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Article

Huge Carbon Sequestration Potential in Global Forests

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Abstract: Forests play an important role in mitigating climate change by absorbing carbon from atmosphere. The global forests sequestrated 2.4±0.4 Pg C y^{-1} from 1990 to 2007, while the quantitative assessment on the carbon sequestration potential (CSP) of global forests has much uncertainty. We collected and compiled a database of site above-ground biomass (AGB) of global mature forests, and obtained AGB carbon carrying capacity (CCC) of global forests by interpolating global mature forest site data. The results show that: (i) at a global scale, the AGB of mature forests decline mainly from tropical forests to boreal forests, and the maximum AGB occurs in middle latitude regions; (ii) temperature and precipitation are main factors influencing the AGB of mature forests; and (iii) the above-ground biomass CCC of global forests is about 586.2±49.3 Pg C, and with CSP of 313.4 Pg C. Therefore, achieving CCC of the existing forests by reducing human disturbance is an option for mitigating greenhouse gas emission.

Key words: climatic gradient; global forests; mature forest; above-ground biomass (AGB); carbon carrying capacity (CCC); carbon sequestration potential (CSP)

1 Introduction

Forests are important terrestrial ecosystems. On one hand, the biomass carbon storage of global forests is 289–356 Pg C (IPCC 2000; FAO 2010; Pan *et al*. 2011), accounting for 77% biomass carbon storage of global terrestrial ecosystems (IPCC 2000). On the other hand, the carbon exchange between global forests and the atmosphere is huge. For example, the average GPP of global forests between 1998 and 2005 is about 59 Pg C (Beer *et al*. 2010), and the global intact forests sequestrated 2.4±0.4 Pg C y^{-1} from 1990 to 2007 (Pan *et al*. 2011). There are two factors primarily limiting the forest carbon sequestration. First, the forest can not absorb carbon permanently. With forest growth, the carbon stock would achieve a saturated state, called carbon carrying capacity (CCC) (Keith *et al*. 2009). That means that the forest carbon sequestration has an upper limit (Odum 1969), named carbon sequestration potential (CSP) (Keith *et al*. 2009). Second, not all the forests can be conserved due to deforestation and forest degradation. Therefore, focusing attention onto the forests with high CCC and CSP would be a trade-off between protecting forest carbon sink and meeting human demand for forest products.

For the regional average biomass of existing forests, the tropical rainforests (IPCC 2006), Northwest of USA (Hudiburg *et al*. 2009) and Southeast of Australia (Keith *et al*. 2009) have high biomass carbon density. There are two factors determining the high carbon density. One is forest age or recovery years from disturbance, which determines forest biomass directly (Pregitzer and Euskirchen 2009). The other is climate (temperature, precipitation, etc.), which have important impacts on the ecosystem succession, pattern and production (Odum 1969; Stegen *et al*. 2011).

Climatic gradient is believed to determine the spatial pattern of forest biomass. Correspondingly, the average forest biomass decreases from tropical to subtropical, temperate and boreal forests based on IPCC reports (IPCC 2006). Some scholars proposed that the average biomass of old-growth forests, much higher than that of current forests as advised by IPCC (2006), could represent the potential biomass carbon storage (carbon carrying capacity) of the biomes (Keith *et al*. 2009). According to Keith (Keith *et al*. 2009), the old-

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growth forests in temperate moist forests have the highest carbon storage, higher than both of tropical and boreal forests. That means the CCC of temperate moist forests is higher than those of tropical and boreal forests. The forest CSP is the difference between the current carbon storage and CCC under current climate regime and disturbances (Odum 1969; Keith *et al*. 2009; Liu *et al*. 2011). It can be inferred that temperate moist forests also have higher CSP than tropical forests. Therefore, the relationship between the CCC, CSP and current biomass (or climatic factors) of global forests may be not a linear positive correlation in different ecological zones. The assessments of CCC and CSP of global forests are mostly based on simulating carbon balance of productivity and respiration determined by climatic factors (Cramer *et al*. 2001). However, it is difficult to evaluate the uncertainty in simulation results (Cramer *et al*. 2001; Keenan *et al*. 2012) and assess the carbon sequestration potential of global forests due to the lack of old-growth forest site data.

We collected and compiled global mature forest site inventory data, because the biomass and growth stage of mature forests were close to those of old-growth forests under similar climate. Based on these data, we calculated the average above-ground biomass carbon density of mature forests in each ecological zone, analyzed the spatial pattern of carbon carrying capacity of global forests, and finally evaluated the carbon sequestration potential of global existing forests.

2. Materials and methods

2.1 Data collection and compilation

The data used in this study include: global mature forests biomass site data, climate data, global ecological zoning data from FAO (http://www.fao.org/), and global forests distribution data from the Global Land Cover 2000 database (http://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php) with a spatial resolution of 1 km.

2.1.1 Mature forest biomass

Mature forests have a similar meaning with old-growth forests, especially for the above-ground biomass and growth stage of forests. A mature forest is when the growth of timber has reached a stage of being extremely slow or being almost saturated, and the timber volume begins to decrease or quality begins to degrade due to various reasons (Meng 2007). The methods are different for determining whether a forest is old-growth forests (Kira and Shidei 1967; Odum 1969; Luyssaert et al. 2007; Pregitzer and Euskirchen 2009; Goulden *et al*. 2011). To make the data comparable between different sites and cover more ecological zones, we treated both of "the old-growth forest sites" in the literature and the forests ≥ 80 years (Odum 1969) as mature forests, taking into account of both the amount and pattern of the forest sites. The stand age of mature forests were obtained from the literature or from tree core rings in our field work (Liu *et al*. 2011).

The global mature forest biomass data, with a total of 728 sites, are primarily from literatures and site surveys, among which 118 from Keith *et al*. (2009), 79 from Lewis *et al*. (2009), 112 from Luyssaert *et al*. (2007), 297 from Luo (1996), and 119 from other literatures (CERN) and 3 from our field investigations (Liu *et al*. 2011). All the sites biomass data were collected from forest inventory. The forest sites were invented in permanent plots, or temporary plots located at random. The size of each sample plot is ≥0.06 h[a] in boreal and temperate forests (Liu *et al*. 2011), and ≥0.1 ha in subtropical and tropical forests (Feng *et al*. 1999; Lewis *et al*. 2009). All trees ≥4 cm in diameter at breast height (DBH) were measured in boreal and temperate forests (Liu *et al*. 2011), and ≥10 cm in tropic forests (Lewis *et al*. 2009). The diameter and height measurements were converted to biomass using the published allometric equations (Feng *et al*. 1999; Lewis *et al*. 2009; Liu *et al*. 2011).

The factor of biomass to carbon stock was assumed 0.5 g C g^{-1} (Lewis *et al*. 2009). All the site locations are shown in Fig. 1. The dataset covers 15 ecological zones, including all the zones listed in the IPCC except tropical shrubs, subtropical dry forests and subtropical grasslands. For the sites that lack of latitude or longitude, we obtained them in

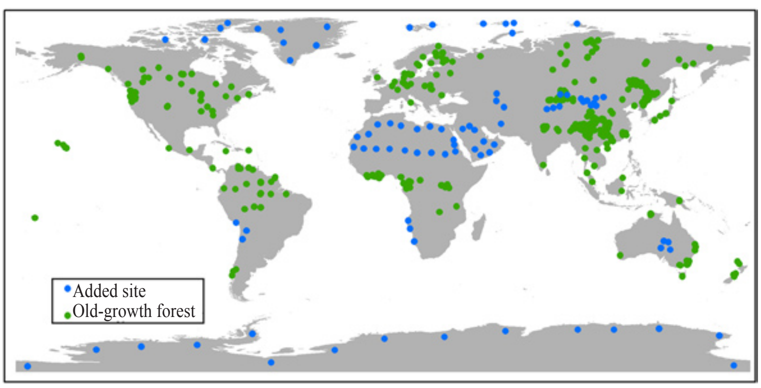

Fig. 1 Distribution of mature forest sites and added sites.

Note: Mature forest (green point) data is collected from literatures and field survey; of added sites (blue point), assuming the above-ground biomass is 0 Mg C hm^{-2}. The added sites are distributed in Antarctic, Sahara, Arabia, Patagonia, Kalahari, Great Sandy, Kara-kum, Taklimakan Desert, Gurbantunggut Desert, Tenger Desert, and Gobi Desert

Google Earth according to the site names.

2.1.2 Spatial dataset of climate

The mean annual temperature and precipitation of China from 1980 to 2000, with a spatial resolution of 1km (Yu *et al*. 2004; He *et al*. 2004; Liu *et al*. 2004), were collected from the Chinese Ecosystem Research Network (CERN). The climate data in other regions of the world is the average monthly temperature and precipitation from 1961 to 1990, were obtained from IPCC (http://www.ipcc-data.org/, New *et al*. 2002). Two spatial resolutions of the global climate were used, 10′ and 0.5°, respectively. The mean annual temperature data used in this paper is the average of the 12 monthly temperature, and the mean annual precipitation is the sum of the 12 monthly precipitation. The mean annual temperature and mean annual precipitation of mature forest sites are mainly collected from the literature. We only extracted for the sites that lack of temperature and precipitation from the global (with a spatial resolution of 10′) or China's climatic data. The global climatic data, with a spatial resolution of 0.5°, is used in Partial Thin Plate Smoothing Spline interpolation (See 2.2.3).

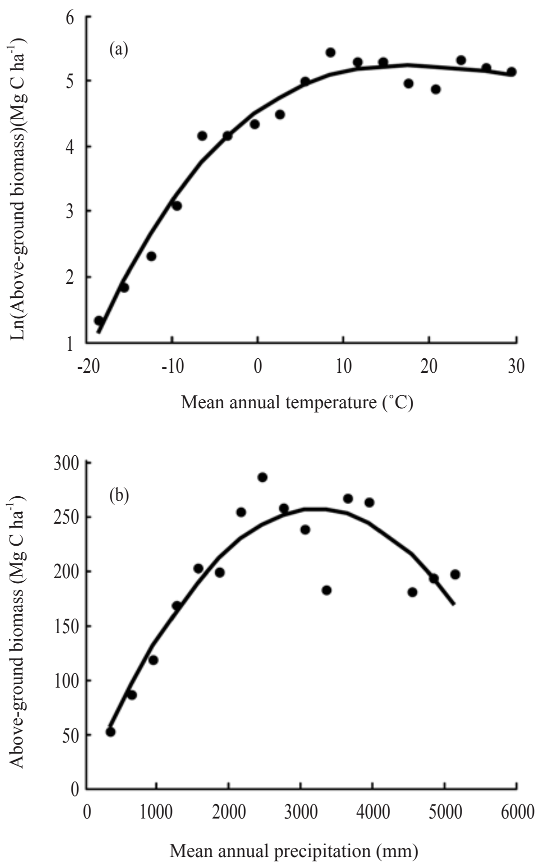

Fig. 2 The pattern of above-ground biomass of global mature forests with mean annual temperature (a) and mean annual precipitation (b).

The points are the average above-ground biomass of mature forests, calculated with every 3˚C mean annual temperature or 300mm mean annual precipitation

2.2 Forest above-ground biomass carbon carrying capacity

According to the classical theory of ecology (Odum 1969): the carbon storage increases rapidly when the forests are in developmental stage or recovery stage from disturbance, thus, the forests act as carbon sink. When the forests are older than 80 or 100 years, called old-growth forests, the carbon stocks grow slowly, and the carbon exchange between forests and the atmosphere gradually approaches an equilibrium state, thus, the forests act as a relatively weak carbon sink or mainly in a state of carbon neutrality (Jarvis *et al*. 1989; Zhou *et al*. 2002). Therefore, the carbon stocks of old-growth forests can be regarded as a reference of the carbon carrying capacity of the forests under similar climate.

The spatial climate data was interpolated from site observations for the limited amount of observation sites. Similarly we can obtain regional carbon carry capacity from site data by interpolation. Or, if old-growth forest biomass and climatic variables, such as temperature and precipitation, can be combined with empirical regression relationships, the regional carbon carry capacity could be simulated based on spatial climate data.

We applied Above-ground Biomass-Climate Regression Kriging, Inverse Distance Weighted interpolation (Bartier and Keller 1996), and Thin Plate Smoothing Spline interpolation (Hutchinson 2001) to simulate carbon carrying capacity of forest above-ground biomass, with a spatial resolution of 1 km. We added 82 points with 0 Mg C ha^{-1} of above-ground biomass in the Arctic, Antarctic and deserts to increase the number of control points and enhance the precision of interpolation (Fig. 1).

2.2.1 Above-ground Biomass-Climate Regression Kriging

We used equation (1), primarily based on the "law of the minimum" (Lieth 1973), to determine the relationship of mature forest above-ground biomass to mean annual temperature and mean annual precipitation (Fig. 2).

$$B_t=\exp(0.000048T^3-0.003959T^2+0.094659T+4.535219),\quad R^2=0.97,\ P<0.01$$
$$B_p=-0.000024P^2+0.155735P+5.15818,\ R^2=0.82,\ P<0.01$$
$$B_m=\min(B_t, B_p) \tag{1}$$

where B_t is the above-ground biomass of mature forests primarily limited by mean annual temperature (Mg C ha^{-1}); T is the mean annual temperature (℃); B_p is the above-ground biomass of mature forests primarily limited by mean annual precipitation, Mg C ha^{-1}; P is the mean annual precipitation, mm; and B_m is the above-ground biomass of mature forests controlled by both mean annual temperature and mean annual precipitation, Mg C ha^{-1}.

Apart from the equation (1), we also tried binary linear equation (B_m=61.7+2.3294T+0.00427P, R^2=0.31, P<0.01) in describing the relationships of above-ground biomass of mature forests to mean annual temperature and mean annual precipitation. Consequently, the root mean square error (RMSE) of the binary linear equation is 163 Mg C ha^{-1}, higher than the 136 Mg C ha^{-1} of the equation (1). So, equation (1) was chosen.

The above-ground forest biomass (B) is also affected by disturbances, site conditions and other factors. These factors cannot be quantified at the global scale, nor explained by climatic factors. We classified the effects of these factors into the residual (ε). Thus, the actual above-ground biomass (B, Mg C ha^{-1}) of mature forests is the sum of the above-ground biomass (B_m) controlled by climatic factors and the residual error caused by other factors (equation (2)).

$$B = B_m + \varepsilon \tag{2}$$

We called the equation (1) and (2) the Regression Kriging model for the above-ground biomass of mature forests and climate (cited below as the "Regression Kriging"). We used the model in combination with global mean annual temperature and mean annual precipitation data to generate the potential above-ground biomass (B) of global forests. In the process, 70% of the sites were used in the model and 30% of the sites were used for validation.

We compared the simulated forest above-ground biomass with measured values (Fig. 3). They mainly follow a positive linear relationship (y=1.0296x, R^2 = 0.65).

2.2.2 Inverse Distance Weighted interpolation

Inverse Distance Weighted interpolation assumes the character of geographic factor is more similar with nearer sites (Bartier and Keller 1996); this relationship can be described by equation (3):

$$B = \frac{\sum_{i=1}^{n} B_i W_i}{\sum_{i=1}^{n} W_i} = \frac{\sum_{i=1}^{n} B_i d_i^{-\beta}}{\sum_{i=1}^{n} d_i^{-\beta}} \tag{3}$$

where B is the forest site above-ground biomass to be estimated, Mg C ha^{-1}; n is the total number of sites that control the value of site B. We applied fixed site number (n =6), not fixed radius, for nonuniform distribution of forest sites. The results were in accord with the pattern of actual forest biomass. B_i is the forest above-ground biomass of the i^{th} control site, Mg C ha^{-1}; W_i is the weight of the i^{th} control site; d_i is the distance between the i^{th} control site and the estimated site; β is an exponent to describe the decay rate of weight along with distance. We defined β=2 to guarantee the estimated sites were controlled by the nearest forest site. We implemented Inverse Distance Weighted interpolation in ArcGIS 10.0 (ESRI 2010).

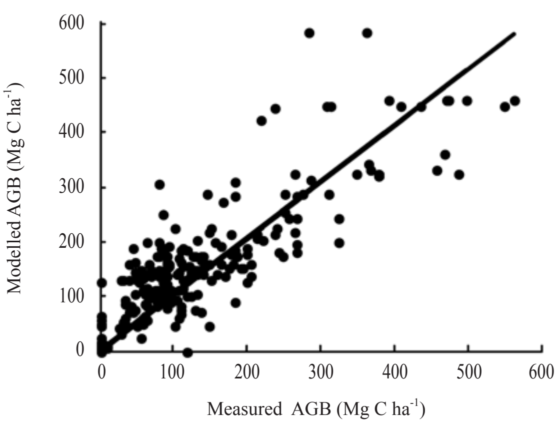

Fig. 3 The simulated forest above-ground biomass against measured above-ground biomass.

The bold line is the fitted line y=1.0296x, R^2= 0.65

2.2.3 Partial Thin Plate Smoothing Spline interpolation

Partial thin plate smoothing spline is an extension of thin plate smoothing spline incorporates multi-variate linear regression, in addition to the independent variables. The method can be interpreted to equation (4):

$$B = f(B_i) + b^T (P,T) + \varepsilon \tag{4}$$

where B is the forest site above-ground biomass to be estimated, Mg C ha^{-1}; B_i is the above-ground biomass of mature forest sites, also spline independent variables; f is the smooth function of B_i; P and T are independent covariates, represent precipitation and temperature, respectively; b is the coefficients of P and T; ε is the error.

We used ANUSPLIN 4.2 (Hutchinson 2001) to implement the partial thin plate smoothing spline interpolation. In the process of interpolation, the above-ground biomass of mature forests was the independent variable, the mean annual temperature and mean annual precipitation were covariates, and the cubic spline interpolation was used.

2.3 Forest above-ground biomass carbon sequestration potential

The major approaches to study forest carbon sequestration potential include: long-term continuous forest inventory (Jarvis *et al*. 1989; Fang *et al*. 2001; Pan *et al*. 2004; Roxburgh *et al*. 2006); space-for-time, i.e. to investigate the forest carbon storage in different succession stages instead of long-term investigation (Odum 1969; Shvidenko and Nilsson 2002; Kull *et al*. 2007); and comprehensive analysis of environmental limiting factors (Lieth 1973; Shi *et al*. 2009; Wang *et al* 2010), etc.

The carbon stocks of old-growth forests can be treated as the reference of the carbon carrying capacity (or Carbon Stock of referred Ecosystem, CSr, Mg C ha^{-1}). We could evaluate the carbon sequestration potential of each ecological zone or global forests by assessing the differences of carbon storage between old-growth forests and current forests (Smithwick *et al*. 2002; Hudiburg *et al*. 2009; Liu *et al*. 2011).

$$\text{CSP} = \text{CSr} - \text{CS} = \text{CCC} - \text{CS} \tag{5}$$

where CSP is Carbon Sequestration Potential of forest, Mg

C ha^{-1}; CS is current Carbon Stock of forest, Mg C ha^{-1}; CCC is Carbon Carrying Capacity of forest, Mg C ha^{-1}.

3 Results

3.1 Carbon carrying capacity of forest above-ground biomass

We compared the results from Regression Kriging with that from Thin Plate Smoothing Spline, Inverse Distance Weighted, and Sites Mean (see Appendix S2). The results suggest that the values of carbon carrying capacity derived from different methods is consistent with each other for most ecological zones; the spatial patterns of carbon carrying capacity of forest above-ground biomass is similar for the results of Regression Kriging, Thin Plate Smoothing Spline and Inverse Distance Weighted (Fig. S4). We therefore used the average results of the three methods as the carbon carrying capacity of global forests (Fig. 4).

The total above-ground biomass carbon carrying capacity of forests in major biomes (Table 1) mainly decreases from tropical to temperate, boreal and subtropical forests, are 354.2, 85.4, 79.5 and 65.9 Pg C, respectively (Fig. 4). Tropical rainforests have the highest total above-ground biomass carbon carrying capacity, is 220.6 Pg C, followed by tropical moist deciduous forests and boreal coniferous forests with 78.2 and 44.9 Pg C, respectively. The potential forest above-ground biomass carbon density of ecological zones declines from tropical to subtropical, temperate and boreal forests, which are 186, 160, 136 and 65 Mg C ha^{-1}, respectively.

The total above-ground biomass carbon carrying capacity of forests in each continent (Table 2) decreases from South America to Africa, North America, Asia, Europe and Australia, are 140, 133, 103, 100, 73 and 23 Pg C, respectively. The carbon carrying capacity of Australia is up to 196 Mg C ha^{-1}, which is the highest among all continents, followed by Africa (186 Mg C ha^{-1}), and the lowest one is

Table 1 Carbon carrying capacity and carbon sequestration potential of the forest above-ground biomass in each ecological zone.

Ecological zone	Area (10^9 ha)	Biome default above-ground biomass* (Mg C ha^{-1})	Default total above-ground biomass*, (Pg C)	Average carbon carrying capacity† Mean ± SD (Mg C ha^{-1})	Total carbon carrying capacity† Mean ± SD (Pg C)	Carbon sequestration potential§ (Pg C)
World	4.19		298.5	140 ± 12	586.2 ± 49.3	287.7
Tropical	1.91		211.6	186 ± 20	354.1 ± 39.0	142.5
Tropical rainforest	1.03	141	147.4	213 ± 42	220.6 ± 43.3	73.2
Tropical moist deciduous forest	0.47	85	39.8	168 ± 19	78.2 ± 8.5	38.4
Tropical dry forest	0.22	61	13.3	112 ± 35	24.3 ± 7.6	11.0
Tropical mountain system	0.15	66	9.8	181 ± 16	26.7 ± 2.3	16.9
Tropical shrubland	0.04	33	1.3	105 ± 49	4.3 ± 2.0	3.0
Tropical desert	0.00		–	43 ± 29	0.0 ± 0.0	0.0
Subtropical	0.41		31.6	160 ± 18	65.9 ± 7.4	34.3
Subtropical humid forest	0.19	103	20	186 ± 22	35.9 ± 4.0	15.9
Subtropical mountain system	0.12	66	8	140 ± 27	17.1 ± 3.3	9.1
Subtropical steppe	0.04	33	1.4	153 ± 22	6.6 ± 0.9	5.2
Subtropical dry forest	0.04	61	2.2	126 ± 26	4.5 ± 0.9	2.3
Subtropical desert	0.02		–	89 ± 5	1.8 ± 0.1	1.8
Temperate	0.63		31.7	136 ± 13	85.4 ± 7.9	53.7
Temperate continental forest	0.28	56	16	114 ± 16	32.4 ± 4.4	16.4
Temperate mountain system	0.24	47	11.5	152 ± 13	37.2 ± 3.0	25.7
Temperate oceanic forest	0.05	85	4.2	210 ± 13	10.3 ± 0.6	6.1
Temperate steppe	0.03		–	93 ± 14	3.1 ± 0.5	3.1
Temperate desert	0.01		–	162 ± 4	2.4 ± 0.0	2.4
Boreal	1.22		23.6	65 ± 2	79.5 ± 2.5	55.9
Boreal coniferous forest	0.65	26	16.9	69 ± 8	44.9 ± 5.3	28.0
Boreal mountain system	0.39	14	5.4	62 ± 9	23.9 ± 3.6	18.5
Boreal tundra woodland	0.19	7	1.3	58 ± 14	10.7 ± 2.6	9.4
Polar	0.03		–	49 ± 18	1.3 ± 0.5	1.3

* Biome default above-ground biomass is the above-ground biomass for each forest biome from IPCC (2006) vol.4 Table 4.12 multiplied by the carbon factor in Table 4.3. Default total above-ground biomass is the result of the Biome default above-ground biomass multiplied by the forest area.

† Average and total carbon carrying capacity for each ecological zone are the average results of the three interpolation methods, including: Regression Kriging, Inverse Distance Weighted, and Thin Plate Smoothing Spline.

§ Carbon sequestration potential is the difference of total carbon carrying capacity and default total above-ground biomass.

Table 2 The above-ground biomass, carbon carrying capacity and carbon sequestration potential of forests for each continent.

Continent	Area	Above-ground biomass*		Carbon carrying capacity†		Carbon sequestration potential
		Mean	Total	Mean ± SD	Total ± SD	
	(10^9 ha^a)	(Mg C ha^{-1})	(Pg C)	(Mg C ha^{-1})	(Pg C)	(Pg C)
Africa	0.71	63	44.5	198±19	140.1±13.5	95.6
Asia‡	0.57	49	28.1	173±33	99.5±18.2	71.4
Australia	0.12	70	8.2	217±18	25.6±1.8	17.4
Europe§	1.08	33	35.8	69±9	74.0±9.2	38.2
North America	0.89	35	31.5	123±4	110.0±3.6	78.5
South America	0.82	100	81.5	167±40	137.0±32.4	55.5
World	4.19	55	229.6	140±12	586.3±49.3	356.7

* The above-ground biomass is total biomass from FAO (2010) multiplied by 0.8.
† The carbon carrying capacity of forest above-ground biomass was calculated with the three interpolation methods of Regression Kriging, Inverse Distance Weighted, and Thin Plate Smoothing Spline. The Mean and SD are the mean and standard deviation for the results of the three methods.
‡ Asia excludes Russian Federation.
§ Europe includes Russian Federation.

Europe (68 Mg C ha^{-1}).

3.2 Carbon sequestration potential of global forests

We took the carbon sequestration potential as the difference between the carbon carrying capacity and the current carbon storage. The current above-ground forest biomass is 298.5 Pg C from IPCC (Table 1), 290.4 Pg C from Pan *et al*. (2011), 229.6 Pg C from FAO (Table 2), and the average is 272.8 Pg C. The carbon carrying capacity of the global above-ground forest biomass can reach 586.2±49.3 Pg C totally, based on the interpolation results of the above-ground biomass of the mature forests (Fig. 4). Therefore, the carbon sequestration potential of the global forest above-ground biomass should be 287.7–356.6 Pg C based on the three versions of current carbon stocks, with an average of 313.4 Pg C, approximately equivalent to the current forest above-ground biomass carbon storage, which means the global forests would be expected to have huge capacity of carbon sequestration and play a significant role in mitigating climate change.

The carbon sequestration potential decreases from tropical to boreal, temperate and subtropical forests. Based on the current carbon storage of each ecological zone from the IPCC report, tropical rainforests have the highest above-ground biomass carbon sequestration potential, which is 73.2 Pg C, followed by tropical moist deciduous forests and boreal coniferous forests, which have carbon sequestration potential of 38.4 and 28.0 Pg C, respectively.

Based on the current carbon storage of each ecological zone from the FAO, the carbon sequestration potential of Africa, North America, and Asia are 95.6, 78.5 and 71.4 Pg C, respectively, more than the other continents. For the biomes, the carbon sequestration potential mainly decreases from tropical to boreal, temperate and subtropical forests, with 142.5, 55.9, 53.7 and 34.3 Pg C, respectively.

4 Discussion

4.1 Carbon sequestration potential of global forest vegetation

Above-ground biomass represents one part of forest ecosystem carbon stocks. Other stocks, including below-ground biomass, litter, dead wood and soil organic matter should be accounted for too. We calculated the ratio (R_a) of above-ground biomass to total biomass (including living and dead biomass), approximately 0.77 for global mature forests (n = 538), where n is the number of sites, and R_a

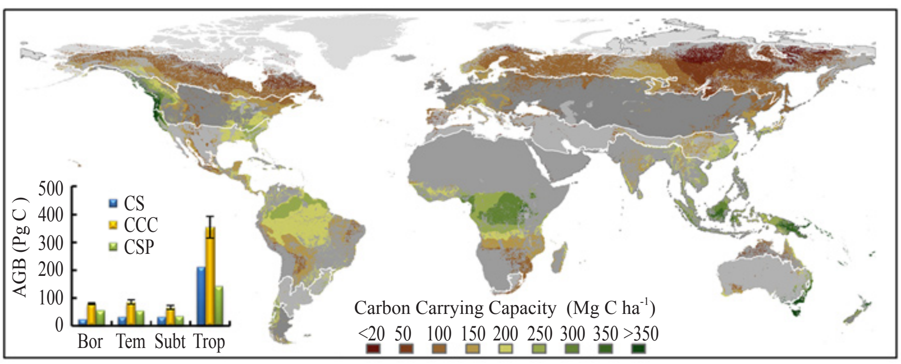

Fig. 4 Pattern of carbon carrying capacity of global forest above-ground biomass.

Note: AGB is total above-ground biomass of forests for each climatic zone. Bor is boreal forests, Tem is temperate forests, Subt is subtropical forests, and Trop is tropical forests. CSP is carbon sequestration potential of forest (Mg C ha^{-1}); CS is current carbon stock of forest (Mg C ha^{-1}); and CCC is carbon carrying capacity of forest (Mg C ha^{-1})

declines as forest age. For example, R_a is 0.80 (n = 364) for the 80–200 year forests, 0.73 (n = 41) for the 200–300 year forests, and 0.63 (n = 34) for the forests over 300 years. If we conservatively set the R_a to 0.80 (Houghton 2005; Chapin *et al*. 2011), the carbon sequestration potential of global forest biomass (including both above- and below-ground biomass) would be about 391.8 Pg C.

4.2 Carbon sequestration potential of global forest soils

About 44% of the current forest carbon is stocked in soil (Pan *et al*. 2011). Increased forest biomass will lead to more litter fall, which means more organic carbon input to soils. We cannot estimate soil carbon sequestration potential of global forests due to limitation of fewer sites. Some studies showed that the ratio (R_s) of soil organic carbon (SOC) to total ecosystem carbon storage was about 0.74 (n = 12) in Savanna (Chen *et al*. 2003), about 0.40 (n = 284) of old-growth forests in southeastern Australia (Keith *et al*. 2010), and 0.20 of old-growth forests in the West Coast of U.S.A. (Hudiburg *et al*. 2009). Thus, we deduced that forest soil would have great carbon sequestration potential.

4.3 Uncertainty for estimating carbon sequestration potential of global forests

There was no agreed method for estimating forest biomass carbon sequestration potential at a global scale (Keith *et al*. 2010). We tried three methods in up-scaling the biomass carbon carrying capacity from mature forest site data to a regional scale. But, the following issues may lead to some uncertainties: first, in this study, the mature forest site data covered most of the global ecological zones, but in some regions only had a few sites. Second, each ecosystem under same climate would develop toward climax based on the succession theory (Chapin *et al*. 2002). We did not consider the significant difference of biomass, may existed within the same climate grid, caused by topography, forest age and disturbance. Third, human activities (such as afforestation and reforestation), nitrogen deposition, increased CO_2 concentration, and increased temperature all affect carbon sequestration capacity of the global forest ecosystems (Muller-Landau 2009; Pan *et al*. 2011). Therefore, an improved approach is needed to provide more reliable carbon accounting system.

4.4 Improve forest management to stock more carbon

Forests are one of the most important carbon stocks. IPCC includes land use/land cover change (including deforest, afforest and reforest) into the greenhouse gas inventory (IPCC 2006). This study suggests the biomass of mature forests is much higher than the average biomass of the current forests, and the carbon storage of global forests may increase to about a twofold stock of the current forests. So, to achieve the carbon carrying capacity of forests and reduce the human-induced disturbance on current forests would be another approach in reducing green house gas emission effects (Keith *et al*. 2009).

Appendix S1 The global mature forest above-ground biomass-climate relationship

The relationship between the above-ground biomass and mean annual temperature, mean annual precipitation for all mature forest sites can be described with the function: B=61.7604+0.0427P+2.3294T, R^2=0.31, P<0.01. Where, B is the above-ground biomass of mature forests (Mg C ha^{-1}), P is mean annual precipitation (mm), T is mean annual temperature. The forest biomass increases with increasing mean annual temperature and mean annual precipitation (Fig. S1). This trend is similar to the regions like East of Asia (B=107.4244+0.065098P+6.5139T, R^2=0.33, P<0.01), but different from tropical rainforests in Africa (B=909.591+0.022274P-29.764T, R^2=0.29, P<0.01) where the biomass decrease with increasing temperature (Fig. S2).

Appendix S2 The carbon carrying capacity of the above-ground biomass of global forests

We compared the results of carbon carrying capacity of the above-ground forest biomass of each ecological zone

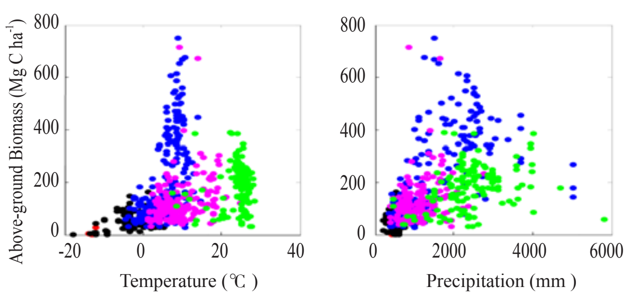

Fig. S1 The patterns of above-ground biomass of global mature forests with mean annual temperature and mean annual precipitation.

The points with colors of red, black, blue, pink and green are the forests located in the climatic zones of polar, boreal, temperate, subtropical and tropic.

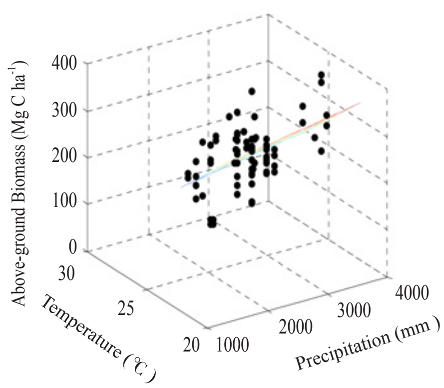

Fig. S2 The patterns of above-ground biomass of mature forests in tropical rainforest with mean annual temperature and mean annual precipitation in Africa.

The dot is the above-ground biomass of mature forest sites; the colored plane is the regress relationship of above-ground biomass to mean annual temperature and mean annual precipitation.

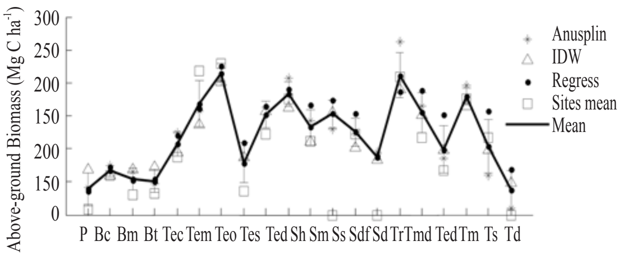

Fig. S3 Carbon carrying capacity of the above-ground forest biomass of each ecological zone.

Anusplin is Thin Plate Smoothing Spline interpolation; IDW is Inverse Distance Weighted interpolation; Regress is above-ground biomass-climate Regression Kriging; Sites mean is the mean of above-ground biomass of all sites for each ecological zone; and Mean is the mean of the four results. The error bar is the standard deviation with the four results. P: polar; Bc: boreal continental forest; Bm: boreal mountain system; Bt: boreal tundra woodland; Tec: temperate continental forest; Tem: temperate mountain system; Teo: temperate oceanic forest; Tes: temperate steppe; Ted: temperate desert; Sh: subtropical humid forest; Sm: subtropical mountain system; Ss: subtropical steppe; Sdf: subtropical dry forest; Sd: subtropical desert; Tr: tropical rainforest; Tmd: tropical moist deciduous forest; Tdf: tropical dry forest; Tm: tropical mountain system; Ts: tropical shrubland; and Td: tropical desert.

for four methods (Fig. S3), and compared spatial pattern of forest carbon carrying capacity of the above-ground biomass for three interpolation methods (Fig. S4).

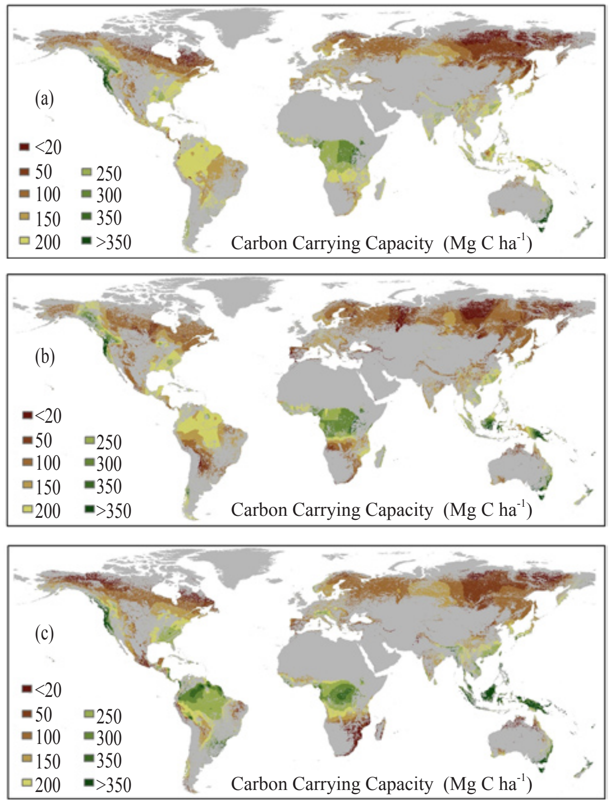

Fig. S4 The carbon carrying capacity of global forests above-ground biomass.

The results of Regression Kriging (a), Inverse Distance Weighted (b) and Thin Plate Smoothing Spline (c) from up to down

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全球森林固碳潜力巨大

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摘 要： 森林是重要的陆地生态系统碳汇。1990–2007年间全球森林平均每年从大气中吸收固定2.4±0.4 Pg C，但对全球森林未来固碳量的评价多是基于气候因素的过程模型的模拟结果，很少有基于森林调查样地数据评价全球森林固碳潜力的研究。我们收集整理野外调查和已发表的成熟林生物量数据728条，建立全球成熟林生物量数据库。根据成熟林地上生物量碳储量空间插值，得到全球森林地上生物量碳容量，进而评估全球森林地上生物量的固碳潜力。结果显示：(1)全球成熟林地上生物量自赤道向两极整体呈递减趋势，但最大值出现在中纬度区；(2)气温和降水是影响成熟林地上生物量的重要因素；(3)全球森林地上生物量碳容量约为586.2±49.3 Pg C，其地上生物量固碳潜力为313.4 Pg C。因此，充分发挥现有森林的碳吸存能力，减少对现有森林碳库的干扰，是土地利用变化之外减缓温室气体排放的又一可选途径。

关键词： 气候梯度；全球森林；成熟林；地上生物量；碳容量；固碳潜力