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Carbon stocks and environmental controls of China's grasslands

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Abstract Ecosystem carbon stocks in the northern grasslands play an important role in the global carbon cycles; however, little information on those is available for China's temperate and alpine grasslands. During the last five years from 2001 to 2005, we conducted large-scale field campaigns to investigate biomass carbon stocks and soil organic carbon (SOC) storage for these grasslands. We have collected 978 soil profiles and 1700 biomass plots from 326 sites across the regions (including Qinghai, Tibet, Inner Mongolia, and Xinjiang). Over the whole area with 185×10^4 km^2, the biomass carbon stock was estimated at 536.1 Tg C (1 Tg $= 10^{12}$ g) with a mean biomass density of 41.8 g C m^{-2} for aboveground and 246.0 g C m^{-2} for belowground, and SOC storage in the top 1 meter was estimated at 14.9 Pg C (1 Pg $= 10^{15}$ g), with an average density of 8.0 kg C m^{-2}. Generalized linear model analysis showed that region, climatic variables and soil texture together explained 50% of total variance in biomass and about 70% of that in SOC density. Of the variables examined, water availability explained the largest proportion (~25% and 60%) of the biomass and SOC variation. Our results suggest an important control of water availability on plant production and soil carbon storage in China's grasslands.

Key words: aboveground biomass, alpine grasslands, belowground biomass, soil organic carbon, temperate grasslands.

Terrestrial ecosystems in middle and high latitudes of the Northern Hemisphere have functioned as carbon (C) sinks for atmospheric CO_2 over the past 20 years (Schimel *et al.*, 2001), but such evidence mainly comes from forest ecosystems (Fang *et al.*, 2001; Myneni *et al.*, 2001). Grassland covers nearly 1/3 of China's total territory (Department of Animal Husbandry Veterinary, 1996). Therefore, accurate estimation of C stocks in China's grasslands is critical for precise evaluation of China's terrestrial C cycling and sustainable use of China's grassland resources (Piao *et al.*, 2007).

During the past 10 years, biomass C stocks in China's grasslands have been evaluated using the data from resource inventory (Fang *et al.*, 1996; Ni, 2004), global biomass database (Ni, 2002), field measurements (Luo *et al.*, 2002), and satellite-based statistical model (Piao *et al.*, 2007). Similarly, soil organic carbon (SOC) storage in China's grasslands has also been estimated using the data either from China's national soil survey (Fang *et al.*, 1996; Wang *et al.*, 2003; Wu *et al.*, 2003) or global soil database (Ni, 2002). However, large uncertainties still exist in these studies due to the lack of field observations in belowground biomass (Ma *et al.*, 2008) and the small number of soil profiles from the Tibetan Plateau and other northwestern regions in the second national soil survey (Yang *et al.*, 2007). Overcoming these shortages is the key for the accurate estimation of C storage in China's grasslands.

During the summers (July and August) of 2001-2005, we conducted five-year field sampling campaigns across the grassland regions (including Qinghai, Tibet, Inner Mongolia, and Xinjiang) and collected 1700 biomass plots and 978 soil profiles from 326 sites. Using these data, we estimated biomass and SOC storage in China's grasslands and further analyzed their relationships with environmental factors.

Materials and Methods

Large-scale biomass survey We sampled 326 sites across the grassland regions during the summers (June to August) of 2001-2005
(Figure 1). At each site (10 × 10 m), all plants in five plots (1 × 1 m) were harvested to measure aboveground biomass (AGB). Either three soil pits of 50 × 50 cm or nine soil cores with the diameter of 8 cm at depth intervals of 10 cm to maximum soil depth were sampled to determine belowground biomass (BGB) (For details, see Ma *et al.*, 2008). Live roots were distinguished by their color, resiliency and attached fine roots (Vogt and Persson, 1991). Biomass samples were oven-dried at 65℃ to constant mass, and weighed to the nearest 0.1 g. To compare with previous studies, biomass was converted into C content using a conversion factor of 0.45 (Piao *et al.*, 2007).

Field soil investigation and laboratory analysis We sampled 978 soil profiles from the 326 sites (i.e. 3 soil profiles at each site) in the grasslands by the five field sampling campaigns (Figure 1). At each sampling site, three soil pits were excavated to collect samples for analyses of physical and chemical properties. For each pit, soil samples were collected at depths of 0-10, 10-20, 20-30, 30-50, 50-70, and 70-100 cm (For details, see Yang *et al.*, 2008). Soil samples for C analysis were air-dried, sieved (2 mm mesh), handpicked to remove fine roots, and then ground on a ball mill. Soil organic carbon (SOC) was measured using the wet oxidation method (Nelson and Sommers, 1982). Soil texture in Tibetan soils was determined by a particle size analyzer (Mastersizer 2000, Malvern, UK) after removal of organic matter and calcium carbonates, while that in other soils was derived from a digitized map of soil texture of China (Deng, 1986).

SOC estimation We calculated SOC density for different depth intervals for each soil profile using Eq. 1 (30 and 100 cm).

$$SOCD = \sum_{i=1}^{n} T_i \times BD_i \times SOC_i \times (1 - C_i)/100 \quad (1)$$

where $SOCD$, T_i, BD_i, SOC_i, and C_i are SOC density (kg C m^{-2}), soil thickness (cm), bulk density (g cm^{-3}), soil organic carbon (g kg^{-1}), and volume percentage of the fraction > 2 mm at layer i, respectively.

Climate data and grassland types Mean annual temperature (MAT) and annual precipitation (AP) data at a resolution of 0.1 × 0.1 degrees were complied from the climate database of China during 1970-1999 (Piao *et al*., 2003). Information on the distribution of grassland types was extracted from Vegetation Map of China with a scale of 1 : 1,000,000 (Chinese Academy of Sciences, 2001). Based on China's vegetation classification system, we divided China's northern grasslands into six types: alpine steppe, alpine meadow, desert steppe, typical steppe, meadow steppe, and mountain meadow.

Statistical analysis Regression analyses were conducted to evaluate the relationships between biomass/SOC density and MAT, AP, soil moisture, and soil texture. The general linear model (GLM) was used to assess integrative effects of region (Qinghai-Tibetan Plateau, Inner Mongolia, and Xinjiang), MAT, AP, grassland type, soil moisture, and silt content on biomass and SOC density. All analyses were performed using the software package R (R Development Core Team, 2005).

Results

Regional distribution of biomass and SOC storage Biomass and SOC storage exhibited large differences among different regions (Table 1). The highest biomass and SOC density was observed in Xinjiang (409 g C m^{-2} and 12.1 kg C m^{-2}), while the lowest in Tibet (155.8 g C m^{-2} and 4.8 kg C m^{-2}). The biomass stocks of Qinghai was largest (159.5 Tg), accounting for about 1/3 of the total stocks. Moreover, the contribution of Qinghai (4.8 Pg) to total SOC storage was the largest among the four regions, accounting for about 1/3 of the total storage. Xinjiang stored the lowest biomass and SOC (108.3 Tg and 3.2 Pg), mainly due to its small grassland area. Overall, total biomass and SOC storage in the study area was estimated at 536.1 Tg and 14.9 Pg, with the average density of 289.1 g C m^{-2} and 8.0 kg C m^{-2}, respectively.

Relationships between C density and environmental factors
Biomass in China's grasslands did not show any significant trend with MAT ($P > 0.05$), but significantly increased with AP ($P < 0.05$). Biomass in China's grasslands was positively correlated with moisture ($P < 0.05$). In addition, biomass in alpine grasslands significantly increased with silt content ($P < 0.05$), but that in temperate grasslands did not show any significant trend. SOC density in temperate grasslands significantly decreased with MAT, while that in alpine grasslands showed weak increasing trend with MAT ($P < 0.05$). SOC density in China's grasslands increased with both AP and moisture ($P < 0.05$). Additionally, SOC density in alpine grasslands was positively correlated with silt content ($P < 0.05$), while not in temperate grasslands. GLM analysis showed water availability explained the largest proportion (~25% and 60%) of the biomass and SOC variation (Table 2). Region and grassland type could explain 15%-24% of the variation in biomass and 4% of that in SOC density. Overall, environmental variables could explain about 50% and 69% of the overall variation in biomass and SOC density, respectively.

Discussion

Size of biomass and SOC storage in China's grasslands Our results of biomass density are largely different from earlier estimates (Table 3). AGB in this study was about 30% higher than those estimated by Ni (2004), which was based on the forage field data. In addition, AGB in temperate grasslands was 30% larger and that in alpine grasslands was 10% lower than estimate of Piao et al. (2007), which were derived from a satellite-based statistical model. These discrepancies may be due to the different data source or estimation method (Ma et al., 2008). Moreover, larger difference in BGB (-105%-38.5%) was observed between Piao et al. (2007) and this study, due probably to a large error in the R : S ratios used in the previous studies (Mokany et al., 2006).

SOC density in this study significantly differed from the previous estimates (Table 3). Our values of SOC density were much lower than those estimates based on global SOC database (e.g. Ni, 2002), indicating that the global database is unlikely suitable for investigating detailed soil carbon stocks for a region. Moreover, large differences existed between our estimates and those derived from the national level (e.g. Wu et al., 2003; Yang et al., 2007), possibly due to the small number of soil profiles from the Tibetan Plateau and other northwestern regions in the second national soil survey (Yang et al., 2007).

Effects of environmental factors on biomass and SOC storage The relationship between AGB and precipitation obtained in alpine grasslands was similar with that observed in temperate grasslands. However, precipitation-use efficiency (the slope of the AGB-precipitation relationship) observed in alpine grasslands (0.08 g C m^{-2} mm^{-1}) was lower than that in temperate grasslands (0.23 g C m^{-2} mm^{-1}). The difference may be derived from different growth-limiting factors in temperate and alpine grasslands. AGB in temperate grasslands was strongly influenced by the amount and distribution of precipitation (Sala *et al*., 1988), but in alpine grasslands it was also constrained by low temperature, especially at high precipitation levels (Fang *et al*., 2005; Kato *et al*., 2006).

Significant linear relationships were observed between SOC density and AP ($P < 0.01$) , and between SOC density and soil moisture ($P < 0.01$) . Further , water availability explained the largest proportion (~60%) of the SOC variation . These results suggest that water availability could stimulate plant production and thus contribute to the accumulation of SOC in a water-limiting area (Wynn *et al* ., 2006) . A similar relationship between SOC density and water availability has also been observed in other temperate regions , such as in the Great Plains of the United States (Burke *et al* ., 1989) and Australia (Wynn *et al* ., 2006) , implying that water availability may be a powerful variable for predicting SOC density across broad biogeographic regions .

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Table 1 *Density and storage of biomass and soil organic carbon (SOC) in grasslands for different regions of China. AGB, aboveground biomass; BGB, belowground biomass; TB, total biomass; R: S ratio, root: shoot ratio; AS, alpine steppe; AM, alpine meadow; DS, desert steppe; TS, temperate steppe; MS, mountain steppe; MM, mountain meadow.*

Region	Grassland type	Site/profile	Area /10^4 km^2	Biomass density (g C m^{-2})				Biomass stock (Tg C)			SOCD (kg C m^{-2})		SOC stock (Pg C)	
				AGB	BGB	TB	R: S ratio	AGB	BGB	TB	0-30cm	0-100cm	0-30 cm	0-100 cm
				Mean/SE	Mean/SE	Mean/SE	Mean/SE	Mean/SE	Mean/SE	Mean/SE	Mean/SE	Mean/SE	Mean/SE	Mean/SE
Qinghai	AS	40/120	14.44	36.8/3.6	189.8/25.3	227.1/28.3	5.1/0.3	5.3/0.5	27.4/3.7	32.8/4.1	4.1/0.4	6.9/0.8	0.6/0.1	1.0/0.1
	AM	32/96	27.57	59.4/5.6	397.5/62.5	459.6/66.6	6.6/0.8	16.4/1.5	109.6/17.2	126.7/18.4	8.9/0.7	13.6/1.6	2.5/0.2	3.8/0.5
	Total	72/216	42.01	51.7	326.1	**379.7**	**5.7**	21.7	137.0	**159.5**	7.4	**11.4**	3.1	**4.8**
Tibet	AS	38/114	49.01	11.3/1.0	71.3/6.9	82.6/7.6	6.9/0.5	5.5/0.5	35.0/3.4	40.5/3.7	2.1/0.1	3.3/0.2	1.0/0.1	1.6/0.1
	AM	25/75	24.17	37.3/3.0	268.5/25.1	304.2/27.2	7.9/0.6	9.0/0.7	64.9/6.1	73.5/6.6	6.6/0.6	8.0/0.7	1.6/0.1	1.9/0.2
	Total	63/189	73.18	19.8	136.5	**155.8**	**7.2**	14.5	99.9	**114.0**	3.6	**4.8**	2.6	**3.5**
Inner Mongolia	DS	39/117	8.91	25.4/2.9	130.2/10.6	154.9/11.7	6.5/0.6	2.3/0.3	11.6/0.9	13.8/1.0	2.5/0.2	4.5/0.4	0.2/0.0	0.4/0.0
	TS	56/168	28.6	59.4/4.0	290.3/22.3	353.4/22.0	6.0/0.6	17.0/1.1	83.0/6.4	101.1/6.3	4.2/0.2	7.5/0.4	1.2/0.1	2.1/0.1
	MS	18/54	6.26	88.5/7.8	538.3/77.9	629.9/80.6	6.2/1.1	5.5/0.5	33.7/4.9	39.4/5.0	7.1/0.6	13.5/1.7	0.4/0.0	0.8/0.1
	Total	113/339	43.77	56.7	293.1	**352.5**	**6.2**	24.8	128.3	**154.3**	4.1	**7.5**	1.8	**3.3**
Xinjiang	DS	32/96	6.15	35.2/3.5	241.6/20.3	280/22.5	7.2/0.6	2.2/0.2	14.9/1.2	17.2/1.4	2.7/0.3	4.8/0.5	0.2/0.0	0.3/0.0
	TS	22/66	11.91	58.7/7.3	376.6/21.5	437.4/25.4	7.2/0.5	7.0/0.9	44.9/2.6	52.1/3.0	5.1/0.6	9.0/1.1	0.6/0.1	1.1/0.1
	MS	8/24	1.08	78.3/12.2	598.5/102.7	690.1/106.6	7.0/1.5	0.8/0.1	6.5/1.1	7.5/1.2	8.7/0.9	14.3/0.8	0.1/0.0	0.2/0.0
	MM	16/48	7.34	87.8/14.2	336.8/32.9	428.8/38.7	4.7/0.7	6.4/1.0	24.7/2.4	31.5/2.8	11.8/0.9	21.9/2.0	0.9/0.1	1.6/0.1
	Total	78/234	26.48	61.9	343.7	**409.0**	**6.6**	16.4	91.0	**108.3**	6.8	**12.1**	1.8	**3.2**
China	**Total**	326/978	185.43	41.7	246.0	**289.1**	**6.4**	77.4	456.2	**536.1**	5.0	**8.0**	9.3	**14.9**

Table 2 *Summary of the results obtained from a general linear model (GLM), showing the integrative effects of region, MAT, AP, grassland type, soil moisture, and soil texture on AGB, BGB, and SOCD in the top 30 cm.*

	df	MS	*F*	*P*	SS%
AGB					
Region	2	9.2	24.7	< 0.01	8.4
MAT	1	8.4	22.5	< 0.01	3.8
AP	1	57.9	155.6	< 0.01	26.4
Moisture	1	6.5	17.6	< 0.01	3.0
Grassland type	4	3.4	9.1	< 0.01	6.2
Silt	1	1.0	2.8	0.096	0.5
BGB					
Region	2	12.6	35.7	< 0.01	14.3
MAT	1	2.5	7.1	< 0.01	1.4
AP	1	41.6	117.5	< 0.01	23.5
Moisture	1	1.0	2.7	0.101	0.5
Grassland type	4	3.8	10.8	< 0.01	8.6
Silt	1	2.5	6.9	< 0.01	1.4
SOC					
Region	2	1.0	5.8	< 0.01	1.2
MAT	1	4.3	25.0	< 0.01	2.7
AP	1	54.8	318.0	< 0.01	34.0
Moisture	1	38.2	221.7	< 0.01	23.7
Grassland type	4	1.0	5.7	< 0.01	2.5
Silt	1	7.7	44.9	< 0.01	4.8

Notes: Biomass and SOC data were $\log_{10}$-transformed before analysis. df: degrees of freedom; MS: mean squares; SS: proportion of variances explained by variable.

Table 3 *Comparison of biomass and soil organic carbon (SOC) density with previous studies. AS: alpine steppe; AM: alpine meadow; DS: desert steppe; TS: temperate steppe; MS: mountain steppe; MM: mountain meadow.*

Grassland type	AGB (g C m^{-2})			BGB (g C m^{-2})		SOCD (kg C m^{-2})			
	This study	Ni *et al*., 2004	Piao *et al*., 2007	This study	Piao *et al*., 2007	This study	Ni *et al*., 2002	Wu *et al*., 2003	Yang *et al*., 2007
AS	24.3	12.8	28.9	132.9	272.8	5.2	17.0	7.5	4.7
AM	49.7	39.7	53.2	351.2	421.0	11.2	18.2	16.7	13.4
DS	29.8	20.5	19.6	182.2	197.6	4.6	8.7	4.8	4.1
TS	59.2	40.0	41.2	319.0	278.4	8.0	12.3	9.5	9.9
MS	85.4	65.9	65.2	557.3	343.0	13.7	11.2	12.9	11.3
MM	87.8	74.2	48.7	336.8	303.4	21.9	18.2	20.0	20.5

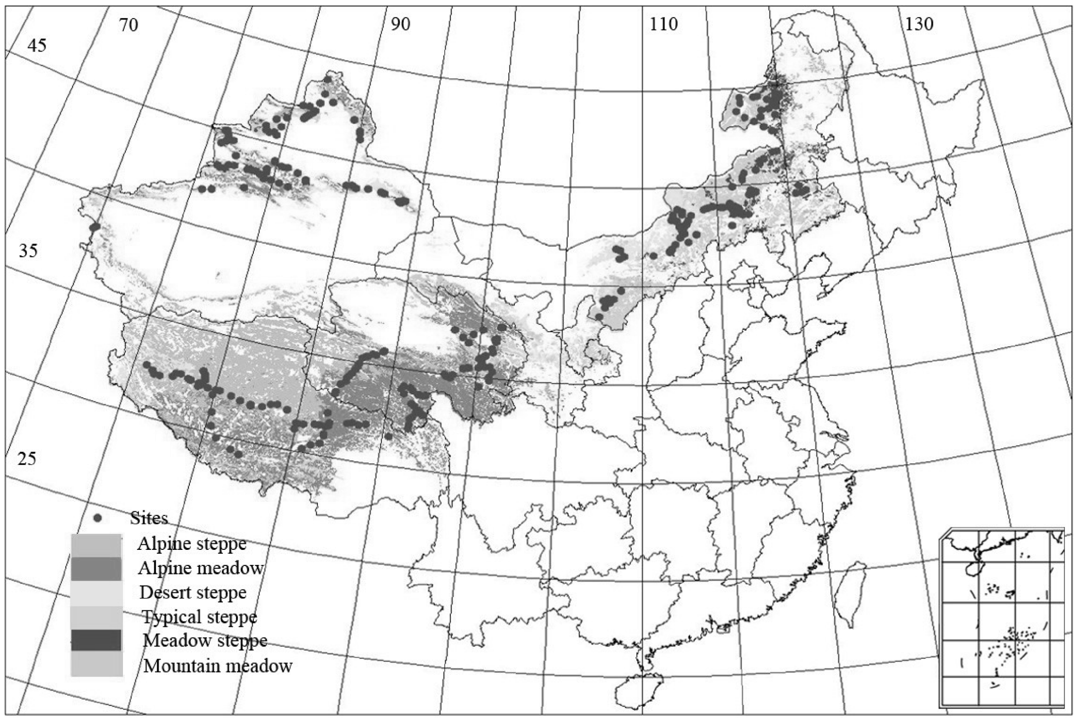

Figure 1 *Locations of 326 sampling sites in China's grasslands at the background of China's vegetation map. The sampling campaigns were conducted during the summers (July and August) of 2001-2005. The distribution of grassland types was derived from the vegetation map of China with a scale of 1:1 000 000 (Chinese Academy of Sciences, 2001).*