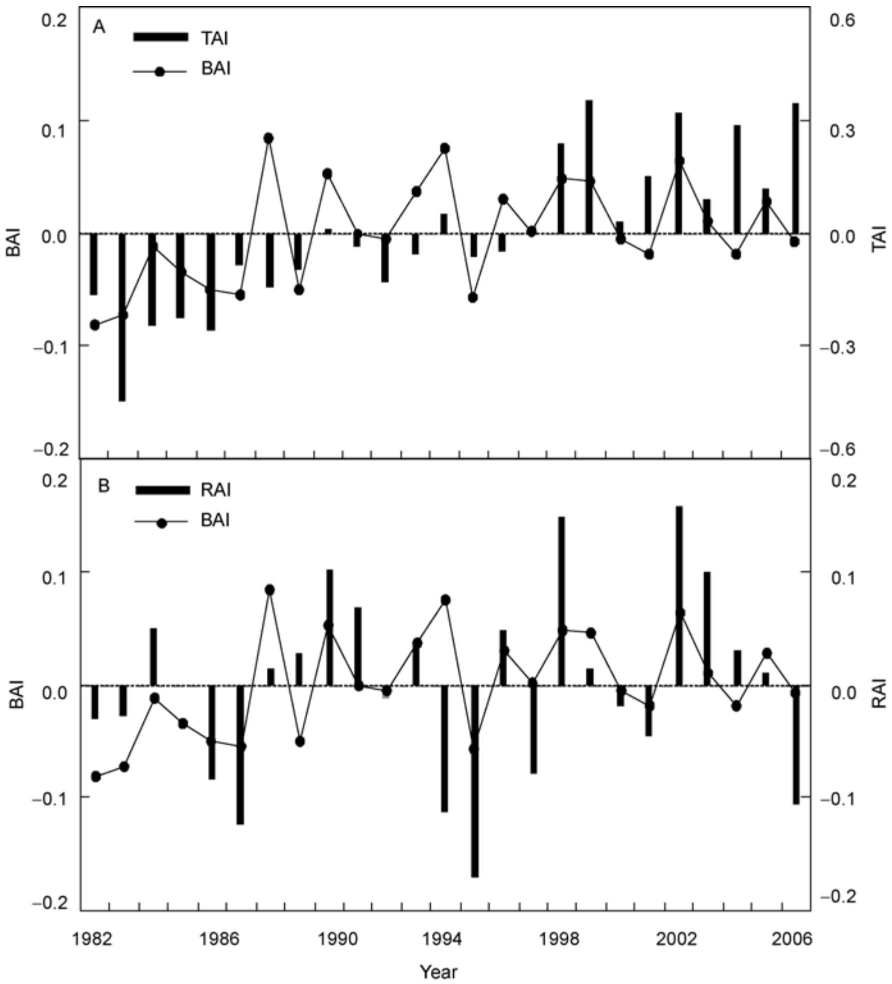

Figure 6 Coupled patterns between the above-ground biomass (AGB) anomaly index (BAI) and the mean temperature anomaly index (TAI) (January–July) during 1982–2006 (A) or the rain anomaly index (January–July) (RAI) (B). The AGB anomaly index was calculated from the followed equation: BAI=(AGBi–AGBl)/AGBl; where AGBi is individual year AGB and AGBl is the mean, long-term AGB value during 1982–2006; TAI and RAI were calculated by the same method.

Table 2 Trends of climate variables (mean temperature and precipitation from January to July) and the relationship between AGB and climate variable anomalies during 1982–2006[a)]

Grassland type	*T*-trend		*P*-trend		$Y=a+bx+e$		$Y=a+b_1x+b_2\text{time}+e$	$\Delta Y=a+b\Delta x+e$	
	slope	r^2	slope	r^2	r^2_T	r^2_P	r^2_{DT}	r^2_P	r^2_T
Ds	0.09	0.63**	0.36	0.02	0.01	0.69**	0.01	0.09	0.63**
Ts	0.07	0.49**	−0.21	0.00	0.04	0.51**	0.00	0.07	0.49**
Ms	0.06	0.31**	−1.09	0.04	0.03	0.15	0.01	0.06	0.31**
Mm	0.05	0.20**	1.41	0.15	0.01	0.07	0.00	0.05	0.20**
As	0.07	0.60**	0.70	0.09	0.11	0.05	0.01	0.07	0.60**
Am	0.07	0.55**	0.24	0.01	0.31**	0.00	0.04	0.07	0.55**
Total	0.07	0.75**	0.26	0.02	0.24*	0.22*	0.10	0.07	0.75**

a) *T*, mean January–July temperature averaged by all pixels in the entire grassland region from 1982–2006; *P*, January–July precipitation averaged by all pixels; DT, detrended temperature; Y, mean AGB by all pixels in the entire grassland region; $Y=a+bx+e$, ordinary least squares (OLS) regression model; $Y=a+b_1x+b_2\text{time}+e$, the detrended regression model including a deterministic variable. **, Statistically significant at the 0.01 level; *, statistically significant at the 0.05 level.

Table 3 Comparison of biomass C density and C stock estimated by different studies for northern China's grasslands[a)]

Author	Area (10^4 km^2)	Biomass density (g C m^{-2})			Biomass C stock (Tg C)			Reference
		AGB	BGB	Total	AGB	BGB	Total	
Fang *et al*. (1996)	430.7	NA	NA	236.8	NA	NA	1020	[17]†
Ni (2001)	220.1	NA	NA	1208.5	NA	NA	2660	[15]‡
Ni (2002)	189.2	NA	NA	1020.0	NA	NA	1930	[16]*
Piao *et al*. (2007)	227.8	41.5	306.6	348.1	94.6	698.4	793	[11]§
Fan *et al*. (2008)	189.2	77.3	1209.7	1287.0	146.3	2288.7	2435	[18]§
Ma *et al*. (2010)	196.3	39.5	244.6	284.0	77.4	480.1	558	This study

a) NA, no available data; †, including meadow steppe, typical steppe, desert steppe, alpine steppe, tussock, savannas, and grasslands in desert areas; ‡, arid shrublands/steppe, temperate savannas, temperate desert steppe, alpine steppe, alpine meadows, and swamps; *, temperate meadow-steppe, temperate steppe, temperate desert-steppe, alpine meadow-steppe, alpine steppe, alpine desert-steppe, mountain meadow, and alpine meadow; §, temperate meadow-steppe, temperate steppe, temperate desert-steppe, alpine meadow-steppe, alpine steppe, alpine desert-steppe, mountain meadow, and alpine meadow.

(1982–2004) [40] and in alpine grassland on the Tibetan Plateau [41] support constant interannual variation in AGB.

Rainfall has been widely reported to be the primary driver of interannual biomass variation in grassland ecosystems [42–47]. In this study, the year to year biomass pattern was well coupled with interannual variation of January–July precipitation, which explained the fluctuating pattern of AGB in northern China grasslands over the past 25 years. Our results are supported by a 24-year biomass record collected in temperate grassland communities in Inner Mongolia [29], and long-term biomass records obtained in north and south grasslands also demonstrate similar effects of seasonal precipitation on AGB [26,48]. The strong relationship between precipitation and biomass could be due to soil water availability, which is most important in promoting plant production in dry grassland biomes [49].

A growing archive of satellite observations reveals a close coupling between vegetation production and increasing temperature [5,50]. Climatic records in this study also indicate that most regions in northern China have experienced significant warming, and OLS regression indicates a statistical correlation between AGB and mean January–July temperature. Caution is needed in interpreting this influence of warming on biomass in grasslands because the positive trends in both AGB and temperature probably enhance correlation between these two variables. As shown in this study, the r_{DT} values were smaller after temperature and biomass data were detrended. This indicates that the warming climate in northern China may not have promoted a larger biomass C stock in these grassland ecosystems.

4 Concluding remarks

Based on a regional biomass survey during 2001–2005 and a remote sensing dataset over 1982–2006, we investigated biomass C stocks and their changes from 1982–2006 across the grasslands of northern China. Total biomass stock was estimated at 557.5 Tg C, with 58% of the total biomass C occurring in Tibetan alpine grasslands. Biomass C stock increased slightly at a rate of 0.2 Tg C yr^{-1} over the 25-year period, but no significant change has occurred since the late 1980s. Interannual variation of biomass was mainly driven by January–July precipitation rather than by the increased temperature. However, biomass in arid grasslands (i.e., desert steppe and typical steppe) showed significant associations with precipitation, while biomass in humid grasslands (i.e., alpine meadow) was positively correlated with mean January–July temperatures. These results suggest that grassland ecosystems may respond differently to future climate change.

We thank members of the Peking University Sampling Teams of the Tibetan Plateau (2001–2004), the Inner Mongolia Autonomous Region (2002–2005), and the Xinjiang Uyghur Autonomous Region (2004) for assistance with field investigation. This work was supported by the National Natural Science Foundation of China (Grant Nos. 90711002 and 90211016).

1 Schlesinger W H. Carbon balance in terrestrial detritus. Ann Rev Ecol Syst, 1977, 8: 51–81
2 Cao M K, Woodward F I. Net primary and ecosystem production and carbon stocks of terrestrial ecosystems and their responses to climate change. Global Change Biol, 1998, 4: 185–198
3 Turner D P, Ritts W D, Cohen W B, *et al*. Site-level evaluation of satellite-based global terrestrial gross primary production and net primary production monitoring. Global Change Biol, 2005, 11: 666–684
4 Myneni R B, Keeling C D, Tucker C J, *et al*. Increased plant growth in the northern high latitudes from 1981 to 1991. Nature, 1997, 386: 698–702
5 Schimel D S, Emanuel W, Rizzo B, *et al*. Continental scale variability in ecosystem processes: Models, data, and the role of disturbance. Ecol Monogr, 1997, 67: 251–271
6 Hall D O, Scurlock J M O. Climate Change and Productivity of Natural Grasslands. Ann Bot-London, 1991, 67: 49–55
7 Scurlock J M O, Hall D O. The global carbon sink: a grassland perspective. Global Change Biol, 1998, 4: 229–233
8 Sala O E, Lauenroth W K, Burke I. Carbon budgets of temperate grasslands and the effects of global change. In: Breymeyer A I, Hall D O, Melillo J M, *et al*. eds. Global Change: Effects on Coniferous Forests and Grasslands. New York: John Wildy & Sons Ltd, 1996

9 Scurlock J M O, Johnson K, Olson R J. Estimating net primary productivity from grassland biomass dynamics measurements. Global Change Biol, 2002, 8: 736–753

10 Parton W J, Scurlock J M O, Ojima D S, *et al*. Impact of climate-change on grassland production and soil carbon worldwide. Global Change Biol, 1995, 1: 13–22

11 Piao S L, Fang J Y, Zhou L M, *et al*. Changes in biomass carbon stocks in China's grasslands between 1982 and 1999. Global Biogeochem Cy, 2007, 21: 1–10

12 Jones M B, Donnelly A. Carbon sequestration in temperate grassland ecosystems and the influence of management, climate and elevated CO2. New Phytol, 2004, 164: 423–439

13 Department of Animal Husbandry and Veterinary Medicine, and General Station of Animal Husbandry and Veterinary Medicine of the Ministry of Agriculture of China. Rangeland resources of China (in Chinese). Beijing: China Agriculture Science and Technology Press, 1996

14 Bai Y F, Wu J G, Xing Q, *et al*. Primary production and rain use efficiency across a precipitation gradient on the Mongolia plateau. Ecology, 2008, 89: 2140–2153

15 Ni J. Carbon storage in terrestrial ecosystems of China: estimates at different spatial resolutions and their responses to climate change. Clim Change, 2001, 49: 339–358

16 Ni J. Carbon storage in grasslands of China. J Arid Enviorns, 2002, 50: 205–218

17 Fang J Y, Liu G H, Xu S L. Carbon reservoir of terrestrial ecosystem in Chin. In: Wang G C, Wen Y P, eds. Monitoring and Relevant Process of Greenhouse Gas Concentration and Emission (in Chinese). Beijing: China Environmental Science Publishing House, 1996

18 Fan J W, Zhong H P, Harris W, *et al*. Carbon storage in the grasslands of China based on field measurements of above- and below-ground biomass. Clim Change, 2008, 86: 375–396

19 Ma W H, Han M, Lin X, *et al*. Carbon storage in vegetation of grasslands in Inner Mongolia (in Chinese). J Arid Land Resour Environ, 2006, 20: 192–195

20 Ma W H, Yang Y H, He J S, *et al*. Above- and belowground biomass in relation to environmental factors in temperate grasslands, Inner Mongolia. Sci China Ser C-Life Sci, 2008, 51: 263–270

21 Titlyanova A A, Romanova I P, Kosykh N P, *et al*. Pattern and process in above-ground and below-ground components of grassland ecosystems. J Veg Sci, 1999, 10: 307–320

22 Editorial board of vegetation map of China, Chinese Academy of Sciences. Vegetation Atlas of China (1: 1,000,000) (in Chinese). Beijing: China Science and Technology Press, 2001

23 Vogt K A,Vogt D J, Palmiotto P A, *et al*. Review of root dynamics in forest ecosystems grouped by climate, climatic forest type and species. Plant Soil, 1996, 187: 159–219

24 Tucker C J, Slayback D A, Pinzon J E, *et al*. Higher northern latitude Normalized difference vegetation index and growing season trends from 1982 to 1999. Int J Biometeorol, 2001, 45: 184–190

25 Zhou L M, Tucker C J, Kaufmann R K, *et al*. Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. J Geophys Res, 2001, 106(D17): 20069–20083

26 Holben B N. Characteristics of maximum value composite images from temporal AVHRR. Int J Remote Sens, 1986, 7: 1417–1434

27 Fang J Y, Piao S L, He J S, *et al*. 2004. Increasing terrestrial vegetation activity in China, 1982-1999. Sci China Ser C-Life Sci, 2004, 47: 229–240.

28 Lauenroth W K, Sala O E. Long-Term forage production of North-American shortgrass steppe. Ecol Appl, 1992, 2: 397–403

29 Bai Y F, Han X G, Wu J G, *et al*. Ecosystem stability and compensatory effects in the Inner Mongolia grassland. Nature, 2004, 431: 181–184

30 Piao S L, Fang J Y, Zhou L M, *et al*. Interannual variations of monthly and seasonal normalized difference vegetation index (NDVI) in China from 1982 to 1999. J Geophys Res, 2003, 108, doi: 10.1029/2002JD002848

31 Running S W, Nemani R R, Heinsch F A, *et al*. A continuous satellite-derived measure of global terrestrial primary production. Bioscience, 2004, 54: 547–560

32 Turker C J, Sellers P J. Satellite remote sensing of primary production. Int J Remote Sens, 1986, 7: 1395–1416

33 Jobbàgy E G, Sala O E, Paruelo J M. Patterns and controls of primary production in the Patagonian steppe: A remote sensing approach. Ecology, 2002, 83: 307–319

34 Yang Y H, Fang J Y, Pan Y D, *et al*. Aboveground biomass in Tibetan grasslands. J Arid Enviorn, 2009, 73: 91–95

35 Mokany K, Raison R J, Prokushkin A S. Critical analysis of root: shoot ratios in terrestrial biomes. Global Change Biol, 2006, 11: 1–13

36 Yang Y H, Fang J Y, Ji C J, *et al*. Above- and belowground biomass allocation in Tibetan grasslands. J Veg Sci, 2009, 20: 177–184

37 Wang L, Niu K, Yang Y H, *et al*. Patterns of above- and belowground biomass allocation in China's grasslands: evidence from individual-level observations. Sci China Life Sci, 2010, 53: 851–857

38 Yang Y H, Fang J Y, Ma W H, *et al*. Large-scale pattern of biomass partitioning across China's grasslands. Global Ecol Biogeogr, 2010, 19: 268–277

39 Olson R J, Watts J A, Allison L J. Carbon in live vegetation of major world ecosystem. Oak Ridge National Laboratory, Oak Ridge, 1983, 50–51

40 Ma W H, Liu Z L, Wang Z H, *et al*. Climate change alters interannual variation of grassland aboveground productivity: evidence from a 22-year measurement series in the Inner Mongolian grassland. J Plant Res, DOI: 10.1007/s10265-009-0302-0

41 Zhou H K, Zhou L, Zhao X Q, *et al*. Stability of alpine meadow ecosystem on the Qinghai-Tibetan Plateau. Chinese Sci Bull, 2006, 51: 320–327

42 Fang J Y, Piao S L, Zhou L, *et al*. Precipitation patterns alter growth of temperate vegetation. Geophys Res Lett, 2005, 32, L21411, doi: 10.1029/2005GL024231

43 Yang Y H, Fang J Y, Ma W H, *et al*. Relationship between variability in aboveground net primary production and precipitation in global grasslands. Geophys Res Lett, 2008, 35, doi: 10.1029/2008GL035408

44 Fang J Y, Yang Y H, Ma W H, *et al*. Biomass carbon and soil organic carbon stocks and their changes in China's grasslands, Sci China Life Sci, 2010, 53: 757–765

45 Briggs J M, Knapp A K. Interannual variability in primary production in tallgrass prairie-climate, soil-moisture, topographic position, and fire as determinants of aboveground biomass. Am J Bot, 1995, 82: 1024–1030

46 Fang J Y, Piao S L, Tang Z Y, *et al*. Interannual variability in net primary production and precipitation. Science, 2001, 293: U1–U2

47 Knapp A K, Fay P A, Blair J M, *et al*. Rainfall variability, carbon cycling, and plant species diversity in a mesic grassland. Science, 2002, 298: 2202–2205

48 McCulley R L, Burke I C, Nelson J A, *et al*. Regional patterns in carbon cycling across the Great Plains of North America. Ecosystems, 2005, 8: 106–121

49 Lauenroth W K, Sala O E. Long-Term forage production of North-American shortgrass steppe. Ecol Appl, 1992, 2: 397–403

50 Tucker C J, Slayback D A, Pinzon J E, *et al*. Higher northern latitude normalized difference vegetation index and growing season trends from 1982 to 1999. Int J Biometeorol, 2001, 45: 184–19