# Changes in biomass carbon stocks in China's grasslands between 1982 and 1999

Shilong Piao,[1] Jingyun Fang,[1] Liming Zhou,[2] Kun Tan,[1] and Shu Tao[1]

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[1] Terrestrial ecosystems in the northern latitudes are significant carbon sinks for atmospheric $CO_2$; however, few studies come from grassland ecosystems. Using national grassland resource inventory data, NDVI (normalized difference vegetation index) time series data set, and a satellite-based statistical model, this study identifies changes in the size and distribution of aboveground biomass carbon (C) stocks for China's grasslands between 1982 and 1999. Biomass C stocks averaged 145.4 Tg C for the study period for a total area of $334.1 \times 10^4$ km$^2$, and have increased by 17.7 Tg C (1 Tg = $10^{12}$ g) from 136.3 Tg C in the early 1980s (average of 1982–1984) to 154.0 Tg C in the late 1990s (average of 1997–1999), with an annual increase of 0.7%. This suggests that the aboveground biomass of China's grasslands may have functioned as the C sinks in the past 2 decades. Assuming a constant ratio of aboveground to belowground biomass for each grassland type, we also estimated belowground biomass C and its change over time for each grassland type, generating an average estimate of 1051.1 Tg C for the total (aboveground and belowground) biomass C and an annual increase of 126.67 Tg C for China's grasslands over the 18 years. However, the accuracy of these estimates has limitations due primarily to uncertainties in estimates of belowground C, biomass inventories, and satellite time series data sets.

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## 1. Introduction

[2] Terrestrial ecosystems of the Northern Hemisphere have been a significant carbon (C) sink in the past several decades [*Schimel et al.*, 2001], but such evidence comes mainly from forest ecosystems [*Pacala et al.*, 2001; *Myneni et al.*, 2001; *Fang et al.*, 2001, 2005; *Goodale et al.*, 2002; *Shvidenko and Nilsson*, 2002]. Several studies have suggested that the widely distributed grasslands in the northern latitudes may be a potential C sink [*Tate et al.*, 1995; *Scurlock and Hall*, 1998; *Batjes*, 1998; *Janssens et al.*, 2003; *Jacobs et al.*, 2003], but the evidence is very limited [*Hall and Scurlock*, 1991; *Hall et al.*, 1995]. Grassland is one of the most widespread vegetation types worldwide, occupying about 1/5 of the world's land surface [*Hall et al.*, 1995; *Scurlock and Hall*, 1998]. Accordingly, accurate evaluation of the global C cycle requires a precise understanding of the magnitude and spatial distributions of grasslands' C stocks and their changes.

[3] Grassland covers nearly 1/3 of China's total territory and is experiencing notable effects of anthropogenic activities [*Department of Animal Husbandry Veterinary*, 1996; *Chen and Wang*, 2000]. Quantifying changes in China's grassland biomass C stocks is critical not only for precise evaluation of spatial distribution and changes of China's terrestrial C stocks, but also for the sustainable use of China's grassland resources [*Ni*, 2002].

[4] Developments in the field of remote sensing have greatly increased the opportunity for monitoring and detecting vegetation and land cover changes [*Defries and Townshend*, 1994; *Myneni et al.*, 2001; *Schino et al.*, 2003]. The normalized difference vegetation index (NDVI), which measures the contrast between red and near-infrared reflection of solar radiation, can reflect vegetation photosynthetic activity, and is therefore often used to estimate vegetation biomass [*Paruelo et al.*, 1997, 2004; *Paruelo and Lauenroth*, 1998; *Myneni et al.*, 2001; *Dong et al.*, 2003; *Piao et al.*, 2005a]. Compared with its application in the estimation of forest biomass, NDVI data have more potential in the estimation of leaf area index (LAI) and thus green biomass of grasslands. This is because the NDVI does not saturate in most grasslands due to a low LAI, as it does in dense forest canopy [*Asner et al.*, 2004]. Accordingly, the application of satellite data to the estimation of grassland biomass and net primary production (NPP) has been conducted worldwide [e.g., *Paruelo et al.*, 1997, 2004; *Holm et al.*, 2003; *Di Bella et al.*, 2004; *Brogaard et al.*, 2005].

[5] Several studies have documented a positive relationship between NDVI derived from National Oceanic and

[1]Department of Ecology, College of Environmental Science and Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing, China.

[2]School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia, USA.


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Atmospheric Administration's Advanced Very High Resolution Radiometer (NOAA/AVHRR) and either biomass or aboveground NPP for different grassland ecosystems [e.g., *Burke et al.*, 1991; *Prince*, 1991; *Hobbs*, 1995; *Paruelo et al.*, 1997, 2004; *Holm et al.*, 2003; *Di Bella et al.*, 2004]. In this study, we are to integrate China's grassland resource inventory and NDVI time series data to construct the relationship between the AVHRR-NDVI and aboveground biomass for China's grasslands and then to estimate magnitude, distribution and changes of the biomass C stocks for China's grassland between 1982 and 1999.

## 2. Data Sets and Methods

### 2.1. Grassland Resource Inventory and Grassland Map

[6] China has conducted the first national grassland resource inventory from 1981 to 1988. The inventory aimed at investigating types, distribution, area, and forage yield of grasslands and carrying capacity of rangelands all over China [*Department of Animal Husbandry Veterinary*, 1996]. The field measurement relevant with forage yield followed the following standards [*North Region Office for Grassland Resources Inventory*, 1986; *Department of Animal Husbandry Veterinary*, 1996].

#### 2.1.1. Definition of Grassland

[7] The grassland inventoried refers to the primary and secondary grasslands with a vegetation cover of $\geq$5%, shrubby grasslands with a shrub cover of <40%, alpine thickets suitable for grazing, and seeded grasslands.

#### 2.1.2. Locating Inventory Site

[8] Topographical maps with a scale of 1:50,000, 1:100,000 and 1:200,000 (depending on grassland types) were used to locate inventory sites. The resolution of the inventory sites was set at 50–100 km$^2$ across all the inventoried area ($\sim$95% of the country territory and >2000 counties).

#### 2.1.3. Plot Size and Data Record

[9] Each inventory site contained 4–10 plots of varying size depending on grassland types: 1 m$^2$ for typical grasslands, 4 m$^2$ for desert grasslands, 0.5 m$^2$ for meadows, and 100 m$^2$ for tall herbaceous and shrubby grasslands. For each plot, community height, coverage, abundance, and life form were recorded for dominant and subdominant species.

#### 2.1.4. Measurement of Forage Yield

[10] Fresh forage weight was measured in the field at the period with annual peak standing yield with >3 replicates for each plot, and air-dried and weighed in the lab.

#### 2.1.5. Data Error and Representative

[11] The error of area and forage yield was controlled at <1% and <10%, respectively. The inventoried grassland type required high representative: for each county, at least 2 inventory sites for each grassland type and at least 3 plots for each grassland type were surveyed.

[12] The grassland resource inventory has provided a powerful data source for estimating China's grassland biomass C stocks. The aboveground biomass data used in the present study were documented from forage yield reported by *Department of Animal Husbandry Veterinary* [1994] which recorded detailed information on area, forage yield, and carrying capacity of rangelands for each grassland type for each province.

[13] Information on the distribution of grassland types was extracted from the Map of Grassland Resources in China at 1: 4, 000, 000 scale [*Commission for Integrated Survey of Natural Resources*, 1996]. On the basis of this map, China's grasslands were grouped into 17 types [*Department of Animal Husbandry Veterinary*, 1996; *Chen and Fischer*, 1998]. Figure 1 and Table 1 present the details for these grassland types.

### 2.2. NDVI and Climate Data Set

[14] The NDVI data used were 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) Land data set, at a spatial resolution of 8 $\times$ 8 km$^2$ and 15-day interval, for the period January 1982 to December 1999 [*Tucker et al.*, 2001; *Zhou et al.*, 2001]. The data set has been modified to minimize the effects of volcanic eruptions, solar zenith angle, sensor degradation and other factors, and thus has been carefully optimized [*Slayback et al.*, 2003] and been widely used for large-scale studies of ecological processes [*Myneni et al.*, 2001; *Tucker et al.*, 2001; *Zhou et al.*, 2001; *Fang et al.*, 2003; *Piao et al.*, 2003]. The NDVI in sparsely vegetated areas is influenced by the spectral characteristics of the soil, and the signal associated with the vegetation can be difficult to separate from that of the background [*Huete*, 1989]. Hence, similar to *Zhou et al.* [2001] and *Myneni et al.* [2001], we only analyzed areas with annual mean NDVI > 0.1 unit in this study.

[15] In order to match remote sensing data with the average grassland forage yield obtained from the grassland resource inventory, we first converted the provincial map of China and the grassland map of China to a grid format at 8 $\times$ 8 km$^2$ resolution from original coverage format using ARCINFO 7.1.1 software. We then overlaid the NDVI images during the period of 1982–1988 over a provincial map of China and the grassland map of China, and thus obtained average NDVI corresponding to locations of each grassland type for each province.

[16] Climatic data used in this study included monthly precipitation and temperature records for 1982–1999, which were produced from 680 well-distributed climate stations across China [*Piao et al.*, 2003]. We generated growing seasonal (April to October) temperature and precipitation data from the monthly climate records in order to explore possible relationships between grassland biomass and climate variables.

### 2.3. Relationship Between Aboveground Biomass C and NDVI and Error Analysis for Biomass Estimates

[17] *Department of Animal Husbandry Veterinary* [1994] have provided detailed information on average forage yield (air-dried weight, or aboveground yield, kg ha$^{-1}$) by grassland type by province in China (except Taiwan). Aboveground biomass (dry weight mass) was calculated using forage yield and water content for each grassland type [*Fang et al.*, 1996]. Aboveground biomass was converted

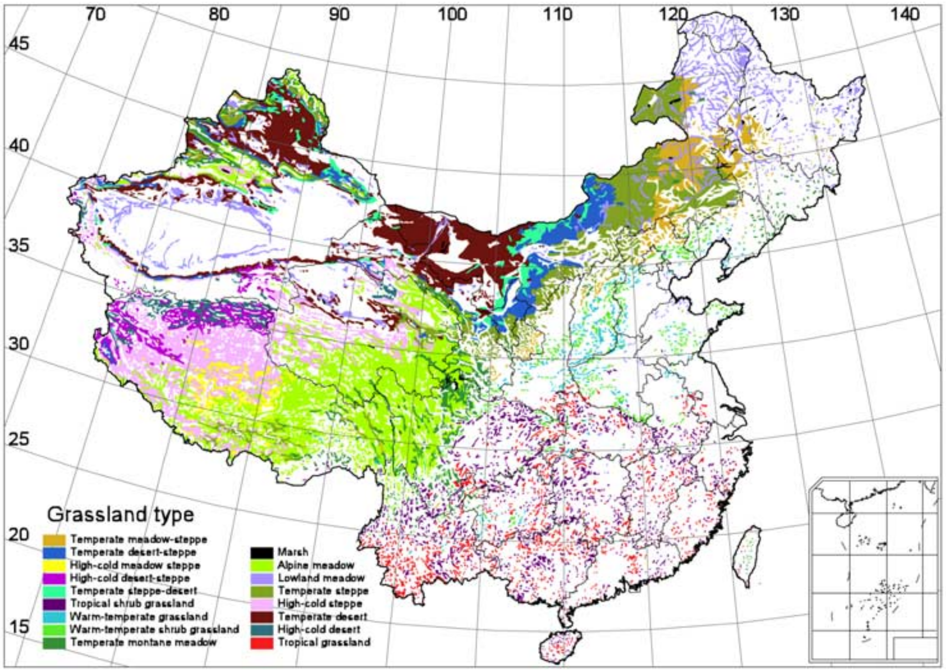


**Figure 1.** Spatial distribution of 17 grassland types in China (based on *Department of Animal Husbandry Veterinary* [1996] data). These types were grouped on the basis of climatic zonation, humidity index, vegetation type of grassland, and their importance in livestock husbandry [*Department of Animal Husbandry Veterinary*, 1996; *Chen and Fischer*, 1998]. Among the grassland types, temperate steppe, temperate desert-steppe, temperate steppe-desert, and temperate deserts are mainly distributed in arid and semiarid areas in northern China. High-cold meadow steppe, high-cold steppe, high-cold desert steppe, and alpine meadows appear in the Tibetan Plateau. Tropical grassland, tropical shrub-grassland, warm-temperate grassland, and warm-temperate shrub-grassland occur primarily in the eastern part of temperate and subtropical zones.

**Table 1.** Average Aboveground Biomass C Stock for the Early 1980s, the Late 1990s, and Averaged Over 18 Years, and the Trend and Relative Trend of the C Stock Over the Year and Their *p* Value, From 1982 to 1999, for Each Grassland Type and Country Total in China[a]

| | | Aboveground C Stock, Tg C | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Grassland Type | Area, $10^4$ km$^2$ | Early 1980s | Late 1990s | 1982–1999 | Trend, TgC yr$^{-1}$ | Relative Trend, % yr$^{-1}$ | r (*p* Value) | Uncertainty, % |
| Temperate meadow-steppe | 16.21 | 9.99 | 11.19 | 10.57 | 0.072 | 0.69 | 0.73 (0.001) | 41.1 |
| Temperate steppe | 42.47 | 16.34 | 18.95 | 17.49 | 0.166 | 0.95 | 0.66 (0.003) | 47.1 |
| Temperate desert-steppe | 17.80 | 3.28 | 3.71 | 3.49 | 0.031 | 0.88 | 0.49 (0.039) | 25.9 |
| High-cold meadow-steppe | 6.50 | 1.35 | 1.54 | 1.46 | 0.011 | 0.74 | 0.54 (0.021) | 56.0 |
| High-cold steppe | 45.97 | 8.04 | 8.87 | 8.48 | 0.049 | 0.57 | 0.50 (0.035) | 60.8 |
| High-cold desert steppe | 8.33 | 0.88 | 0.96 | 0.92 | 0.005 | 0.50 | 0.42 (0.084) | 78.0 |
| Temperate steppe-desert | 8.11 | 1.18 | 1.32 | 1.24 | 0.011 | 0.85 | 0.48 (0.046) | 29.6 |
| Temperate desert | 27.10 | 3.85 | 4.84 | 4.36 | 0.058 | 1.32 | 0.67 (0.002) | 29.6 |
| High-cold desert | 4.85 | 0.48 | 0.52 | 0.50 | 0.003 | 0.52 | 0.44 (0.071) | 101.6 |
| Tropical grassland | 10.90 | 8.58 | 9.57 | 9.08 | 0.046 | 0.50 | 0.47 (0.047) | 34.8 |
| Tropical shrub-grassland | 14.75 | 10.90 | 12.35 | 11.60 | 0.069 | 0.59 | 0.50 (0.033) | 22.9 |
| Warm-temperate grassland | 3.89 | 2.57 | 2.96 | 2.79 | 0.018 | 0.66 | 0.45 (0.062) | 23.1 |
| Warm-temperate shrub-grassland | 7.05 | 4.83 | 5.64 | 5.27 | 0.039 | 0.75 | 0.52 (0.027) | 29.1 |
| Lowland meadow | 25.88 | 14.24 | 16.08 | 15.23 | 0.102 | 0.67 | 0.82 (0.000) | 36.4 |
| Temperate montane meadow | 17.41 | 12.45 | 13.98 | 13.30 | 0.085 | 0.64 | 0.72 (0.001) | 25.9 |
| Alpine meadow | 73.10 | 36.69 | 40.75 | 38.86 | 0.244 | 0.63 | 0.69 (0.002) | 48.1 |
| Marsh | 1.10 | 0.71 | 0.78 | 0.75 | 0.004 | 0.60 | 0.82 (0.000) | 41.4 |
| **Country total** | **334.1** | **136.3** | **154.0** | **145.4** | **1.01** | **0.7** | **0.79 (0.000)** | **35.9** |

[a]Early 1980s are average of 1982–1984, late 1990s are average of 1997–1999, and average over 18 years are for 1982–1999. Error evaluation (uncertainty) and coefficient of correlation (r) are also indicated. The grid cells with a monthly mean NDVI of < 0.1 are excluded from data analysis to eliminate impact of bare and sparsely vegetated grids on the NDVI trend.

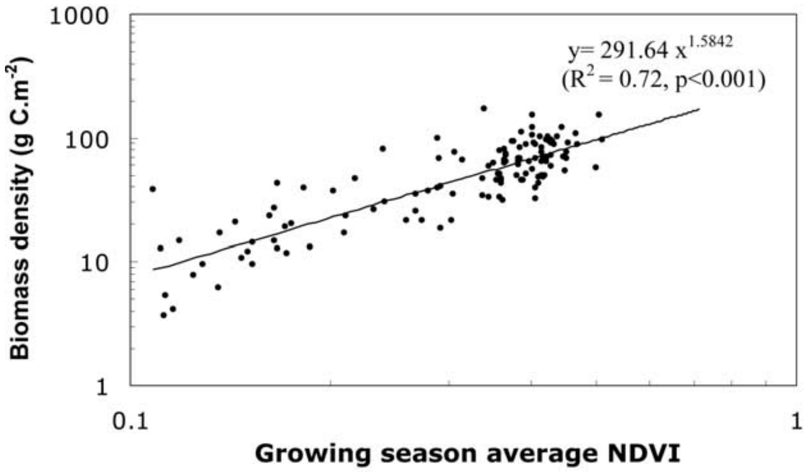


**Figure 2.** Relationship between aboveground biomass C density (C stock per area) and growing season NDVI of grasslands in China. The C density values are annual peak standing mass for the period 1981–1988 for each grassland type by each province, and NDVI values are 7-year (1982 to 1988) averaged growing season NDVI.

into units of C, using a conversion factor of 0.45 [*Lieth and Whittaker*, 1975].

[18] Because forage yield reported by *Department of Animal Husbandry Veterinary* [1994] was measured during the period 1981–1988, we calculated growing season average NDVI for each pixel for the same period to develop the regressive relationship between aboveground biomass C and growing season NDVI (equation (1) and Figure 2). We then used equation (1) and NDVI to estimate aboveground biomass C for each pixel for different periods.

$$Y = 291.64 \times NDVI^{1.5842} \quad \left(\mathrm{R}^2 = 0.72, \mathrm{P} < 0.001\right), \qquad (1)$$

where $Y$ is aboveground biomass C per area (g C m$^{-2}$).

[19] To evaluate the errors of the biomass estimates derived from the statistic model, we compared predicted values with inventory observations by grassland type using the following equation [*Smith et al.*, 1997]:

$$RMSE = \frac{100}{\bar{O}} \sqrt{\sum_{i=1}^{n} (P_i - O_i)^2 / n}, \qquad (2)$$

where $RMSE$ is root mean square error for grassland type, $P_i$ and $O_i$ are the predicted and observed values, $\bar{O}$ is averaged observed values, and $n$ is number of samples.

## 2.4. Estimation of Belowground Biomass

[20] In grassland ecosystems, a large portion of biomass C is stored below ground [*Coupland*, 1992]. In order to identify changes in total (above- and below-ground) biomass C stocks for China's grasslands over the past 2 decades, it is necessary to estimate the changes in belowground biomass C stocks. To estimate this change, we assumed a constant ratio of belowground to aboveground biomass C for each grassland type through the study period and collected these average ratio for major grassland types (Table 2).

[21] The approach of the aboveground *vs.* belowground biomass ratio has been the most common method for estimating belowground biomass at different scales from local to landscape, region and biome [*Intergovernmental Panel on Climate Change*, 2003; *Mokany et al.*, 2006]. Physiologically the ratio is explained as reflecting the differential investment of photosynthates between the aboveground and belowground organs [*Titlyanova et al.*, 1999; *Mokany et al.*, 2006]. However, because of a strong effect by the accumulated dead biomass over time, this functional explanation is often questioned [*Klepper*, 1991]. Therefore *Shackleton et al.* [1988] suggested that the interpretation based on the fine root *vs.* leaf biomass ratio is much reasonable. In addition, as stated hereafter, the

**Table 2.** Ratios of Belowground to Aboveground Biomass for 17 Grassland Types in China

| Grassland Type | Ratio | Reference |
|---|---|---|
| Temperate meadow-steppe | 5.26 | *Fang et al.* [1996] |
| Temperate steppe | 6.76 | *Wu* [2002] |
| Temperate desert-steppe | 10.08 | *Wu* [2002] |
| Temperate steppe-desert | 7.89 | *Wu* [2002] |
| Temperate desert | 7.89 | *Wu* [2002] |
| Temperate montane meadow | 6.23 | *Department of Animal Husbandry Veterinary* [1994] |
| Warm-temperate grassland | 3.50 | *Wu* [2002] |
| Warm-temperate shrub- grassland | 3.80 | *Wu* [2002] |
| Tropical grassland | 2.01 | *Wu* [2002] |
| Tropical shrub-grassland | 0.45 | *Wu* [2002] |
| High-cold meadow steppe | 7.91 | *Li et al.* [1998] |
| High-cold desert | 7.89 | *Li et al.* [1998] |
| High-cold steppe | 9.43 | *Wu* [2002] |
| High-cold desert steppe | 7.89 | *Li et al.* [1998] |
| Alpine meadow | 7.92 | *Li et al.* [1998] |
| Lowland meadow | 6.31 | *Department of Animal Husbandry Veterinary* [1994] |
| Marsh | 15.68 | *Department of Animal Husbandry Veterinary* [1994] |

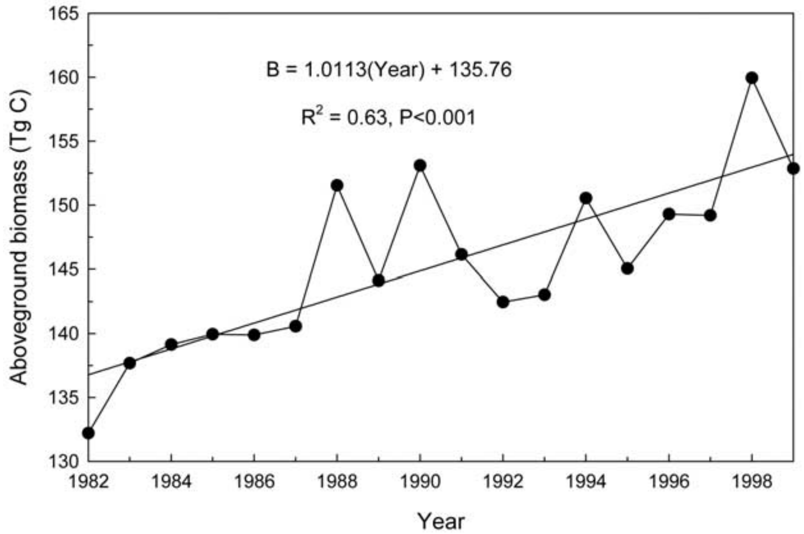


**Figure 3.** Interannual variations in aboveground biomass C for China's grassland over the period of 1982–1999.

approach has several other limitations; for example, the ratio may be influenced by the relatively long turnover time of the structural roots and the climate change [*Gill et al.*, 2002; *Hui and Jackson*, 2006]. Despite these limitations, our study still applies this approach to estimate belowground biomass, as many previous studies have been done [e.g., *Jackson et al.*, 1996; *Gill et al.*, 2002; *Mokany et al.*, 2006]. This is because the spatial variation (across different places and thus different climate, soil, and topography) in the ratios seems be much larger than its year-to-year change [*Mokany et al.*, 2006], and because the focus of our study is on the estimation of aboveground biomass and its pattern at the biome and national scales.

## 3. Results

### 3.1. Interannual Changes in Aboveground Biomass Carbon Stocks

[22] Using equation (1) and growing season average NDVI data, we calculated average aboveground biomass C stock for the early 1980s (average of 1982–1984), the late 1990s (average of 1997–1999), and the 18-year overall average for each grassland type and country total (Table 1). Over the 18 years, aboveground biomass C stocks averaged 145.4 Tg C $yr^{-1}$ over a total area of 334.1 $\times$ $10^4$ $km^2$, and significantly increased from 136.3 Tg C in the early 1980s to 154.0 Tg C in the late 1990s ($r = 0.79$, $p < 0.001$), with a net increase of 17.7 Tg C or an annual increase of 1.01 Tg C (annual rate of 0.7%) (Figure 3).

[23] The C stock by grassland type also tended to increase, but the increasing rate differed among the grassland types (Table 1). High-cold desert steppe, high-cold desert and warm-temperate grassland all showed a slight increase ($p > 0.05$) and the rest was significant ($p < 0.05$). The largest annual increase was observed in alpine steppe, with 0.244 Tg C $yr^{-1}$, which accounted for approximately 24% of the total annual C increase. Following this, temperate steppe, lowland meadow, and temperate montane meadow, contributed to 16%, 10%, and 8% of the total annual C increase, respectively. In addition, temperate desert steppe had the largest relative annual increase rate of 1.32% among all grassland types, while tropical grassland and high-cold desert steppe had the smallest value (0.50%).

[24] The error analysis suggests a difference of 35.9% between the model- and inventory-based estimates of the country-level biomass C stock. For the biome level (grassland type), the errors showed a large difference; alpine grassland types (high-cold desert, high-cold desert steppe, and high-cold steppe) were of a large value (56% to 101.6%), while that for temperate meadow-steppe, temperate steppe, tropical grassland, lowland meadow, alpine meadow was between 30% and 50%, and others below 30%.

### 3.2. Spatial Distribution and Changes of Aboveground Biomass C Stocks

[25] Figure 4 illustrates the spatial distribution and frequency distribution of the 18-year averaged C stock per area (aboveground biomass C density). A large spatial heterogeneity was exhibited; high C density appeared in eastern Tibet, eastern Inner Mongol (western slope of Mts. Daxinganling), and western and central parts of Mts. Tian-shan, while small C stock occurred in east and central Inner Mongol, and western and central Tibet (Figure 4a). Overall, the biomass C density ranged from 5 g $C.m^{-2}$ to 125 g $C.m^{-2}$, concentrating on a value of 10–90g C $m^{-2}$ (being 85% of total study area) (Figure 4b).

[26] Figure 5a illustrates the spatial distribution of the difference in aboveground biomass C density between the late 1990s (an average of 1997–1999) and the early 1980s (an average of 1982–1984); the positive value represents an increase in C stock per area (C sink), while the minus value implies a decrease in C stock per area (C source). The statistics indicated that about 70% of the total study area has increased and the rest 30% decreased over the past 2 decades. The largest C increase (>20 g C $m^{-2}$ $yr^{-1}$) occurred in the northern side of Mts. Tian-shan, the oasis

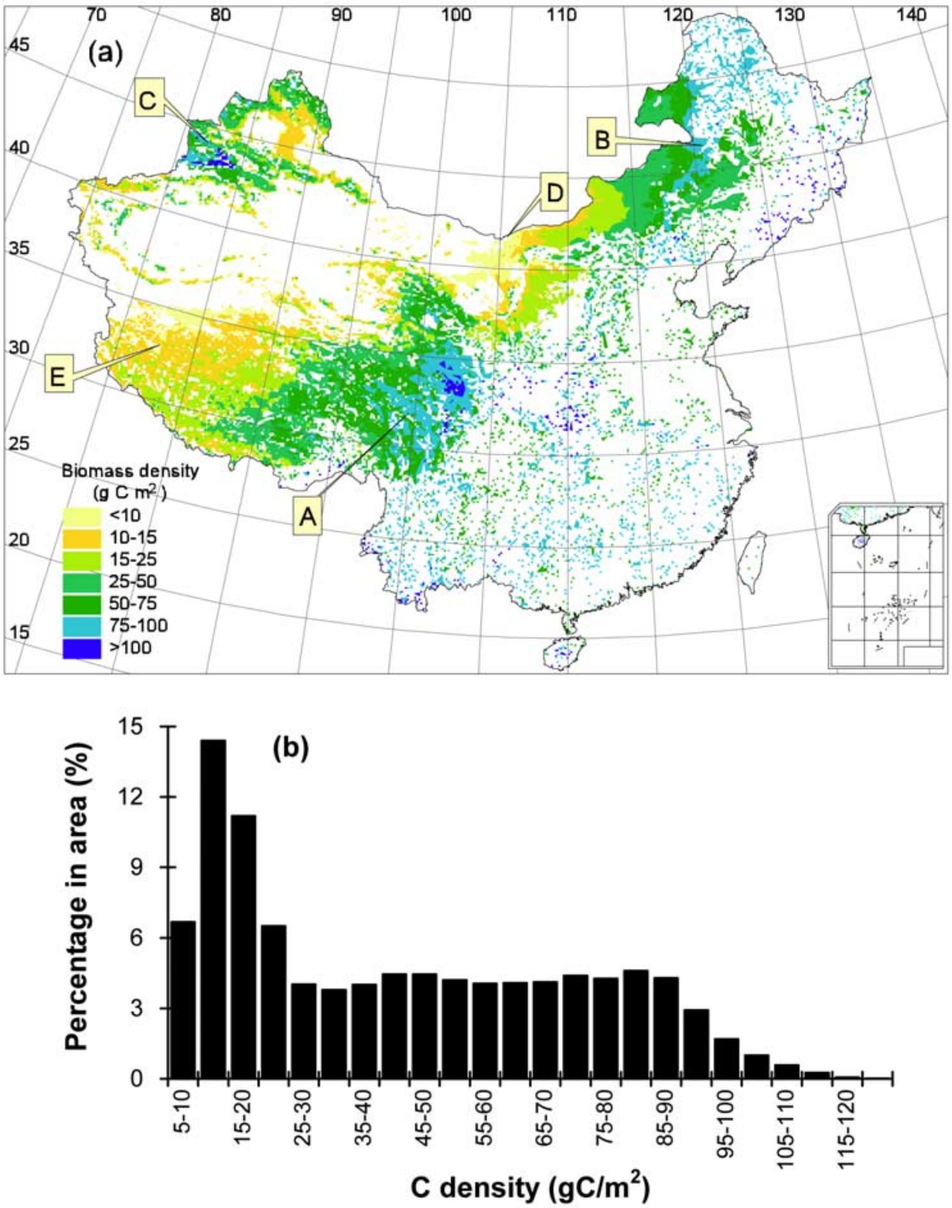


**Figure 4.** The 18-year averaged aboveground biomass C density (C stock per area) during 1982–1999 in China. (a) Spatial distribution of biomass C density. A high C density appears in Eastern Tibet (location A), eastern Inner Mongol (western slope of Mts. Daxinganling) (location B), and western and central parts of Mts. Tian-shan (location C), while small C stock is in east and central Inner Mongol (location D), and western and central Tibet (location E). (b) Frequency distribution of biomass C density.

around the Taklimakan Desert, and Mts. Altai in northwest China, Songnen Plain in Northeast China, and eastern Hulun Buir Plateau and parts of the Horqin Sand Land, Inner Mongolia. The significant C decrease ($<-5$ g C m$^{-2}$) appeared mainly along the Qing-zang highway area (a major road from Xining, Qinghai to Lhasa, Tibet) in the east Tibetan Plateau, possibly resulting from a human-induced degradation of grassland vegetation.

[27] The frequency distribution of the differences in biomass C density between the two periods of the late 1990s and the early 1980s suggested that about 50% of the total study area did not change ($-5.0\sim5.0$ g C m$^{-2}$) and $\sim$35% and $\sim$8% increased by 5–15 g C m$^{-2}$and 15–30 g C m$^{-2}$, respectively, while only about 2% decreased by >5 g C m$^{-2}$ (Figure 5b).

## 4. Discussion

### 4.1. Changes in Aboveground and Belowground Biomass C Stocks

[28] Aboveground biomass C stock of China's grassland averaged 145.4 Tg C and has increased by 17.7 Tg C from

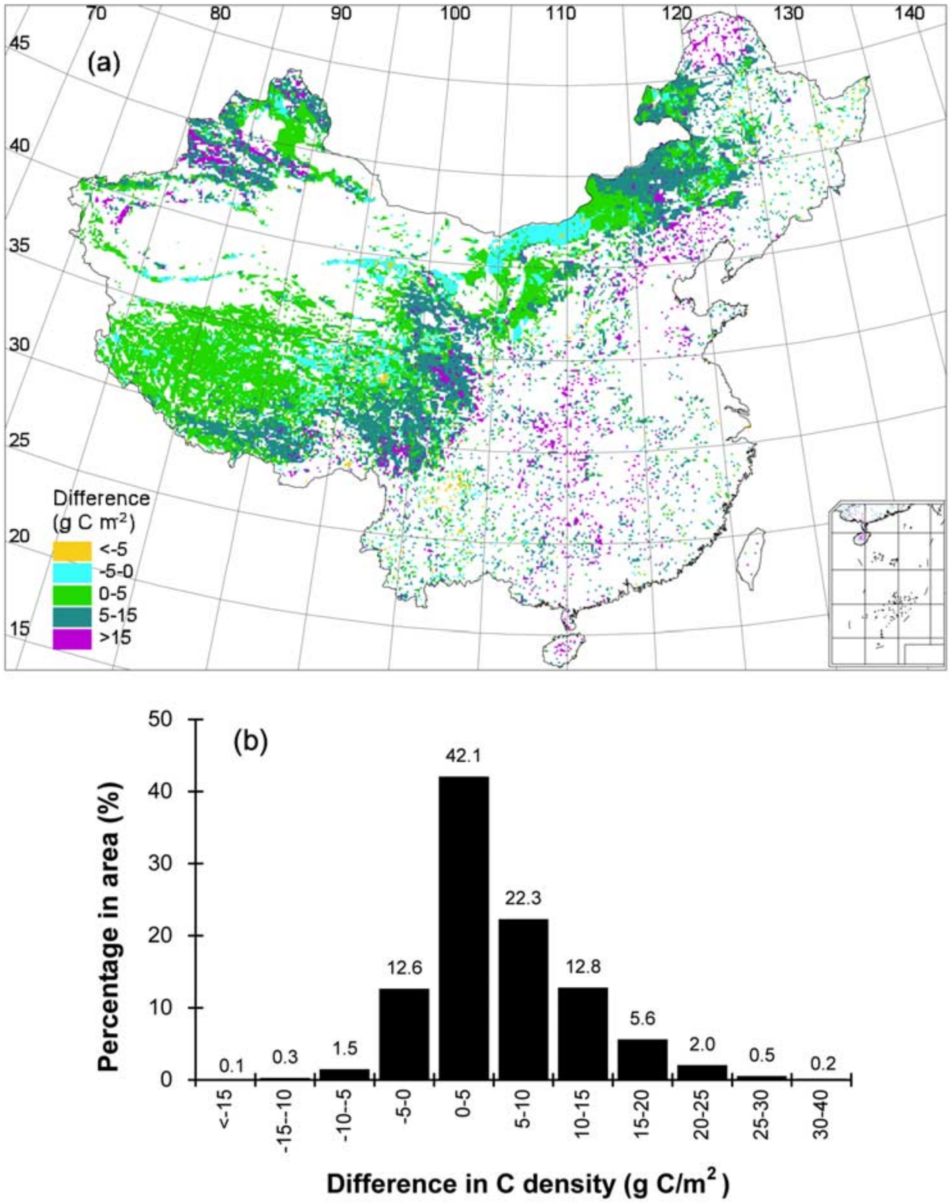


**Figure 5.** Difference between aboveground biomass C density (C stock per area) in the late 1990s (an average of 1997–1999) and in the early 1980s (an average of 1982–1984) over 1982–1999 in China. (a) Spatial distribution of this difference. The difference of the C stocks expresses size of the C increase (C sink) or decrease (C source); the positive value means the C increase, while minus value implies the C decrease. (b) Frequency distribution of this difference.

136.3 Tg C in the early 1980s to 154.0 Tg C in the late 1990s, with an annual increasing rate of 0.7% over the period of 1982 to 1999. Such a significant increase corresponded to pronounced climate changes over the study area (Figure 6). Growing season average temperature for the study area increased by 0.052°C per year (r = 0.69, p = 0.002) and growing season precipitation also tended to increase (0.77 mm/yr), but was not significant at the 5% significance level (r = 0.17, p = 0.478). Statistical analysis revealed that the total mean C density was positively related with both growing season average temperature (r = 0.79, P = 0.0001) and growing season precipitation (r = 0.48, P = 0.04). Because the positive trends in C density, temperature, and precipitation may cause a spurious correlation among the variables, we used the method proposed by *Zhou et al.* [2001] to calculate the relationship between C density and the detrended growing season temperature and precipitation. The results showed that a positive and significant correlation at 5% significance level was between the C density and detrended temperature (r = 0.57, *p* = 0.018) and precipitation (r = 0.55, *p* = 0.019), suggesting that increased temperature may be associated with increasing

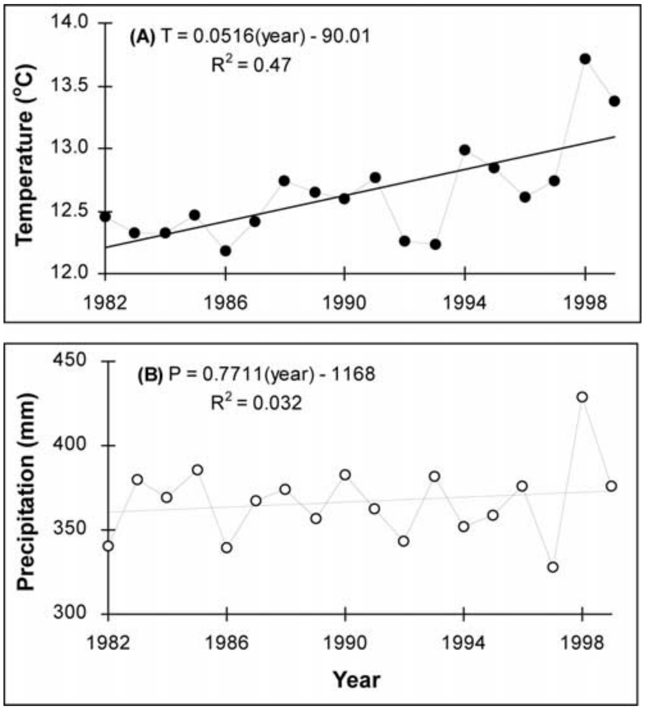


**Figure 6.** Changes in growing season average temperature and precipitation for China's grassland area over the period of 1982–1999.

C stocks and interannual changes in precipitation may be a factor in the fluctuations of C stocks.

[29] Generally, an increase in temperature promotes vegetation productivity primarily through two ways. First, enhanced soil nitrogen (N) mineralization and availability caused by an increase in temperature would stimulate plant N uptake and thus lead to increased NPP and vegetation growth [*Melillo et al.*, 2002]. Second, rising temperature would result in extension of growing season length, and eventually increase in plant photosynthesis [*White et al.*, 1999]. Remote sensing data indicate that over the last 2 decades, growing season length of temperate grassland, deserts, and alpine meadow and tundra in China has extended by about 1.1 day $yr^{-1}$, 2.3 day $yr^{-1}$ and 0.9 day $yr^{-1}$, respectively [*Piao et al.*, 2006]. In addition, atmospheric $CO_2$ fertilization effect [*Polley*, 1997] and human activity such as land management may also partly account for the observed increase in biomass C stocks of China's grassland.

[30] As described above, a large portion of biomass C is stored below ground in grassland ecosystems [*Coupland*, 1992]. We used a constant ratio of aboveground versus belowground biomass through the study period for each grassland type (Table 2) to estimate the total country belowground biomass as 851.5 Tg C in the early 1980s (average of 1982–1984) and 960.5 Tg C in the late 1990s (average of 1997–1999). As a result, the total biomass C stock of China's grasslands averaged 1051.1 Tg C during the past 2 decades and increased from 987.8 Tg C in the early 1980s to 1114.5 Tg C in the late 1990s, with an overall increase of 126.7 Tg C, or an annual increase of 7.04 Tg C (an increase rate of 0.7% annually). This estimate compares favorably with that derived from a carbon cycle model, CASA (Carnegie-Stanford-Ames Approach) [*Potter et al.*, 1993]. The CASA uses NDVI, temperature, precipitation, solar radiation, and soil type and texture to estimate vegetation net primary production (NPP) [*Potter et al.*, 1993; *Field et al.*, 1995]. The CASA-estimated annual NPP increased by 7.2 Tg C $yr^{-1}$ for China's grasslands (temperate grassland, high land vegetation and savanna) from 1982 to 1999 [*Fang et al.*, 2003; *Piao et al.*, 2005b], which was very close to the estimate of 7.04 Tg C $yr^{-1}$ described above.

[31] Note that, like many others [e.g., *Scurlock et al.*, 2002], we used maximum annual biomass as a proxy of NPP in this estimation, although there are several limitations of the peak biomass method. Previous studies have showed that the peak biomass method is only suitable for temperate grassland with short growing season, and may underestimate NPP for tropical grasslands [*Long et al.*, 1989; *Scurlock et al.*, 2002]. However, such an effect on country-level aboveground NPP change may be negligible because of a very small area of tropical grassland in China (about 7.6% of total grassland area).

[32] Our estimates suggest that China's grasslands may have acted as a biomass C sink over the past 2 decades, but this sink is much smaller than that of forests. *Fang et al.* [2001] reported that China's forest has sequestrated 21 Tg of C annually during the last 2 decades, which is about 3 times of that of China's grassland. Considering that the total area of grasslands is about 3 times that of forests in China (331.4 $\times$ $10^4$ $km^2$ for grasslands versus 105.54 $\times$ $10^4$ $km^2$ for forests), the biomass C sink strength of grasslands is only 1/9 of that of forests.

[33] According to *Olson et al.* [1983] and *Prentice et al.* [1993], the area of global grasslands is 4160 $\times$ $10^4$ $\sim$5155 $\times$ $10^4$ $km^2$, with a total biomass C stock of 27.9 $\sim$ 50.4 Pg. The global grassland C sink was estimated as 0.5 Pg C $yr^{-1}$ [*Scurlock and Hall*, 1998]. Applying China's estimate of biomass C sink per area (7.04 Tg C $yr^{-1}$/331 $\times$ $10^4$ $km^2$) and the increase rate (percentage) per biomass (0.7%/yr over the 18 years) in our study, global grassland biomass C sink could be 88–109 Tg C $yr^{-1}$ and 0.20–0.36 Pg C $yr^{-1}$ in the past 2 decades, respectively. Both values are lower than the global C sink estimate by *Scurlock and Hall* [1998], although their estimate included the soil C sequestration. The discrepancy between these two estimates may be attributed to two factors: (1) a relatively smaller biomass C sink of China's grasslands may underestimate the global grassland C absorption, and (2) soil C sequestration for grasslands may be critical to increased terrestrial C sink but is neglected in this analysis. The first factor may be true because China's grassland biomass C per area was less than half of the world average due to anthropogenic activities such as overgrazing [*Chen and Wang*, 2000], but for the second one, it remains uncertain and requires further study.

## 4.2. Uncertainties of Estimate of Biomass C Stocks

[34] In this study, we have explored the biomass C stocks and their changes for China's grasslands over the past 2 decades, but its size still remains uncertain due to an uncertainty of grassland resource inventory data, satellite

time series dataset, and belowground C stocks. Unlike forests with a relatively low-frequency variation, grasslands are very sensitive to environmental changes, and hence show fast and large interannual changes in biomass C stocks resulting from natural events and human activities [*Lauenroth and Sala*, 1992]. Thus here we assume that (1) any standing dead matter or litter was carried from previous year, (2) death in current year is negligible, (3) live biomass was not from previous year, and (4) ratio of aboveground to belowground C is dependent on grassland type, and does not vary with environmental change [*Scurlock et al.*, 2002]. This may influences the analyses of the temporal and spatial patterns of regional biomass C stocks, particularly in the regions with intensively grazed or cut grasslands where biomass C stocks may be underestimated, but may not exert a significant effect on the difference between biomass C stocks in different periods, for example, trend of biomass C stocks over the study period. Furthermore, although the grassland resource inventory was well designed and its sampling sites were across whole the country, uncertainties still exist in the inventory data, mainly coming from measurement errors and sampling errors.

[35] Another possible uncertainty is from the NDVI time series data set. Although every effort has been paid to NDVI corrections, some variations from the satellite drift and changeover and incomplete corrections for calibration loss and atmospheric effects may still remain in the NDVI dataset. This is always a challenge for the application of satellite data in ecological study [*Slayback et al.*, 2003].

[36] Finally, the largest error for the estimation of the large-scale biomass C stocks for whole grassland ecosystem should be induced from the belowground biomass. Due to technical and methodological limitations, the contribution of belowground C stock to the regional and global C cycle remains largely unquantified [*Copley*, 2000; *Gill et al.*, 2002]. Our study used the constant ratios of aboveground to belowground C by grassland type to estimate the belowground biomass C, and thus probably reduces precision of our estimates. For example, belowground root sampling generally includes both live and dead roots, and thus how to eliminate the effect of dead roots is always a challenge for the assessment of a real ratio; the relatively long turnover time of the structural roots suggest that the allocation of grassland production cannot arrive to an equilibrium in a few years [*Mokany et al.*, 2006]; the allocation of plant production generally varies with the climate change [*Gill et al.*, 2002; *Hui and Jackson*, 2006]. Despite these limitations, this approach practically is still applied in most of the recent studies [e.g., *Gill et al.*, 2002; *Mokany et al.*, 2006], because at this moment we do not have better methods to estimate belowground biomass [*Scurlock et al.*, 2002; *Intergovernmental Panel on Climate Change*, 2003]. In fact, interannual change in the ratios seems to be considerably small within an ecosystem, and its spatial variation (across different places and thus different climate, soil, and topography) might be much larger than that in different years [*Mokany et al. 2006*]. Although we do not have data to test this assumption, a study from the US tallgrass prairie suggested that the ratio did not change significantly over time [*Knapp et al.*, 1998]. A 15-year observation in Siberian grasslands also showed an unclear trend of the ratios although there were large seasonal changes [*Titlyanova et al.*, 1999]. Overall, estimating belowground biomass of grassland ecosystems based on available data sources and reasonable methodology is a big challenge for accurately evaluating biomass C stocks of grasslands and require future study.

[37] In closure, while an increase in peak biomass for grasslands over the period indicates a stimulation of initial C sequestration in the ecosystem, we still do not know whether China's grassland ecosystems are carbon sink or source in the past 2 decades, which is dependent on the balance of changes in both plant and soil carbon pools. If the increases of biomass carbon storage exceed that of soil carbon transfers to the atmosphere through carbon decomposition, net carbon sequestration would occur, and eventually the whole ecosystem would function as a carbon sink. In our present study, we focus on the quantification of changes in grassland biomass carbon stocks but not for those of the whole ecosystem (biomass, litterfall and soil organic carbon). To quantify the changes in whole ecosystem carbon stocks for China's grasslands, additional data on geographical and interannual variability in soil carbon storage are greatly needed.

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J. Fang (corresponding author), S. Piao, K. Tan, and S. Tao, Department of Ecology, College of Environmental Sciences, Peking University, Beijing 100871, China. (jyfang@urban.pku.edu.cn)

L. Zhou, School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA 30332-0340, USA.