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Carbon storage in the grasslands of China based on field measurements of above- and below-ground biomass

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Abstract Above- and below-ground biomass values for 17 types of grassland communities in China as classified by the Chinese Grasslands Resources Survey were obtained from systematic replicated sampling at 78 sites and from published records from 146 sites. Most of the systematic samples were along a 5,000-km-long transect from Hailar, Inner Mongolia (49°15′N, 119°15′E), to Pulan, Tibet (30°15′N, 81°10′E). Above-ground biomass was separated into stem, leaf, flower and fruit, standing dead matter, and litter. Below-ground biomass was measured in 10-cm soil layers to a depth of 30 cm for herbs and to 50 cm for woody plants. Grassland type mean total biomass carbon densities ranged from 2.400 kg m^{-2} for swamp to 0.149 kg m^{-2} for alpine desert grasslands. Ratios of below- to above-ground carbon density varied widely from 0.99 for tropical tussock grassland to 52.28 for alpine meadow. Most below-ground biomass was in the 0–10 cm soil depth layer and there were large differences between grassland types in the proportions of living and dead matter and stem and leaf. Differences between grassland types in the amount and allocation of biomass showed patterns related to environments, especially aridity gradients. Comparisons of our estimates with other studies indicated that above-ground biomass, particularly forage-yield biomass, is a poor predictor of total vegetation carbon density. Our estimate for total carbon storage in the biomass of the grasslands of China was 3.32 Pg C, with 56.4% contained in the grasslands of the Tibet-Qinghai plateau and 17.9% in the northern temperate grasslands. The need for further standardized and systematic measurements of vegetation biomass to validate global carbon cycles is emphasised.

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1 Introduction

Grasslands cover 41.7% of the area of China mostly in vast, continuous areas in the north and northwest with temperate continental arid climates and on the Tibetan-Qinghai Plateau at very high elevations (DAHV and CISNR 1996). There are also smaller, often disjunct areas of grassland with monsoonal warm temperate and tropical climates in central, eastern and southern regions (ECVC 1980; Hou et al. 1982). The 3.92 million km^2 of grasslands in China provide 16.3% of the world's total grassland which cover about a fifth of the world's land surface (Scurlock and Hall 1998).

Natural grassland ecosystems may contribute as much as 20% of total terrestrial production to provide an annual sink of about 0.5 Pg carbon (Scurlock and Hall 1998). Consequently they have received attention as their condition may significantly influence regional climates and the global carbon cycle (Hall and Scurlock, 1991; Hall et al. 1995; Sala et al. 1996). There have been various studies of carbon storage and carbon sinks in grasslands at regional to global scales each using different data and methods. These studies are cited by Scurlock and Hall (1998) and Ni (2002, 2004a) and they both concluded that the carbon storage estimates they gave were likely to be inaccurate because of limited data on vegetation area and biomass.

Because of the extent and ecological and economic importance of Chinese grasslands attempts have been made to determine their capacity for carbon storage (Fang et al. 1996; Feng et al. 2001; Ni 2001, 2002, 2004a). Fang et al. (1996) estimated the carbon storage of all vegetation types in China, including eight types of grassland with an area of 569.9 million ha, derived from statistics of land use resources and a 1980s agricultural atlas of China. They used a below- to above-ground biomass ratio derived from only five published records to estimate the below-ground biomass all over the country. Ni (2001) also estimated the carbon storage of terrestrial ecosystems in China including 11 types of grassland with an area of 405.9 million ha based on the vegetation map of Hou et al. (1982). Carbon density ranges defined by Olson et al. (1983) for major world ecosystem complexes, not actual biomass determinations made in China, were used by Ni (2002) as values in estimating the carbon storage of the Chinese ecosystems.

Ni (2002), still using Olson et al. (1983) estimates of carbon density, made more specific and detailed estimation of carbon storage in Chinese grasslands based on a classification system of 18 grassland types with an utilizable area of 298.97 million ha according to the nationwide grassland resource survey of DAHV and CISNR (1994). Ni (2002) omitted the area of scattered grasslands not classified into grassland types in the DAHV and CISNR (1994) survey. In the DAHV and CISNR (1994) survey areas of grassland smaller than 20 ha were not mapped but were grouped together as scattered grasslands covering an area of 32,023,419 ha, i.e., 9.7% of the total Chinese utilizable grasslands area.

Recognizing the appropriateness of using biomass data actually measured for Chinese grasslands Ni (2004a) estimated forage-yield-based carbon storage for the same 18 grassland types and areas used in his previous study (Ni 2002). The 18 grassland types were further divided into grassland subtypes and groups with reference to regional environments, dominant species, and vegetation height. The areas of these subdivisions were used to weight carbon storage estimates for the 18 grassland types. The carbon densities used were based on 10-year records of mean maximum standing-crop forage yields collected from all Chinese counties and provinces in the course of the national grassland resource survey (DAHV and CISNR 1994).

As there are differences in vegetation classification systems between countries and geographical regions this is likely to be a source of error in using carbon density values derived in one country to estimate carbon storage in another. The grasslands resources survey undertaken in 1980–1991 (DAHV and CISNR 1994) is the most comprehensive, systematic and authentic grassland-specific survey for China and the grassland-type areas and distribution it defines are relatively accurate and reliable. As it has been used by Ni (2002, 2004a), information from the DAHV and CISNR (1994) survey provides a satisfactory basis for the estimation of carbon storage in Chinese grasslands.

Biomass data is a basic requirement for the estimation of carbon density and storage and can be acquired in different ways but field-measured data is the most basic, direct and authentic (Wang et al. 1999; Fang et al. 2001). Though some scientists have estimated the carbon density of global vegetation (Olson et al. 1983; Vloedbeld and Leemans 1993; Foley 1995; King et al. 1995), using global average carbon density to estimate grassland vegetation carbon storage in China is likely to be inaccurate. Consequently it is necessary to establish a carbon density database based on field-measured biomass of Chinese vegetation (Wang et al. 1999).

There is a limited amount of readily accessible Chinese grassland vegetation biomass data, especially of below-ground biomass (Yu and Yu 2001; Yu 2002; Ni 2004b; Hu et al. 2005). Consequently there is a need to establish a systematic and comprehensive Chinese grassland vegetation biomass database based on actual and standardized measurements of both above- and below-ground fractions of the biomass. Because of the size of China, the variability of its terrain and climates, and the related complexity of its grassland ecosystems, this is an ambitious and arduous objective.

In this study, based on the grasslands resources survey of DAHV and CISNR (1994), we undertook nationwide systematic measurements of the above- and below-ground biomass of different grassland types. For some grassland types the measurements were elaborated to provide information on the partitioning of biomass among stem, leaf, reproductive, standing dead matter, and litter fractions, and the distribution of biomass in soil layers. Also, to supplement our actual field measurements, we made a comprehensive search for biomass data previously reported in Chinese publications to make accessible information that is not otherwise readily available internationally.

The data gathered are used to estimate the carbon densities and carbon storage of above- and below-ground fractions of Chinese grassland types and to estimate the total current storage of carbon by the grasslands of China. The results will contribute to understanding the role and importance of Chinese grassland in the global carbon cycle and climate change. Measurements of peak biomass, especially when it includes above- and below-ground fractions and separates living and dead standing biomass and litter fractions, are necessary inputs for the development and validation of models estimating net primary production (Scurlock and Olson 2002; Scurlock et al. 2002; Ni 2004b). Definition of grassland biomass levels is also relevant to the assessment of the ecological stability and sustainable livestock production from grasslands (Noy-Meir 1975). This is especially important as population growth and increasing demand for animal products intensifies the utilization of China’s grassland resource.

2 Methods

2.1 Grassland classification system and area

Seventeen major grassland types were defined according to the classification system of the Chinese grassland resources survey (DAHV and CISNR 1994). An 18th category included

Table 1 Grassland types defined in this study according to the classification system of DAHV and CISNAR (1994), their utilizable areas and distribution in China, and physiognomic groups within the grassland types

Grassland types	Grassland area (× 10^6 ha)	Distribution	Physiognomic groups	Sample sites	Record sites
Temperate meadow-steppe	12.83	North-east, north-west	Mg, Mgs, Sg, Sgs, Fb, Fbs, Sb	9 (27)	6 (6)
Temperate steppe	36.37	North	Plain: Mg, Mgs, Sg, Sgs, Fb, Sb Mount: Hg, Mg, Mgs, Sg, Sgs, Fb, Sb Sandy: Mg, Mgs, Sg, Sgs, Fb, Sb	22 (65)	48 (48)
Temperate desert-steppe	17.05	North, north-west	Hg, Mg, Sg, Sgs, Fb, Fbs, Sb	13 (39)	11 (11)
Temperate steppe-desert	9.14	North-west	Ssb, Sb	5 (15)	–
Temperate desert	30.60	North-west	Ssb, Sb, Sa	5 (15)	3 (3)
Alpine meadow	58.83	West, south west	Hg, Mg, Mgs, Sg, Sgs, Fb, Fbs	7 (19)	18 (18)
Alpine meadow-steppe	6.01	West	Sg, Sgs, Fb	3 (8)	–
Alpine steppe	35.44	West	Mg, Sg, Sgs, Fb, Sb	5 (15)	–
Alpine desert-steppe	7.75	West	Sg, Sgs	2 (6)	–
Alpine desert	5.59	West	Fb, Sb	2 (6)	–
Warm-temperate tussock	5.85	Central east, central south	Hg, Mg, Sg, Fb	–	5 (5)
Warm-temperate shrub-tussock	9.77	Central east, central south	Hgs, Mgs, Sgs, Fbs	–	5 (5)
Mountain meadow	14.92	North, west	Hg, Mg, Mgs, Sg, Sgs, Fb, Fbs	1 (3)	18 (18)
Lowland meadow	21.04	Throughout	Hg, Hgs, Mg, Sg, Fb, Fbs	4 (12)	7 (7)
Swamp	2.25	North, west, central	Hg, Fb	–	15 (15)
Tropical tussock	11.42	Central south, south	Hg, Mg, Sg, Fb	–	5 (5)
Tropical shrub-tussock[a]	14.09	Central south, south	Hgs, Mgs, Sgs, Fbs	–	5 (5)
Scattered grasslands	32.02	Throughout			
Total for China	331.00			78 (230)	146 (146)

Sample sites are the number of sites for each grassland type sampled for this study (total number of quadrats in parentheses). Record sites are the number of sites from which biomass data were obtained from 79 published records (total number of published records for each grassland site in parentheses).

Hg Tall grass/sedge; *Hgs* tall grass/sedge + shrub; *Mg* medium grass; *Mgs* medium grass + shrub; *Sg* short grass/sedge; *Sgs* short grass/sedge + shrub; *Fb* forb; *Fbs* forb + shrub; *Sb* shrub; *Ssb* semi-shrub; *Sa* small trees

[a] Combines Tropical shrub-tussock and Tropical dry shrub-tussock with savanna of Ni (2002, 2004a).

the area of other grassland types scattered in small areas throughout China that were not measured in this study. The areas in China covered by each grassland type were derived from the grassland resources survey (DAHV and CISNR 1994). The names of the grassland types, the area they occupy in China, and their regions of distribution, are listed in Table 1. Further, because of its complexity and large area, the temperate steppe was divided into the three subtypes of plain and hill temperate steppe, mountain temperate steppe, and sandy temperate steppe (Table 1). Within each grassland type and subtype communities were further classified according to the physiognomic dominant of the sites sampled, e.g., high grass/sedge, shrub, small tree (Table 1). This procedure defined 90 categories of grassland sampled for biomass. The dominant species of the grassland types are given in DAHV and CISNR (1994) and Ni (2002).

2.2 Location of sample sites

The selection of 78 sample sites (Table 1) from 12 of the grassland types was principally defined by a transect across the grasslands of northern China. This extended in a zone approximately 5,000 km long × 200 km wide from Hailar, Inner Mongolia (49°15′N, 119° 15′E), in the east to Pulan (Burang Xian), Tibet (30°15′N, 81°10′E), in the west. The most important grassland types in China were included in this transect. To achieve systematic sampling the interval between sites was set at about 50 km, but because of difficulties of topography and access, particularly in the Tibetan Plateau, some sites were more widely spaced and the average distance was greater than 50 km. Further, the selection of sampling sites was adjusted to include grassland types missed by the systematic sampling. This was done with reference to the Chinese Grassland Resource map of 1:100 million scale (Compiling Committee: CCMGRC 1992). The numbers of sampling sites for each grassland type are shown in Table 1. The geographical location of each site was determined by a Global Positioning Satellite device together with records of altitude, soil condition, grassland type, total vegetation cover, the proportion of cover provided by the dominant species, and the height of the dominant species.

Data for a further 146 samples of above- and below-ground biomass, referred to as record sites (Table 1), representative of 146 different grassland sites in 12 of the grassland types were obtained from 79 published records. A copy of the references to these records, all published in Chinese, can be provided on request.

2.3 Sampling and separation of biomass components

We aimed to measure the peak standing biomass including both that above- and below-ground at 78 sites by sampling 230 quadrats (Table 1) on areas that had not been defoliated by cutting or grazing during the growing season. These samples were obtained from July to October in 2003 and 2004. For most sites three 1-m^2 quadrats were sampled, but for the Tibetan Plateau alpine grasslands 0.25-m^2 quadrats were used. Where shrubs or small trees were present at a site the quadrats were randomly placed within 10 × 10 or 50 × 50-m quadrats used to measure woody biomass.

Above-ground biomass within the small quadrats was harvested to ground level and separated into living (green), standing dead, and litter biomass. The above-ground living biomass was further separated into leaf, stem, and sexual reproductive (flower and fruit) components.

Below-ground biomass for six of the grassland types was mostly sampled by taking either 9–36 soil cores of 3.1-cm diameter in 10-cm depth layers to 30 cm within each quadrat but some samples were obtained by digging out 25 × 25 cm pits. Roots and other below-ground plant biomass, e.g., rhizomes, contained within the excavated soil were separated with water through a 0.3-mm-mesh sieve.

The numbers of each shrub and tree species present in the 100- or 2,500-m^2 quadrats were recorded. Nine of these trees or shrubs were sampled from the large quadrat with three each representative of small, medium and large plants for the determination of biomass. The roots of these woody plants were excavated to a depth of 30–50 cm. The biomass samples were dried in an oven set at 80°C for 24 h.

2.4 Data analysis

Biomass data collected for shrubs and trees from the 100- or 2,500-m^2 quadrats were combined with those of herbaceous biomass from the small quadrats to standardize the biomass fractions as DM/m^2. Further, as samples were taken over a period extending from July to October, it was considered appropriate to adjust the above-ground biomass data to correspond to the predicted peak biomass attained in a growing season. This was done by application of the seasonal dynamics coefficient of each grassland type defined by ECGRIM (1990). The adjustment was only applied to meadow-steppe samples as these were measured in July before the period of seasonal peak of biomass in August, whereas the measurement of the other grassland types generally was during their period of peak biomass. The adjustment for meadow steppe was measured above-ground biomass × 1.19. Above-ground biomass data obtained from published sources were mostly of the seasonal peak and were not adjusted. No adjustments were made to below-ground biomass measurements we made or to those obtained from published records. Most of the below-ground biomass records from published sources were to the depth of 30 cm as for our samples.

We had no measurements of the biomass of grassland types included in the scattered grassland category (Table 1). These grasslands are patchy and widely dispersed in China, mainly in southern China, but also occur in northern China. Their occurrence is insignificant on the Tibetan Plateau where alpine grassland types occupy a large continuous area. Consequently, we estimated the biomass of the scattered grasslands as the average of the biomass of major grassland types except the alpine grasslands as determined by our measurements and the published records.

Plant carbon content of each biomass sample was calculated as 45% of plant dry matter (Olson et al. 1983; Wang et al. 1999). Thus Carbon Density kg C/m^2=Biomass kg DM/$m^2 \times 0.45$. The carbon density of each of the 90 grassland groups was determined as the average of both the measured quadrats and the values from published records of the group. These group means were then amalgamated into carbon density means for each grassland type. These means were weighted for the area of the grassland groups within each grassland type. Temperate-steppe group means were first amalgamated into the three subtypes of plain and hill temperate steppe, mountain temperate steppe, and sandy temperate steppe and then the subtype means were weighted for area before being amalgamated to provide the mean carbon density for temperate steppe. The distribution of carbon density for the areas of each of the 17 grassland types was drawn on the 1:400 million grassland resource map of China (CISNR 1996; Fig. 1). The separate areas of scattered grassland types were too small to plot at this scale.

Carbon storage of each grassland type was calculated as the mean carbon density of the grassland type × the area of the grassland type. These values were then summed to provide an estimate of the total storage of carbon in the plant biomass of the grasslands of China.

In a similar procedure to that used to obtain carbon density means, the ratios of below- and ground-ground biomass were amalgamated from individual quadrat samples to provide

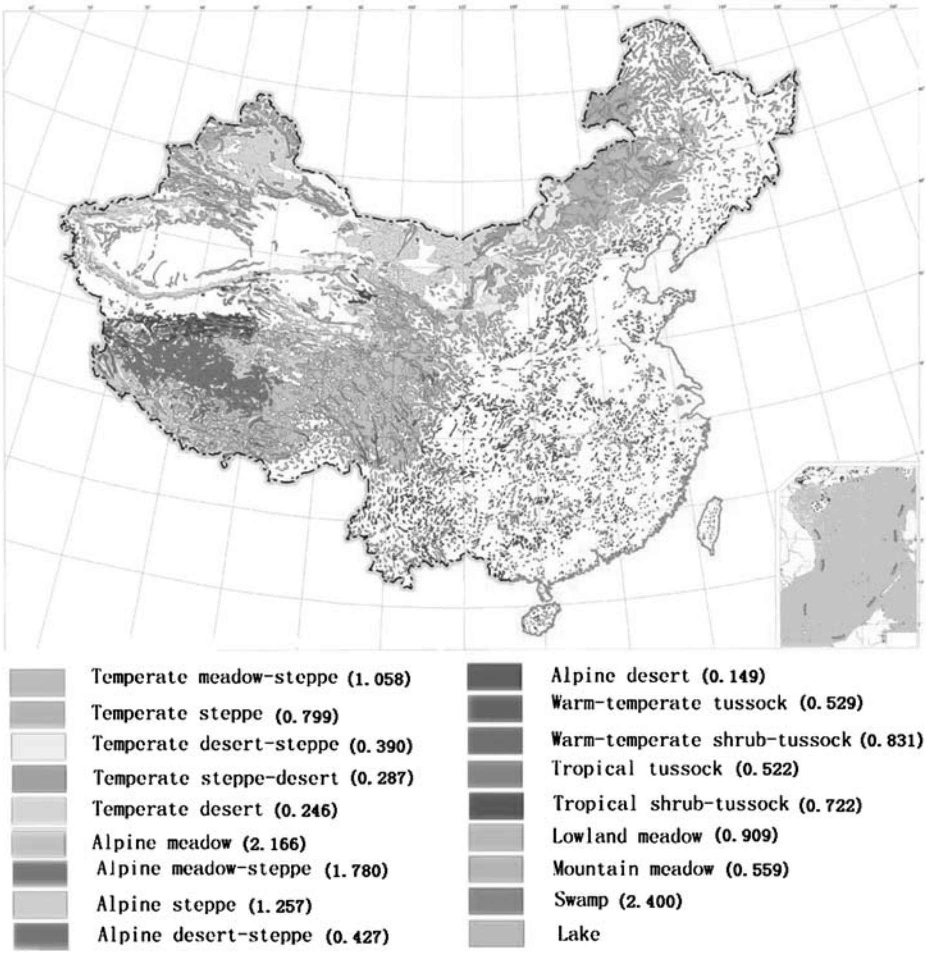

Fig. 1 Distribution of vegetation carbon density (kg m^{-2} shown in parentheses) in China based on the areas of 17 grassland types

means of this ratio for the grassland types. This was also done to provide means of the living and dead components of above-ground biomass and the distribution of carbon in below-ground layers of biomass. For a number of the grassland types there were no samples to provide means for these values. Standard deviations of means and tests for the significance of differences between means were obtained by application of SPSS10.0.

3 Results

3.1 Areas of grassland

For the purposes of this study the utilizable area of grassland in China is 330,995,458 ha (Table 1). This compares with the utilizable area of 298,972,039 ha and the total area of 355,311,993 ha given by Ni (2002). The difference in utilizable area is due to the inclusion of 32,023,419 ha of scattered grasslands in this study. The areas of tropical shrub-tussock and tropical dry shrub-tussock with savanna given by Ni (2002, 2004a) are combined as tropical shrub-tussock in this study.

Temperate steppe, temperate desert, alpine meadow, and alpine steppe together cover 48.7% of the total area of grasslands in China. The remaining 14 grassland types cover 51.3% of the area. Scattered grasslands are the fifth largest category, covering 9.7% of the grassland area. In terms of regional and climatic distribution there are 105,992,522 ha of grassland in northern China, mainly in regions with temperate and temperate-desert climates, that cover 32.0% of the grassland area. Alpine grasslands located on the Tibetan plateau cover 113,629,773 ha (34.3%) of the area. An area of 41,134,182 ha (12.4%) is covered by warm-temperate and tropical grasslands, and together lowland meadow, mountain meadow, marsh and scattered grasslands cover the remaining 70,238,981 ha (21.2%).

3.2 Carbon densities

Means for the above-ground, below-ground, and total vegetation carbon density derived from actual measurements of biomass in the field for the 17 grassland types and the estimate for scattered grasslands are presented in Table 2. The estimates of forage-yield carbon density (Ni 2004a) and the range of total vegetation carbon densities derived by Ni (2002) from Olson et al. (1983) estimates are included in the table for comparison.

Swamp, alpine meadow, alpine meadow-steppe, and alpine steppe have high total carbon densities, temperate steppe and temperate meadow-steppe, lowland and mountain meadows, and warm-temperate and tropical tussock and tussock-shrub types medium densities, and desert types low densities (Table 2). Swamp vegetation carbon density was 16 times that of alpine desert.

The zonal pattern of the total vegetation carbon densities of the grassland types of China is indicated in Fig. 1. The pattern of distribution of the temperate grassland types of northern China and the progressive reduction of their carbon densities follows the decrease of precipitation and increase of aridity from east to west in the order temperate meadow-steppe (400–600 mm rainfall), temperate-steppe (250–400 mm), temperate desert-steppe (150–250 mm), temperate steppe-desert (100–150 mm), temperate desert (50–100 mm). On the Tibetan plateau increasing aridity from southeast to northwest relates to the zonation of grasslands and to the progressive reduction of the carbon densities of the grassland types in the order alpine meadow (400–750 mm rainfall), alpine meadow-steppe (300–500 mm), alpine steppe (200–400 mm), alpine desert-steppe (100–200 mm), alpine desert (<100 mm; DAHV and CISNR 1996).

3.3 Above- and below-ground allocation of carbon

The ratio of below- to above-ground vegetation carbon density (Table 2) was markedly different between grassland types varying from equal proportions in tropical tussock and tropical shrub-tussock to 52 times the amount of carbon above ground being allocated below ground in alpine meadow. Averaged overall the grassland types there was 22 times the amount of carbon in below-ground vegetation as that allocated to above-ground biomass.

For the five temperate grassland types below- to above-ground carbon density ratio increases progressively from 3.1 for temperate desert to 14.9 for temperate meadow-steppe following the gradient of increasing rainfall from east to west as described for carbon density above. The change of the ratio is largely influenced by the trend of increasing below-ground carbon density as rainfall increases but the relatively high density of temperate-desert grassland contradicts this trend for above-ground biomass (Table 2).

Table 2 Means and standard deviations (± s.d.) for above-ground, below-ground, and total biomass carbon density derived from systematic samples and published records relating to 18 grassland types in China

Grassland type	*n*	Above-ground vegetation carbon density (kg m^{-2}) (± s.d.)	Ni (2004a) estimate forage-yield carbon density (kg m^{-2})[a] (% of above ground)	Below-ground vegetation carbon density (kg m^{-2}) (± s.d.)	Total vegetation carbon density (kg m^{-2}) (± s.d.)	Olson et al. (1983) total vegetation carbon density estimate range (kg m^{-2})	Below-ground/ above-ground vegetation carbon density ratio (± s.d.)
Temperate meadow-steppe	33	0.082 (0.023)	0.0659 (80.4)	0.975 (0.266)	1.058 (0.264)	1.0 1.5 2.0	14.95 (6.82)
Temperate steppe	113	0.068 (0.032)	0.0400 (58.8)	0.731 (0.373)	0.799 (0.371)	0.5 1.0 2.0	10.86 (6.37)
Temperate desert-steppe	50	0.050 (0.042)	0.0205 (41.0)	0.339 (0.191)	0.390 (0.211)	0.5 1.0 2.0	8.70 (5.16)
Temperate steppe-desert	15	0.045 (0.019)	0.0209 (46.4)	0.242 (0.190)	0.287 (0.186)	0.3 0.6 1.0	7.62 (7.23)
Temperate desert	18	0.117 (0.052)	0.0148 (12.6)	0.129 (0.097)	0.246 (0.125)	0.2 0.4 1.0	3.04 (4.41)
Alpine meadow	37	0.103 (0.076)	0.0397 (38.5)	2.063 (1.116)	2.166 (1.141)	0.5 1.0 4.0	52.28 (40.31)
Alpine meadow-steppe	8	0.041 (0.007)	0.0138 (33.7)	1.740 (0.041)	1.780 (0.048)	0.5 1.0 4.0	43.80 (5.68)
Alpine steppe	15	0.031 (0.006)	0.0128 (41.3)	1.226 (0.328)	1.257 (0.330)	0.5 1.0 2.0	40.12 (10.17)
Alpine desert-steppe	6	0.017 (0.001)	0.0088 (51.8)	0.410 (0.044)	0.427 (0.045)	0.5 0.8 1.5	24.07 (2.03)
Alpine desert	6	0.009 (0.001)	0.0053 (58.9)	0.140 (0.016)	0.149 (0.017)	0.02 0.05 0.2	16.43 (0.27)
Warm-temperate tussock	5	0.113 (–)	0.0739 (65.4)	0.415 (–)	0.529 (0.000)	0.5 1.0 2.0	4.26 (0.50)
Warm-temperate shrub-tussock	5	0.328 (–)	0.0796 (24.3)	0.503 (–)	0.831 (0.000)	1.0 1.6 3.0	1.69 (0.00)
Mountain meadow	21	0.183 (0.009)	0.0742 (40.5)	0.376 (0.147)	0.559 (0.154)	0.5 1.0 2.0	2.41 (1.15)
Lowland meadow	19	0.085 (0.015)	0.0778 (91.5)	0.824 (0.193)	0.909 (0.195)	1.0 1.5 2.0	11.53 (3.93)
Swamp	15	0.698 (0.319)	0.0982 (14.1)	1.702 (0.549)	2.400 (0.683)	1.5 3.0 6.0	4.01 (5.17)
Tropical tussock	5	0.263 (0.007)	0.1189 (45.2)	0.259 (–)	0.522 (0.007)	0.5 1.0 2.0	0.99 (0.05)
Tropical shrub-tussock[b]	5	0.362 (0.036)	0.1137 (31.4)	0.359 (0.012)	0.722 (0.048)	1.0 1.6 3.0	1.02 (0.04)
Scattered grasslands		0.166 (0.194)	n.v.	0.617 (0.458)	0.783 (0.535)	n.v.	3.71 (0.00)
All China		0.119 (0.050)		0.883 (0.378)	1.002 (0.397)	0.64 1.15 2.37	22.09 (12.85)

Estimates of above-ground carbon density derived from forage yields (Ni 2004a), and low, median and high estimates of total biomass carbon density derived by Ni (2002) from Olson et al. (1983) values are given for comparison.

n Number of samples used to calculate means ± s.d.

[a] The percentages of carbon density estimated from forage yield (Ni 2004a) to that of above-ground carbon determined in this study are given in parentheses.

[b] Tropical shrub-tussock type combines the tropical shrub-tussock and tropical dry shrub-tussock with savanna category of Ni (2002, 2004a). Value 0.1137 is the average of Ni's two values.

The five alpine grassland types showed a well-defined trend of increasing below- and above-ground carbon density associated with a gradient of increasing rainfall in the order alpine desert, alpine desert-steppe, alpine steppe, alpine meadow-steppe, alpine meadow. The proportional increase of below-ground carbon density along this gradient was greater than that above ground providing a well-defined trend for increased below- to above-ground biomass ratio (Table 2).

The below- to above-ground carbon density ratios of the warm-temperate grassland types together with swamp grassland are intermediate between those of the temperate grassland types and the low ratios of the tropical grassland types. The three meadow grassland types appear to be unrelated in their carbon densities and the allocation they have below and above ground (Table 2).

Below-ground vegetation carbon density was the highest in the 0–10 cm below-ground layer with an obvious reverse pyramid reduction of carbon into deeper layers (Table 3). The trend was similar for the six grassland types for which this measure was obtained, the range for the shallowest layer being 66–57%. The five temperate grassland groups showed a trend to deeper distribution of below-ground carbon as aridity increased from temperate meadow-steppe to temperate desert.

3.4 Carbon allocation among above-ground biomass components and species

The percentages of the living biomass (stem, leaf, and flower and fruit) of the five temperate grassland types increased progressively from 54.0 to 98.8% in a zonal pattern as aridity increased to temperate desert (Table 4). Lowland meadow (56.8%) and temperate meadow-steppe (54.0%) had similar proportions of living biomass. There was a corresponding decrease of dead biomass in the reverse direction that was more clearly defined for standing dead matter than for litter. The trend for living above-ground biomass for the temperate grasslands was well defined for the stem fraction as this increased progressively from 14.0% for temperate meadow-steppe to 75.7% for temperate desert. For leaf the trend was generally in the reverse direction, i.e., plants became leafier as aridity decreased (Table 4). The zonal trends related to aridity were not as well defined for the five alpine grassland types. Their proportions of living above-ground biomass ranged from 76.1 to 87.5%. The alpine grasslands types were generally leafier (leaf /(stem + leaf) ratio, 91.9–43.4%) than the temperate grassland types (73.2–22.1%), and also showed a trend of decreased leafiness as aridity increased. Allocation of carbon to sexual reproductive tissue (flower and fruit) varied from a maximum of 10.7% for alpine meadow to less than 1% for temperate desert. There was an erratic trend for the proportion of reproductive tissue to decrease with aridity and it was generally higher for the alpine than for the temperate grasslands.

Table 3 Mean percentages (standard deviations in parentheses) of below-ground carbon in three soil depth layers for seven grassland types in China

Grassland types	*n*	0–10 cm Mean (± s.d.)	10–20 cm Mean (± s.d.)	20–30 cm Mean (± s.d.)
Temperate meadow-steppe	27	66.114 (2.994)	21.702 (2.354)	12.184 (1.718)
Temperate steppe	65	65.685 (3.936)	20.062 (2.611)	14.254 (1.624)
Temperate desert-steppe	39	60.969 (7.484)	25.220 (4.255)	13.811 (4.410)
Temperate steppe-desert	15	57.365 (8.839)	29.274 (6.362)	13.360 (3.146)
Temperate desert	15	57.330 (1.110)	30.693 (2.261)	11.977 (1.785)
Lowland meadow	12	61.541 (2.840)	29.349 (2.176)	9.109 (2.740)

n Number of samples used to calculate means ± s.d.

Table 4 Mean percentages (standard deviations in parentheses) of living and dead components of above-ground carbon of 11 grassland types in China

Grassland types	*n*	Stem	Leaf	Flower and fruit	Standing dead matter	Litter
		Mean (±s.d.)	Mean (±s.d.)	Mean (±s.d.)	Mean (±s.d.)	Mean (±s.d.)
Temperate meadow-steppe	27	14.02 (4.92)	38.21 (10.61)	1.76 (2.03)	19.65 (9.95)	26.36 (9.75)
Temperate steppe	65	18.66 (5.90)	42.08 (8.72)	4.64 (3.16)	15.72 (8.26)	18.91 (8.33)
Temperate desert-steppe	39	23.89 (8.62)	36.60 (8.08)	2.79 (1.26)	8.45 (8.66)	28.28 (5.82)
Temperate steppe-desert	15	73.06 (10.02)	20.78 (7.25)	0.87 (0.94)	2.34 (5.67)	2.95 (3.62)
Temperate desert	15	75.75 (17.95)	22.30 (16.64)	0.82 (1.48)	n.v.	1.13 (2.13)
Alpine meadow	19	5.97 (3.33)	62.58 (7.13)	10.69 (3.00)	1.10 (1.91)	19.65 (6.75)
Alpine meadow-steppe	8	13.38 (0.41)	66.95 (10.37)	7.17 (4.04)	3.24 (4.60)	9.26 (1.76)
Alpine steppe	15	6.82 (2.18)	76.89 (11.23)	1.53 (0.58)	n.v.	14.76 (8.60)
Alpine desert-steppe	6	46.26 (2.52)	24.56 (1.58)	5.30 (1.19)	4.74 (0.31)	19.15 (3.31)
Alpine desert	6	41.49 (1.93)	31.76 (4.07)	4.49 (2.06)	5.07 (1.26)	17.20 (2.21)
Lowland meadow	12	10.97 (5.29)	43.97 (9.36)	1.87 (1.30)	24.93 (6.83)	18.27 (7.22)

n.v. No value; *n* number of samples used to calculate means±s.d.

3.5 Carbon storage

Above-ground and total vegetation carbon storage values derived from our study are compared with those derived from the estimates of Olson et al. (1983; Ni 2002) and from forage yields (Ni 2004a; Table 5).

As the grassland type with the largest area (Table 1) and the second highest total vegetation carbon density (Table 2) alpine meadow provides the largest portion of carbon storage (38.4%) in Chinese grassland vegetation (Table 5). The order of vegetation carbon storage of the other grasslands is alpine steppe (13.4%), temperate steppe (8.8%), scattered grasslands (7.6%), lowland meadow (5.8%), temperate meadow-steppe (4.1%), alpine meadow-steppe (3.2%), tropical shrub-tussock (3.1%) warm-temperate shrub-tussock (2.5%), mountain meadow (2.5%), temperate desert (2.3%), temperate desert-steppe (2.0%), tropical tussock (1.8%), swamp (1.6%), alpine desert-steppe (1.0%), warm-temperate tussock (0.9%), temperate steppe-desert (0.8%), alpine desert (0.3%). Together, the estimate derived from our measurements of total vegetation carbon storage in the grasslands of China is 3.316 Pg of which 1.868 Pg (56.4%) is contained in the Tibetan plateau grasslands. Temperate grasslands of northern China store 0.594 Pg (17.9%), warm-temperate and tropical grasslands of southern China 0.273 Pg (8.3%), and the remaining 0.580 Pg C (17.5%) is stored in areas throughout the country in lowland meadow, mountain meadow, swamp and the scattered grasslands.

4 Discussion

4.1 Grassland areas and carbon density estimation

The area of grassland in China that we use differs from that used by Ni (2002, 2004a) by the addition of scattered grasslands. A surrogate value of carbon density, derived from the average of what we determined for the grassland types in China excluding the alpine grasslands, has been used to obtain an estimate of the carbon the scattered grasslands store.

Table 5 Comparison of carbon storage of the utilizable areas of grassland types in China obtained from systematic samples and published records (this study), and estimates based on forage yields (Ni 2004a) and Olson et al. (1983) values for low, medium and high carbon density used by Ni (2002)

Grassland type	Above-ground biomass carbon storage (Pg; this study)	Forage yield carbon storage (Pg; Ni, 2004a)	Total vegetation carbon storage (Pg; this study)	Total vegetation carbon storage (Pg; based on Olson et al. 1983 estimates; Ni 2002)
Temperate meadow-steppe	0.01058	0.00846	0.136	0.13 0.19 0.26
Temperate steppe	0.02457	0.01456	0.290	0.18 0.36 0.73
Temperate desert-steppe	0.00856	0.00350	0.066	0.09 0.17 0.34
Temperate steppe-desert	0.00412	0.00191	0.026	0.03 0.05 0.09
Temperate desert	0.03582	0.00453	0.075	0.06 0.12 0.31
Alpine meadow	0.06050	0.02337	1.274	0.29 0.59 2.35
Alpine meadow-steppe	0.00245	0.00083	0.107	0.03 0.06 0.24
Alpine steppe	0.01101	0.00453	0.446	0.18 0.35 0.71
Alpine desert-steppe	0.00130	0.00068	0.033	0.04 0.06 0.12
Alpine desert	0.00048	0.00030	0.008	0.00 0.00 0.01
Warm-temperate tussock	0.00664	0.00433	0.031	0.03 0.06 0.12
Warm-temperate shrub-tussock	0.03210	0.00778	0.081	0.10 0.16 0.29
Mountain meadow	0.02731	0.01107	0.083	0.07 0.15 0.30
Lowland meadow	0.01790	0.01638	0.191	0.21 0.32 0.42
Swamp	0.01574	0.00221	0.054	0.03 0.07 0.14
Tropical tussock	0.03006	0.01358	0.060	0.06 0.11 0.23
Tropical shrub-tussock[a]	0.05103	0.01607	0.102	0.14 0.23 0.42
Scattered grasslands	0.05320	n.v.	0.251	n.v
All China	0.39335	0.13409	3.316[a]	1.67 3.05 7.08

[a] Tropical shrub-tussock type combines the tropical shrub-tussock and tropical dry shrub-tussock with savanna category of Ni (2002, 2004a).

These scattered grasslands should not be overlooked in future systematic measurements of the carbon density of Chinese grasslands, and assessments could be usefully made of the extent they are used for livestock production and as conservation areas especially as they may be relics of previously more extensive grassland types. They probably are important to the economies of villages in cropping regions of China where farming households keep small numbers of livestock.

Ni (2002) multiplied the Olson et al. (1983) carbon density estimates for major grassland ecosystems to estimate the carbon storage of the grassland types in China. He was mindful that these values might not be appropriate to Chinese grassland types but had no alternative because of the limited number of in situ measurements of above- and below-ground biomass in the grasslands of the country. This prompted the use of records of forage yield (Ni 2004a) as a better surrogate value than the Olson et al. (1983) estimates although Ni was mindful of the shortcomings of this approach. Not only does forage yield exclude below-ground vegetation biomass, it also excludes above-ground standing biomass that is below the cutting height, a significant proportion of which will be standing dead matter and litter (Table 4).

Another limitation of using forage yield is that it is a dynamic value varying for the seasons of the year, differing between years due to climatic factors, and being altered by management for forage production. By definition, using the peak standing crop of forage will give a value higher than the average standing crop throughout the year. This value will also be influenced by the level of utilization of grassland, with ungrazed grassland maintaining higher carbon densities. Our measurements of total vegetation biomass were also subject to these dynamic influences, and being determined only at one time lack the averaging effect of using forage yields recorded over several years (Ni 2004a). It is important to note that the carbon density we present for meadow-steppe grassland (Table 2) has been adjusted upwards 19% from the actual measurement to allow for this grassland type being sampled a month earlier than its period of peak yield. However, by undertaking extensive, systematic sampling of both above- and below-ground biomass of the main grassland types in China our use of actual biomass measurements to determine carbon density and carbon storage can not be as readily dismissed as being based on inadequate data.

4.2 Above-ground carbon density

Comparison of our estimates of above-ground carbon density with the estimates made by Ni (2004a) based on standing forage yield (Table 2) show that they are strongly correlated [r= 0.725 for 15 df, P=0.001, linear regression coefficient, forage-yield carbon density (kg m^{-2})= 0.0275+0.159 above-ground carbon density (kg m^{-2}); Fig. 2]. On average for the 17 grassland types the Ni forage-based estimates are about 34% of our above-ground vegetation carbon density measurements.

Another perspective can be obtained by using the forage-yield value of Ni (2004a) as a measure of the proportion (harvest index) of the total above-ground carbon density that is readily harvestable for utilization. This varies widely from a maximum of 91.5% for lowland meadow to a range of 3.4–5.6% for the alpine grassland types except alpine meadow (Table 2). Possible reasons for the low percentage utilization of the alpine grasslands include a very short growing season during which time yield can be harvested and the short stature of these grasslands may make a greater proportion of their above-ground biomass below easy harvesting height. Of the grassland types lowland meadows are

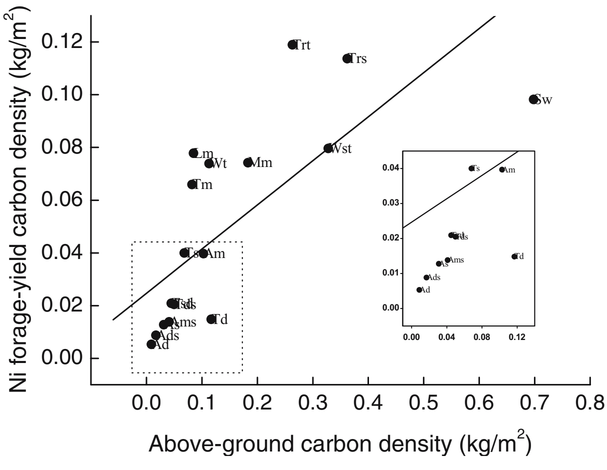

Fig. 2 Relationship between forage-yield carbon density (Ni 2004a) and above-ground vegetation carbon density (this study) for 17 grassland types in China. Grassland type symbols: *Tm*, temperate meadow-steppe; *Ts*, temperate steppe; *Tds*, temperate desert-steppe; *Tsd*, temperate steppe-desert; *Td*, temperate desert; *Am*, alpine meadow; *Ams*, Alpine meadow-steppe; *As*, alpine steppe; *Ads*, Alpine desert steppe; *Ad*, alpine desert; *Wt*, Warm-temperate tussock; *Wst*, warm-temperate shrub tussock; *Mm*, mountain meadow; *Lm*, lowland meadow; *Sw*, swamp; *Trt*, tropical tussock; *Trs*, tropical shrub-tussock

likely to be the most intensively used for forage production and this would have the effect of increasing their harvest index. It is also likely that measurements of forage yield would exclude the woody biomass of shrubs and small trees.

The information gathered for the allocation of carbon to different components of above-ground carbon (Table 4) is indicative of processes of carbon accumulation and recycling of carbon in different grassland types. The well-defined trend beginning with lowland meadow and continuing for the temperate grassland types for the reduction of the proportion of leaf to stem with increasing aridity conforms to the classic xeromorphic characteristics of reduced leaf surfaces and abundant mechanical tissue (Sinnot 1960). This trend is also present for the alpine grasslands but is probably modified by the lower temperatures of these environments reducing evaporation and allowing the development of the leafiest vegetation where precipitation is highest. Although there is a trend for decreased allocation of carbon to reproductive tissue with increasing aridity (Table 4) it is associated with considerable variation and will be strongly influenced by the timing of flowering and fruit and seed development in relation to sampling times. For example, the earlier sampling of temperate meadow-steppe, for which we made an adjustment for biomass data, probably preceded the peak period of flowering and fruit production.

The reduction of standing dead matter and litter in the transition from lowland meadow through the temperate grasslands to temperate desert in these communities associated with increasing aridity (Table 4) can be related to the progressive reduction of plant growth rates, as indicated by forage-yield (Table 2). Higher turnover rates of tissues in the wetter of these communities results in high levels of standing dead matter that in turn contribute to a high level of litter. Apart from temperate steppe-desert and temperate desert, which have low proportions of standing dead matter and litter, the alpine grasslands differ from the temperate grasslands in having low proportions of standing dead matter compared to litter (Table 4). This may be explained by alpine grasslands having slower growth and tissue death rates contributing to standing dead matter, but when dead matter enters the litter layer it decays more slowly because of lower temperature and acidic–anaerobic conditions. Further, as carbon from litter of alpine grasslands is incorporated as soil carbon it is released more slowly into atmospheric carbon. Consequently soil carbon densities of the wetter alpine grasslands, and also mountain meadow, are higher than those of other grassland types (Olson et al. 1983; Ni 2002). Modification of alpine grasslands to increase livestock production has the potential to increase the lability of the carbon they contain.

4.3 Below-ground carbon density

Obtaining measurements of below-ground biomass of plant communities is much more difficult compared to that of obtaining measurements of biomass that is above ground. Consequently there is a dearth of information about the amount of below-ground biomass of grasslands even though it has been stressed that it has an essential role in the functioning of grassland ecosystems (Davidson 1978; Christian 1987; Gillingham 1987). The importance of below-ground biomass in the determination of carbon storage is emphasized by our estimate that, averaged for all the grassland types of China, 88.1% of their carbon density is contained in their below-ground biomass. Our data also emphasizes that using a below- to above-ground ratio to estimate total vegetation carbon density from above-ground measurements only is inappropriate as the below- to above-ground ratio varies widely from 1.0 to 52.3 for different grassland types (Table 2). There are three key aspects of the variation of the below- to above-ground ratio that provide insight into why it differs for different grassland types. These are the decrease of the ratio with increasing aridity of both temperate and alpine grasslands, the particularly high ratio for alpine grasslands, and the low ratio for tropical grasslands.

The trend for the decrease of the below- to above-ground ratio with increasing aridity of the grassland type (Table 2) appears contrary to the tendency for xerophytes to have large root systems (Sinnot 1960). Noy-Meir (1973) pointed out that the root to shoot ratio of crop plants and trees often increases in dry conditions probably as a means to meet water requirements. However, not all desert plants have high root to shoot ratios and many desert winter annuals have similar ratios to non-desert annuals. For perennial plants the below- to above-ground biomass ratio should be interpreted carefully as the fractions include active roots and shoots, reserve organs that may constitute most of the below-ground biomass, and dead biomass in various stages of decomposition towards incorporation into soil carbon. Ratios between 1 and 20 have been reported for perennial grasses and forbs in arid and semiarid regions. For shrubs it is usually between 1 and 3, but in the cold deserts of Central Asia values of 6–12 are common, and for some shrubs in semiarid Australia ratios as low as 0.2–0.3 have been found. Noy-Meir (1973) concluded that a high below- to above-ground biomass ratio is not a characteristic of desert vegetation generally and may be more closely related to certain life forms or to temperature regimes than to aridity.

The below-ground biomass we measured (Table 2) did not distinguish between living roots, storage organs, or dead and decomposing plant material and is likely to give a ratio different to root to shoot ratios of single plants. In arid areas grassland vegetation is sparse, and shrubs are predominant. Han et al. (1999) in collating reports about plant biomass found that below- to above-ground biomass ratios of woody plants were much lower than those of herbaceous plants. This relates particularly well to the higher proportion of woody plants (Table 1), the high proportions of stem (Table 4), and the relatively low below- to above-ground vegetation carbon density ratios (Table 2) of temperate desert-steppe and temperate desert grasslands.

Shrubs usually extend roots deeper into the soil whereas herbaceous plants have fine and fibrous roots often at high density in the upper layers of the soil profile. Our measurements of the depth distribution of below-ground carbon of the temperate grasslands, indicating it was distributed more deeply as aridity increases (Table 3), conform to the higher shrub content of the temperate steppe-desert and temperate desert grasslands. Functionally this would allow uptake of water from a greater volume of soil, a relevant adaptation to arid

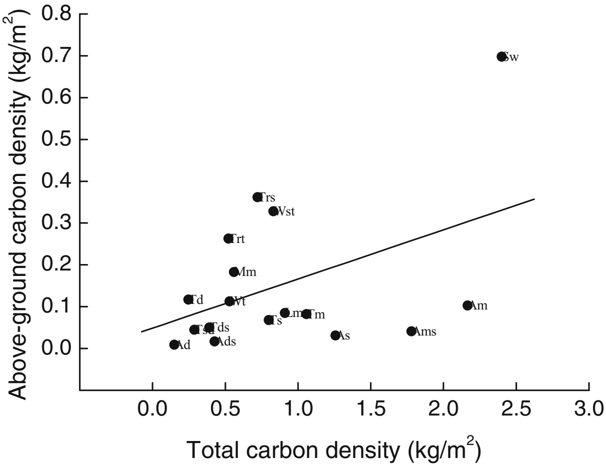

Fig. 3 Relationship between above-ground carbon density and total carbon density (above- plus below-ground) for 17 grassland types in China. Grassland type symbols: *Tm*, temperate meadow-steppe; *Ts*, temperate steppe; *Tds*, temperate desert-steppe; *Tsd*, temperate steppe-desert; *Td*, temperate desert; *Am*, alpine meadow; *Ams*, Alpine meadow-steppe; *As*, alpine steppe; *Ads*, Alpine desert steppe; *Ad*, alpine desert; *Wt*, Warm-temperate tussock; *Wst*, warm-temperate shrub tussock; *Mm*, mountain meadow; *Lm*, lowland meadow; *Sw*, swamp; *Trt*, tropical tussock; *Trs*, tropical shrub-tussock

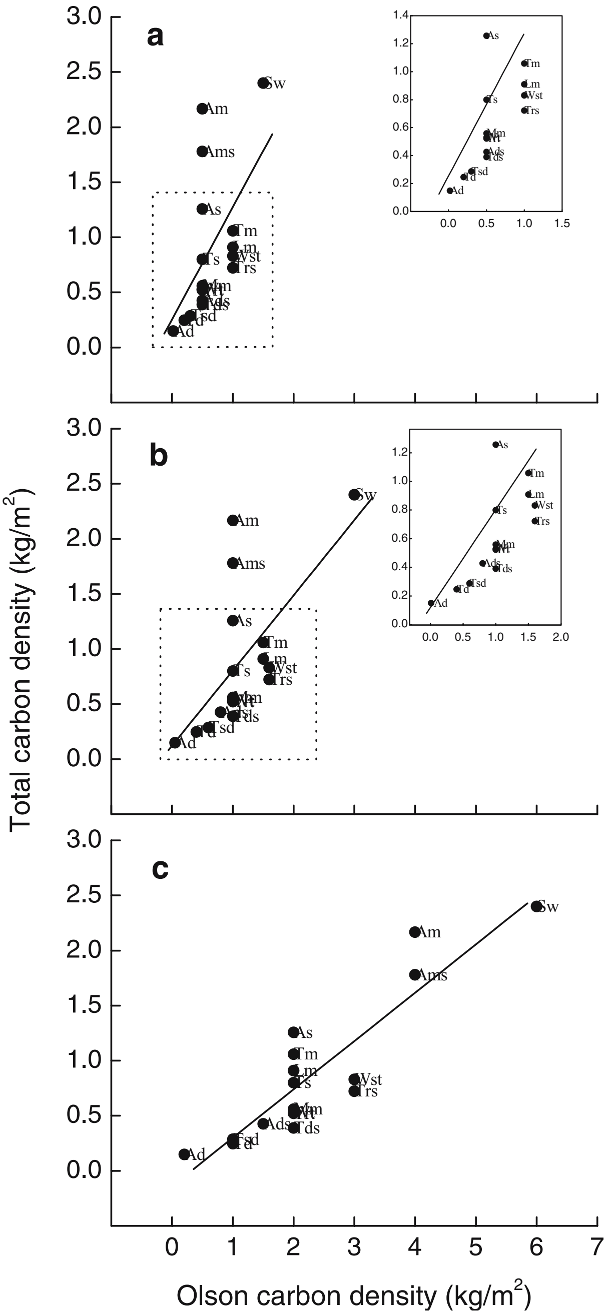

Fig. 4 Relationship between total carbon density determined in this study and **a** low, **b** medium, and **c** high carbon density estimates defined by Olson et al. (1983) and applied to 17 grassland types in China by Ni (2002). Grassland type symbols: *Tm*, temperate meadow-steppe; *Ts*, temperate steppe; *Tds*, temperate desert-steppe; *Tsd*, temperate steppe-desert; *Td*, temperate desert; *Am*, alpine meadow; *Ams*, Alpine meadow-steppe; *As*, alpine steppe; *Ads*, Alpine desert steppe; *Ad*, alpine desert; *Wt*, Warm-temperate tussock; *Wst*, warm-temperate shrub tussock; *Mm*, mountain meadow; *Lm*, lowland meadow; *Sw*, swamp; *Trt*, tropical tussock; *Trs*, tropical shrub-tussock

environments. The pattern of reduction of below-ground vegetation carbon determined for seven grassland types consistently indicates that it is concentrated in the upper layers of the soil. Because of the difficulty of measuring below-ground biomass, to obtain more data of this area of carbon storage it may be sufficient to sample only the upper 10 cm of soil and to extrapolate what additional vegetation carbon lies below this layer using formulae for each grassland type.

The higher below- to above-ground carbon density ratios of alpine compared to temperate grasslands (Table 2) is consistent with other observations of the characteristics of alpine vegetation (Körner 1989). Reasons for this include different shrub proportions, lower root turnover and decomposition rates, and plant characteristics that aid adaptation to extended periods of low temperature (Noy-Meir 1973; Chapin et al. 1987). Gill et al. (2002) have indicated a high correlation between below-ground biomass and mean annual temperature with more below-ground biomass occurring under lower temperature conditions. Wang et al. (1995), Chen and Wang (2000) and Zhou (2001) found that below-ground biomass was higher in the Tibetan alpine areas than in temperate areas of Inner Mongolia. Their explanation was that plants partition more energy reserves into roots in low temperature conditions, an adaptation that aids their survival. Low temperatures reduce photosynthetic rate of plants, but also reduce respiratory losses (Gill and Jackson 2000) allowing the accumulation of biomass. High root mass in low temperature environments raises soil temperature improving the absorption of soil nutrients (Norbyr and Jackson 2000).

4.4 Total vegetation carbon density

Because of the marked differences between the grassland types in the ratios of their below- to above-ground carbon density ratios (Table 2), the forage-yield-based estimate of carbon density (Ni 2004a) is unrelated to the total vegetation carbon density measured in our study (r=0.173 for 15 *df*, ns.), and there is only a weak relationship between the above-ground and total vegetation carbon density measured in this study [r=0.447 for 15 *df*, P=0.07, linear regression above-ground carbon density (kg m^{-2})=0.049+0.118 total vegetation carbon density (kg m^{-2}); Fig. 3]. On average for the 17 grassland types of the total vegetation carbon density 17% (i.e., 2.595/15.031) is above ground but there is wide variation around this average and three groups of grassland types are clearly separated from it. Swamp grassland is characterized by a high level of above-ground carbon density together with high total carbon density, contrasting with alpine meadow and alpine meadow-steppe that have a low proportion of above-ground carbon relative to their high level of total carbon. The tropical grassland types together with warm-temperate shrub-tussock are similar in having a high proportion of above-ground carbon relative to their total vegetation carbon.

Like alpine meadow and alpine meadow-steppe, the high total carbon densities of swamp grassland can be related to the anaerobic, acidic conditions of the below-ground horizons that restrict decomposition allowing the accumulation of vegetation carbon. The relationship (Fig. 3) indicates that the above-ground vegetation of swamp is on average taller and denser than that of alpine meadow and alpine meadow-steppe even though swamp and alpine

Table 6 Relationships between total vegetation carbon densities of 17 grassland types in China and low, medium, and high estimates for the grassland types given by Olson et al. (1983)

Olson estimate	*df*	*R*	*P*	a	*b*
Low	15	0.561	0.02	0.251	1.024
Median	15	0.654	0.004	0.116	0.686
High	15	0.898	0.0001	−0.141	0.439

The fitted regressions (Fig. 4) are: total carbon density kg m^{-2} =a+b (Olson et al. 1983 estimate carbon density)

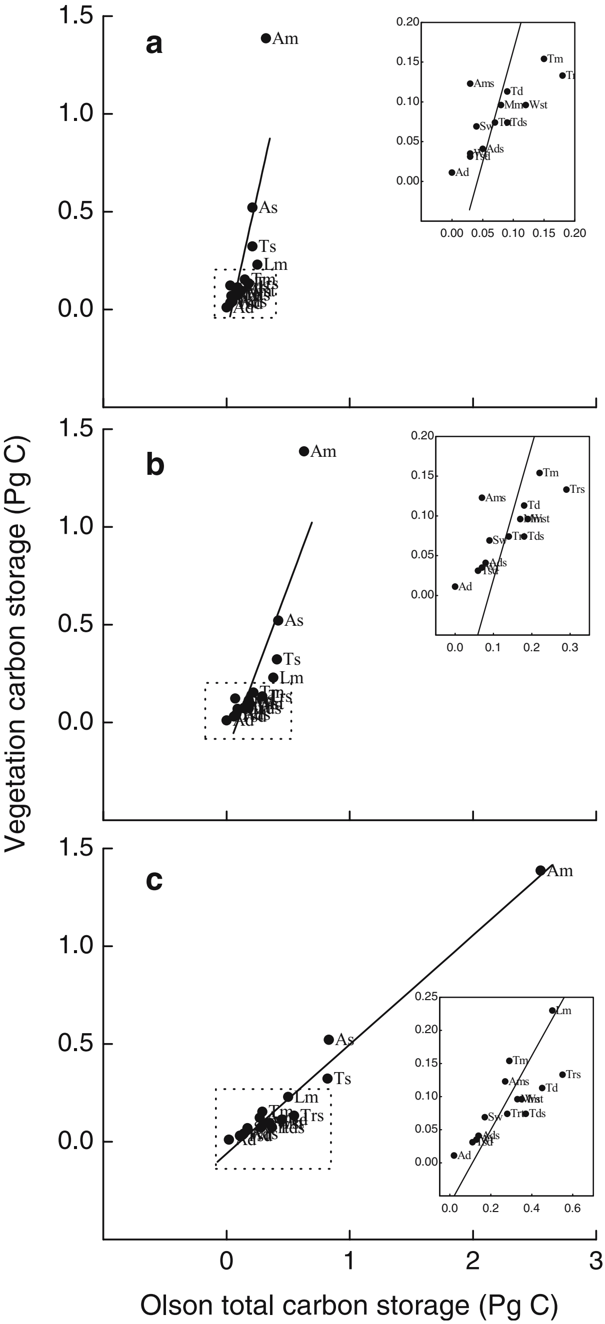

Fig. 5 Relationship between vegetation carbon storage determined in this study and **a** low, **b** medium, and **c** high total storage estimates given by Olson et al. (1983) and applied to 17 grassland types in China by Ni (2002). Grassland type symbols: *Tm*, temperate meadow-steppe; *Ts*, temperate steppe; *Tds*, temperate desert-steppe; *Tsd*, temperate steppe-desert; *Td*, temperate desert; *Am*, alpine meadow; *Ams*, Alpine meadow-steppe; *As*, alpine steppe; *Ads*, Alpine desert steppe; *Ad*, alpine desert; *Wt*, Warm-temperate tussock; *Wst*, warm-temperate shrub tussock; *Mm*, mountain meadow; *Lm*, lowland meadow; *Sw*, swamp; *Trt*, tropical tussock; *Trs*, tropical shrub-tussock

meadow have tall-grass/sedge as physiognomic components and swamp is without shrubs (Table 1). In contrast, root turnover and decomposition rates in tropical grasslands are higher, reducing the accumulation of below-ground vegetation carbon and its proportion relative to total vegetation carbon. The higher proportion of above-ground carbon for tropical shrub-

Table 7 Relationships between vegetation carbon storage determined from actual biomass measurements in this study of 17 grassland types in China and low, medium, and high estimates storage by the grasslands based Olson et al. (1983) values

Olson estimate	*df*	*R*	*P*	*a*	*b*
Low	15	0.804	0.0001	−0.121	3.063
Median	15	0.875	0.0001	−0.134	1.750
High	15	0.987	0.0001	−0.052	0.558

The fitted regressions (Fig. 5) are: Measured carbon storage Pg C=a+b (Olson et al. 1983 estimated carbon storage)

tussock and warm-temperate shrub-tussock compared to tropical tussock and warm-temperate tussock (Fig. 3) may be due also to the woody biomass provided by shrubs.

Relationships between the total vegetation carbon densities of Chinese grassland types determined in this study and the three levels of estimates provided by Ni (2002) based on Olson et al. (1983) values (Table 2) are examined in Fig. 4 and related statistics are given in Table 6. The relationships are well defined increasing in significance from the low to high estimates. The total carbon densities determined in this study average about 1.4 times the low Olson-based estimate (Fig. 4a) but this is mostly due to the relatively high measured values for swamp, alpine meadow and alpine meadow-steppe grassland. The measured values average about 0.8 times the median Olson-based estimate (Fig. 4b) and 0.4 times the high estimate (Fig. 4c). For the high estimate swamp, alpine meadow, and alpine meadow steppe conform to the same regression coefficient as the other grassland types (Fig. 4c). These relationships pose the question as to whether Chinese grasslands in their present state have carbon densities well below their potential maximum? Although our measurements were on areas not cut or grazed in the year they were sampled, they had been utilized for forage production in previous years with the possibility that a part of the vegetation carbon they stored in their pristine state has been mobilized and lost from their ecosystems. Long-term studies to monitor changes of carbon density of grasslands excluded from cutting or grazing are required to answer the question posed.

4.5 Carbon storage in Chinese grassland vegetation

The relationships between our estimates of the vegetation carbon storage in the 17 grassland types in China and those derived by Ni (2002) from the low, median and high carbon density estimates of Olson et al. (1983; Table 5) are plotted in Fig. 5 and related statistics are given in Table 7. The relationships are highly significant, to a large extent because both estimates are calculated from the same areas, and increase in significance from to the low to the high Olson et al. (1983) estimates. The large effect of alpine meadow on the relationships because of the very large area of this grassland type (Table 1) and its high vegetation carbon density is very apparent.

Our estimate of the carbon storage of Chinese grassland excluding the scattered grasslands are 1.8, 1.0 and 0.4 times those of the low, median and high estimates derived from Olson et al. (1983) values. The low and median average estimates are inflated particularly by the measured total vegetation carbon storage of alpine meadow (Table 5) of 1.274 Pg C compared to the low, median, and high estimates of 0.32, 0.63 and 2.55 Pg C for this grassland type calculated by Ni (2002). It is coincidental that the median value of 3.06 Pg C for the vegetation carbon storage of the grasslands of China emphasized by Ni (2002) approaches the 3.32 Pg C storage derived from our study (Table 5). The median storage value given by Ni (2002) should be increased by 9.6% to adjust for the increased area we use to estimate carbon storage to give an estimate of 3.35 Pg C.

The importance of carbon storage by temperate grasslands has been widely affirmed (Thornley et al. 1991; Hall et al. 1995; Tate et al. 1995; Sala et al. 1996), but, as stated by Ni (2002), the importance of carbon storage in alpine grasslands has not been sufficiently emphasized. Our estimates indicate that 56.4% of the carbon stored in grassland vegetation in China is contained in the alpine grasslands of the Tibetan Plateau of which 68.2% is in alpine meadow. The temperate grasslands of northern China store a further 17.9% of the total. Because alpine grassland ecosystems are fragile, if CO_2 increases associated with climate change impact on cooler regions (Hall et al. 1995), alteration of the lability of alpine grassland carbon storage may have a significant and long-lived effect on global carbon cycles (Ni 2002). A more immediate concern is the possibility of modifying the lability of carbon stored in alpine grasslands as a consequence of more intensive use for livestock production.

5 Conclusions

Of the variety of estimates of the amount of carbon stored in the grassland vegetation of the world none can be accepted with certainty because of the dearth of systematic measurement of above- and particularly below-ground biomass of grasslands, and variations in estimates of grassland area. Olson et al. (1983) estimated the storage of 50.4 Pg C in a world grassland vegetation area of 5,155 million ha. Prentice et al. (1993) estimated 27.9 Pg C in 4160 million ha, WBGU (1988) 75 Pg C in 3,500 million ha, and from the biomass data of Whittaker and Likens (1975) 54.9 Pg C in 5,200 million ha. From these estimates, our measurements indicate that Chinese grasslands cover 6.4–9.5% of the world's grassland area and store 4.4–11.9% of the carbon contained in grassland vegetation. This constitutes a pool for carbon sequestration that should be accounted for in considerations of the global climate cycle and climate change.

Our study indicates the usefulness of, and probably the necessity for, more standardized vegetation measurements, and in particular below-ground biomass measurements, to obtain more meaningful estimates of global carbon. It provides a basis for further measurements to complete the picture of carbon storage in Chinese grasslands and this should be related and extended to other world grassland regions. Also, there is a need for long-term experiments to determine the potential maximum carbon storage capacity of grasslands and to define and better understand how grassland management practices mobilize and return stored carbon to the atmosphere.

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