NEW ESTIMATES OF CARBON STORAGE AND SEQUESTRATION IN CHINA'S FORESTS: EFFECTS OF AGE–CLASS AND METHOD ON INVENTORY-BASED CARBON ESTIMATION

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Abstract. We developed a volume-to-biomass method based on age groups representative of forest development stages to estimate live tree biomass, C, and biomass and C accumulation rates of China's forests between 1973 and 1993. The data were from plot-level forest inventory, national-level inventory statistics, and ecological site studies specified to estimate biomass in different tree components. Our results indicate that carbon storage in China's forests was 4.34 Pg C in the early 1990s, an increase of 13% since the early 1970s. The annual forest C sequestration rate from the late 1980s to early 1990s was 0.068 Pg C/yr and approximately four- to five-times higher than in the 1970s and 1980s. The large C sink in China's forests in the early 1990s was likely related to age structure changes that had developed to more productive stages, a consequence of reforestation and afforestation programs from the 1960s. The results were compared with other C store estimates, which were based on the same inventory data. Various methods can produce estimates that differ in the direction of C flux as well as its magnitude. Separating age groups with the volume–biomass method could cause a 27% difference in estimated carbon pools but an 89% difference in C sequestration rates whereas the biomass density method would provide an estimate that differs by 65% in the C pools.

1. Introduction

Recent research highlights the importance of understanding terrestrial carbon exchange in the Northern Hemisphere, particularly the role of the Northern Hemisphere as a carbon sink (Schimel et al., 2001; IPCC, 2001). Forest ecosystems play dominant roles in the carbon cycle because they store a large amount of C in vegetation and soil, and interact with atmospheric processes through the absorption and respiration of CO_2 (Brown and Schroeder, 1999; Houghton et al., 1999; Goodale et al., 2002). Forest inventory data are valuable resources in forest carbon research because they provide true ground-based estimates of C stock and fluxes across heterogeneous regions, and are statistically representative of land-use change and disturbance (Birdsey, 1992; Brown and Schroeder, 1999).

Our knowledge of forest resource conditions throughout the Northern Hemisphere varies considerably. Comprehensive, long-term data from forest inventories of European and North American countries are readily available and show that these

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two regions have sequestered C for several decades (Kauppi et al., 1992; Apps et al., 1999; Birdsey and Heath, 1995, Goodale et al., 2002). Forest inventory data for Asian countries, on the other hand, were difficult to access until recently. New analyses from forest inventory data suggest that the amount of C in Russia forests is increasing, but the rate of increase cannot yet exhibit sufficient to be estimated with accuracy (see Alexeyev et al., 1995; Liski and Kauppi, 2000; Nilsson et al., 2000). Similarly, the amount of carbon in China's forests could be increasing by a small amount (Fang et al., 2001), but estimates of the increase are uncertain (Fang et al., 2001; Zhang and Xu, 2003).

Few studies synthesize the inventory-based C estimates across several countries in the Northern Hemisphere to depict a large-scale C balance for the forest sector (Goodale et al., 2002). Such a compilation is problematic because the forest C estimates from different countries and data sources are not fully compatible due to inconsistent definitions, inventory designs, estimation methods, and models. We have limited knowledge about uncertainties in most inventory-based forest carbon estimates and about cross-nation comparisons of forest inventory studies for carbon (Smith and Heath, 2000; Goodale et al., 2002).

In this study, we develop an age-based volume-to-biomass method to estimate live tree biomass, and C, and biomass and C accumulation rates in China's forests, based on data from four forest inventories between the 1970s and 1990s. In Data and Method, we present the steps and data sources for estimating forest biomass and C in China's forests (Figure 1). In Discussion, we compare our results with the results from a similar forest carbon study in China (Fang et al., 1998, 2001), and analyze the relevance of separating age groups in forest carbon estimates. We also compare and analyze several methods commonly used in inventory-based forest carbon estimates (i.e. Volume–biomass, Biomass Expansion Factor, Mean Density and Wood/Bark Gravity methods), thus offering insights into the different methods. To present our research in a greater context, we compare our estimates for China's forests with those for the U.S. and Russia and reveal the effect of forest age structure on C sequestration rates. Finally, we analyze sources that cause uncertainties in the inventory-based forest carbon estimates. Our analysis provides information for developing more consistent, accurate estimates of forest carbon stocks in future inventory-based carbon research, which is one of many efforts to improve the understanding of forest carbon sequestration in the Northern Hemisphere.

2. Data and Methods

2.1. ESTIMATION OF TOTAL FOREST TREE BIOMASS USING ALLOMETRIC EQUATIONS

Forest inventory reports usually include estimates of growing stock (the volume of wood typically harvested for products) and lack information about noncommercial

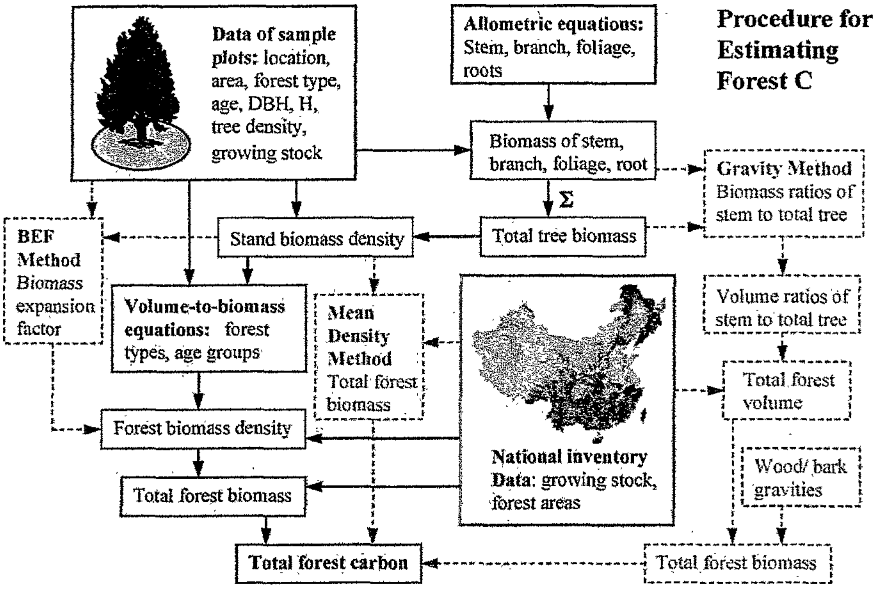

Figure 1. The diagram represents the volume-to-biomass method for estimating forest C. Red boxes are data sources or collected information; blue, the medium and final products. The dashed boxes and lines represent other estimation methods.

components (roots, tops, branches, foliage, and noncommercial species) that should be included to calculate total forest tree biomass. Therefore, before we convert growing stock volume to tree biomass, we need empirical data or equations to estimate biomass in various tree components.

Allometric equations are regression equations that estimate biomass of whole trees or tree components based on tree diameter at breast height (DBH) and tree height (H). We collected 1285 allometric equations, which were grouped into 333 sets (a set includes the equations respectively for calculating biomass of tree stems, branches, foliage, and roots), for 98 major forest types and tree species in China (Luo, 1996). Most of the equations were from the literature and a few were developed using data from supplemental field studies.

We also used the datasets from 4622 routine inventory plots and 793 additional reference plots that represent a wide range of China's forest types and plot conditions (Figure 2). These datasets contain information, among other things, about plot location, coordinates, forest types and species, age classes (young, middle-aged, premature, mature and overmature), arithmetic means of DBH and H (for trees in plots with DBH > 4 cm), area, growing stock volume and tree density. The data were derived from either databases or publications of provincial forest agencies. Most of the data were from plots designed by the National Inventory of the Forest Ministry

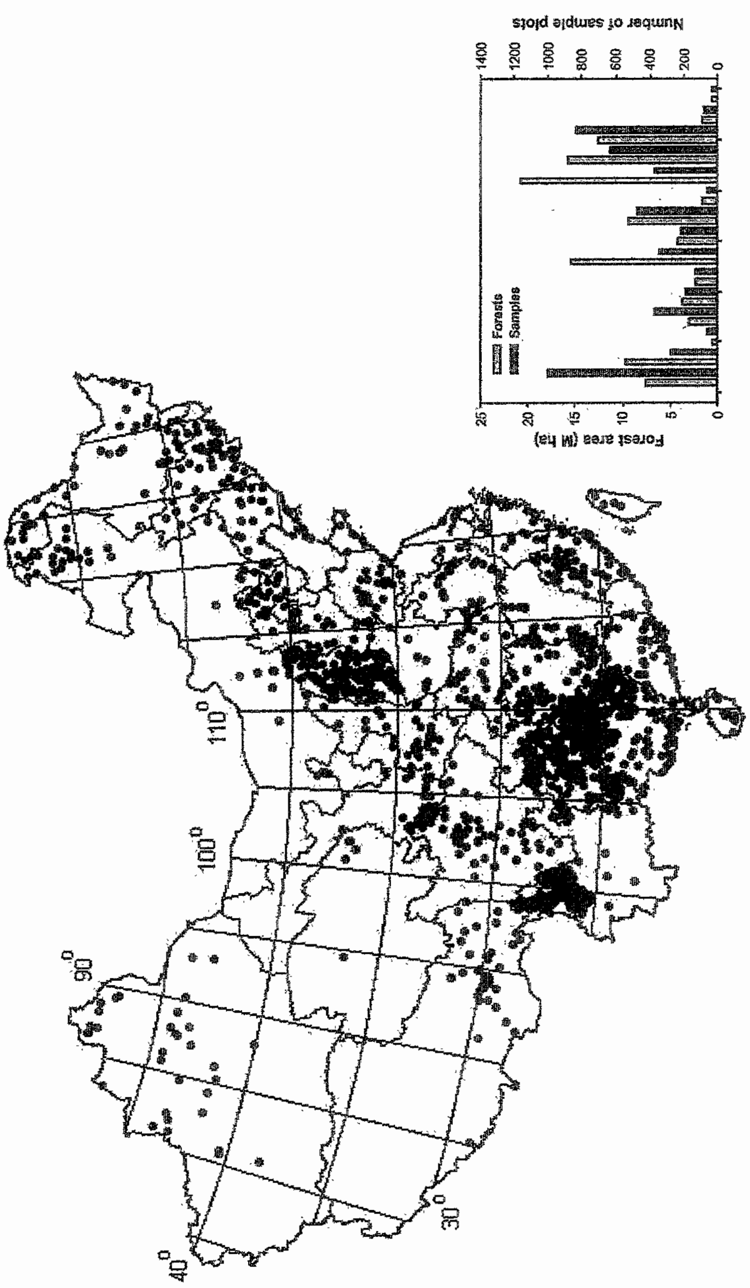

Figure 2. Geographical distribution of the sample plots (5415) used to develop the volume–biomass equations. Inset: the distributions of forest type areas and sample plots.

of China and were collected during 1989–1993 (FRSC, 1994). Some supplemental inventory data were collected in the 1970s from the national inventory reference plots (793 plots) that are independent of the routine inventory plots.

We then used our collected sets of allometric equations specific for certain forest types and regions to calculate biomass of tree stems, branches, foliage, and roots using available information of stand DBH and H of each age group, before adding the biomass of individual tree components to estimate total tree biomass (Figure 1). Sometimes, several sets of allometric equations exist for the same forest type. When this happened, we calculated the tree biomass using each set of equations and averaged their results. If allometric equations did not exist for a certain forest type in a region, we adopted the sets of equations from a neighboring region. We calculated stand biomass density by multiplying the total tree biomass by the number of trees, then dividing the result by the plot area (Figure 1).

2.2. THE VOLUME–BIOMASS EQUATIONS FOR AGE GROUPS AND FOREST TYPES

One method used to convert growing stock data from forest inventories to tree biomass is the volume-to-biomass method (Brown and Lugo 1984; Brown et al., 1989, 1997; Fang et al., 1998, 2001). In this method, linear regression equations are established between growing stock (m^3 ha^{-1}) and stand biomass density (Mg ha^{-1}) for various forest types. However, volume–biomass equations are often developed for universal age groups probably because of insufficient data specific to various age groups. Here, we developed equations separately, using the available data from 5415 plots, for different age groups that represent forest development stages and major forest types in China. In total, 52 equations were developed (Table I).

We included woodlands and bamboo forests in this study. The volume–biomass equations for woodlands are nonlinear and were developed for regions rather than age groups (Table II). For bamboo forests, stand biomass density is simply a linear function of tree (bamboo) density (individuals ha^{-1}) (Table II).

2.3. ESTIMATION OF NATIONAL FOREST BIOMASS AND CHANGE

The China Forestry Administration (CFA) has conducted nation-wide and periodic-forest inventories since the 1970s and compiled national forest inventory statistical data that were reported as the Forest Resource Statistics of China (FRSC). The inventory plots were in grid polygons systematically located across the country, which is similar to the sampling strategy used in the U.S. The inventory plots were remeasured every 5 years by the provincial district's forestry bureaus following the standards designed by CFA. The permanent ground survey plots for forest inventories numbered 140 000 in 1973–1976 and 1977–1981; 255 000 in 1984–1988; and 227 000 in 1989–1993 (Zhang and Xu, 2003). There were about 100 000

TABLE I

Parameters to calculate forest live-biomass density (y, Mg ha^{-1}). Biomass density is expressed as a function of stand growing stock (x, m^3 ha^{-1}), $y = a + b \cdot x$, where a (Mg ha^{-1}) and b (Mg m^{-3}) are constants for a forest type. Data are from 793 field plots and 4622 inventory plots collected by Luo (1996)

Forest type	Age group	Vol range (m^3/ha)	a	b	Plot number	R^2
Larix	≤40a	4–284	15.620	0.6589	94	0.8211
	41–80a	4–611	31.878	0.6367	91	0.7924
	81–100a	69–411	15.857	0.6703	14	0.9003
	101–140a	15–547	12.576	0.7406	37	0.9420
	≥141a	50–792	−7.9247	0.7757	70	0.9403
Abies, Picea, Tsuga	≤40a	6–273	13.210	0.7376	69	0.8605
	41–80a	29–755	12.042	0.6317	227	0.8662
	81–100a	54–933	41.312	0.4982	109	0.8238
	101–140a	48–1235	48.690	0.4306	239	0.7913
	≥141a	69–3831	39.201	0.4313	358	0.8557
Pinus sylvestris var. *mongolica*	≤40a	8–130	18.967	0.6490	26	0.8078
	41–100a	87–379	34.902	0.3927	19	0.5867
	≥101a	198–500	22.470	0.3742	23	0.8375
Pinus tabulaeformis, Platycladus orientalis	≤30a	5–293	11.127	0.6967	239	0.9061
	31–50a	11–395	15.525	0.6296	92	0.9720
	51–60a	35–280	5.4448	0.7648	63	0.9850
	≥61a	59–518	22.791	0.5733	28	0.8664
Pinus yunnanensis, Pinus khasya	≤30a	13–210	3.0350	0.7297	84	0.9578
	31–50a	31-616	0.5789	0.7616	74	0.9621
	51–80a	70–680	12.540	0.7526	25	0.8562
	≥81a	22–922	−14.772	0.8819	38	0.9675
Pinus massoniana and other tropical pines	≤30a	4–504	3.1299	0.6330	273	0.9154
	31–50a	35–563	6.3488	0.6613	52	0.9392
	≥51a	36–900	−9.1731	0.8127	30	0.9091
Pinus armandii, Pinus densada and other mountain pines	≤30a	5–299	7.3904	0.6965	74	0.8809
	31–50a	45–492	54.280	0.4048	45	0.7918
	51–60a	53–889	52.341	0.4234	25	0.8359
	61–80a	24–1080	9.4226	0.5268	28	0.9644
	≥80a	63–705	22.988	0.4630	39	0.8389
Cunninghamia lanceolata	≤10a	0–214	11.599	0.5665	79	0.8005
	10–20a	10–707	12.746	0.4659	268	0.9083
	21–25a	63–783	8.9867	0.4748	96	0.9134
	26–35a	21–855	9.0353	0.4636	79	0.9220
	≥35a	86–1605	7.4509	0.3943	46	0.8885

(*Continued on next page.*)

TABLE I
(Continued).

Forest type	Age group	Vol range (m^3/ha)	a	b	Plot number	R^2
Cryptomeria fortunei, Cupressus funebris and other conifers	≤30a	8–654	19.711	0.5679	64	0.9461
	31–60a	17–465	15.213	0.6220	19	0.9548
	≥61a	16–659	25.568	0.5673	23	0.8712
Pinus koraiensis and its mixed forest	≤60a	9–318	24.946	0.5383	106	0.6013
	≥61a	188–723	115.60	0.2974	51	0.4395
Oaks and other deciduous trees	≤40a	15–500	5.7107	0.9957	162	0.8578
	41–60a	25–280	13.394	1.0564	123	0.8278
	61–80a	33–304	24.774	0.8515	66	0.7246
	≥81a	29–549	50.649	0.4829	42	0.6206
Betula and *Populus*	≤10a	4–244	4.1318	0.8682	71	0.9060
	11–15a	12–276	8.5271	0.8491	77	0.9056
	16–20a	3–360	21.235	0.7594	61	0.8412
	21–30a	9–652	36.308	0.6455	145	0.8434
	≥31a	14–655	33.54	0.6642	314	0.8129
Evergreen broadleaved trees	≤40a	6–366	5.2243	1.1255	437	0.8559
	41–60a	29–584	22.967	1.0014	254	0.8409
	61–80a	75–684	24.653	0.9790	102	0.7460
	≥80a	26–955	42.774	0.8436	145	0.7045

TABLE II
Parameters to calculate woodland and bamboo forest live biomass density (y, Mg ha^{-1}). Biomass density for woodlands is expressed as a function of stand growing stock (x, m^3 ha^{-1}), $y = a \cdot x^b$, where a and b are constants for a region. Plot data are selected from the data set collected by Luo (1996) with stand growing stock of less than 100 m^3 ha^{-1} and tree density of less than 1000 trees per hectare

Woodlands (for province or autonomous region)	a	b	Plot number	R^2
Guangdong, Guangxi, Hainan	0.9129	1.0302	136	0.5959
Guizhou	1.1647	0.9150	82	0.8083
Anhui, Fujian, Hubei, Hunan, Jiangsu, Jiangxi, Shanghai, Zhejiang	1.2776	0.9035	50	0.4797
Beijing, Hebei, Henan, Shandong, Tianjin	1.1356	0.9484	50	0.7357
Gansu, Ningxia, Qinghai, Sanxi, Shanxi, Xinjiang	0.8004	1.0206	227	0.7854
Sichuan, Tibet (Xizang), Yunnan	1.0592	0.9338	123	0.8180
Heilongjiang, Jilin, Liaoning, Neimeng	1.0961	0.9563	54	0.7679
Over China	0.9617	0.9814	723	0.7255
Bamboo forests	$y = 0.0227$* (individuals/ha)+7.9569 $R^2 = 0.6144, n = 19$			

interpretation plots from remote sensing for the period 1989–1993 (Zhang and Xu, 2003). Generally, only statistical data at the provincial level are accessible to the public. The data used in this study for calculating total forest biomass and C were the provincial data compiled from survey plots from the FRSC 1973–1976, 1977–1981, 1984–1988, and 1989–1993 (FRSC, 1977, 1982, 1989, 1994). Although statistical data for 1950–1962 exists, the CFA declared that those data lack statistical reliability and should not be used in a formal report. The inventory data from 1994–1998 were also excluded from this study because the definition of forests changed, reducing the threshold value of the minimum canopy cover from 30 to 20%, which would cause difficulty when comparing estimates.

The FRSC includes the data for forests, special product plantations, bamboo forests, woodlands, sparsely stocked areas, and urban trees. For this study, we included only the categories of woodlands, bamboo forests, and forests (including all natural forests and forest plantations). The FRSC (1977, 1982, 1989, 1994) provided information about forest area and growing stock volume associated with 36 forest types, 5 age classes, and 31 provinces and special city districts. We first calculated, for each forest type, age class and province, the mean growing stock volume per hectare ($\bar{V}$) using growing stock volume and areas for all categories (i, forest type; j, age; and k, province). We then calculated biomass density (BD) using the volume–biomass equations developed earlier (see Figure 1):

$$\mathrm{BD}_{ijk}\,(\mathrm{Mg\ ha^{-1}}) = a_{ij}(\mathrm{Mg\ ha^{-1}}) + b_{ij}(\mathrm{Mg\ m^{-3}})\ \bar{V}_{ijk}(\mathrm{m^{3}\ ha^{-1}})$$

We then aggregated the total national forest tree biomass (BM) from all categories after multiplying the biomass density (BD_{ijk}) by the area (A_{ijk}):

$$\mathrm{BM(Pg)} = 10^{-9} \cdot \sum_{k=1}^{31}\sum_{j=1}^{5}\sum_{i=1}^{36} A_{ijk}(\mathrm{ha}) \cdot \mathrm{BD}_{ijk}(\mathrm{Mg\,ha^{-1}})$$

We regrouped the forest types described in the FRSC to aggregated forest types as necessary according to similar life-forms.

3. Results

3.1. BIOMASS AND CHANGES IN MAIN FOREST TYPES

The total area of the main forests (not including woodlands and bamboo) in China increased by 3.5%, from 105.0 to 108.6 million hectare (Mha), between the first inventory (1973–1976) and the fourth inventory (1989–1993) (Table III). During this time, the area decreased approximately 8.9% from the first to second inventory (1973–1976 to 1977–1981) and increased 13.6% afterward because of intensive national plantation campaigns (FRSC, 1977, 1982, 1989, 1994). The total biomass in forest trees increased from 7.02 to 8.04 Pg over the entire period, and increased 2.6, 2.4, and 9.1% between sequential inventories, which was consistent

TABLE III

Forest areas, stocking, biomass and carbon in four inventory periods (sources: FRSC, 1977, 1982, 1989, 1994)

	Forests	Woodlands	Bamboo	Total
Areas (10^6 ha)				
1973–1976	105.0	15.6	3.0	123.6
1977–1981	95.6	17.2	3.2	116.0
1984–1988	102.2	19.6	3.5	125.4
1989–1993	108.6	18.0	3.8	130.5
Stocking (10^9 m^3)				
1973–1976	7.647	0.557	–	8.204
1977–1981	7.978	0.542	–	8.520
1984–1988	8.091	0.546	–	8.637
1989–1993	9.087	0.545	–	9.632
Biomass (Pg = 10^{15} g)				
1973–1976	7.022	0.501	0.148	7.671
1977–1981	7.203	0.485	0.129	7.817
1984–1988	7.374	0.487	0.136	7.998
1989–1993	8.036	0.481	0.160	8.678
Carbon (Pg C)				
1973–1976	3.511	0.251	0.074	3.836
1977–1981	3.602	0.243	0.065	3.910
1984–1988	3.687	0.244	0.068	3.998
1989–1993	4.018	0.241	0.080	4.339

with changes in growing stock (Table III, Figure 3c). Although forest area decreased from 1973–1976 to 1977–1981, which was likely related to the harvesting of mature forests, an increase of biomass in the middle-aged forests compensated for the biomass lost to harvesting (Figures 3a and 3b). A remarkable increase in forest biomass for the periods 1984–1988 to 1989–1993 is because of an increase in the productivity of large areas of forest established during the plantation campaigns. These middle-aged forests have reached the most productive stages in their life cycle (Figures 3a–3c).

3.2. BIOMASS AND CHANGES IN WOODLANDS AND BAMBOO FORESTS

Generally, the biomass stored in woodlands did not change significantly during four inventories and ranged from 0.48 to 0.50 Pg. The biomass stored in bamboo forests ranged from 0.13 to 0.16 Pg. The biomass of woodlands and bamboo forests contributed approximately 0.61–0.65 Pg to the total forest biomass in China (Table III).

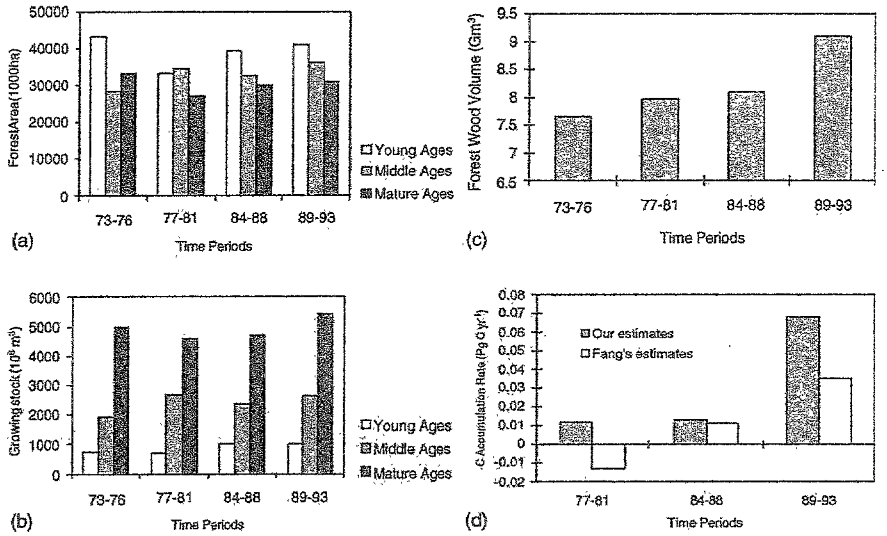

Figure 3. Areas (a) and growing stock (b) of young, middle-aged, and mature forests (including premature, mature and post-mature stages because earlier inventories did not separate them), total growing stock (c) in different inventory periods, and annual C sequestration rates in the periods between inventories (d).

3.3. EFFECT OF AGES ON ESTIMATED FOREST BIOMASS

The results showed that changes in the age structure of forests greatly affect forest biomass. The area-weighted biomass densities for the four inventory periods varied between 66.9 and 75.4 Mg ha^{-1}, corresponding to proportions of young forest areas (Table IV). For different forest types, the ages that correspond to different development stages are not equal. For example, spruce-fir forests require more than 100 years to reach maturity. However, it takes only 30 years for birch and poplar forests to mature (Table I). The plot data show that biomass densities for different forest development stages may change significantly (Table V). For example, the biomass density of *Pinus massoniana* was 71 Mg ha^{-1} in young stands and ranged from 322 to 407 Mg ha^{-1} in more mature stands. For most forest types, biomass densities increased two- to three-times while stands developed to maturity (Table V). The differences in biomass densities among age groups indicate the importance of estimating forest biomass for separate age groups.

3.4. NATIONAL CARBON STORAGE AND CHANGES IN ALL FOREST TYPES

We used 0.5 as the factor to convert the biomass to carbon stored in China's forests. The carbon storage in forested lands for 1973–1976, 1977–1981, 1984–1988, and 1989–1993 was 3.84, 3.91, 4.00, and 4.34 Pg C, respectively (Table III). The total

TABLE IV

Age structure, biomass density, estimates of C stock and sequestration rates (based on the volume-to-biomass methods) in China's forests (not including woodlands and bamboo forests)

	Inventory data (FRSC)				Our estimates		Fang et al. (2001)	
	Forest area (%)			Biomass density	Forest Carbon	Carbon change	Forest carbon	Carbon change
Inventory periods	Young	Mid-age	Mature*	(Mg/ha)	(Pg C)	(Pg C yr^{-1})	(Pg C)	(Pg C yr^{-1})
1973–1976	41	27	32	66.9	3.51	–	4.44	–
1977–1981	35	36	29	75.4	3.60	0.020	4.38	−0.013
1984–1988	39	32	29	72.2	3.69	0.013	4.45	0.011
1989–1993	38	33	29	74.0	4.02	0.066	4.63	0.035

*Mature forests include premature, mature and overmature forests.

C stock increased by 12.9% from the early 1970s to early 1990s. The annual C accumulation rates between the inventories were 0.016, 0.013, and 0.068 Pg C yr^{-1}, respectively. If woodlands and bamboo forests were excluded, the C estimates were 3.51, 3.60, 3.69 and 4.02 Pg C, respectively, and the total C stock increased by 14.5%. The C accumulation rates between periods were 0.020, 0.013, and 0.066 Pg C yr^{-1} (Table IV). Our estimates were consistent with the changes of growing stock in the inventory data and indicate that the forests in China have become a C sink since the early 1970s, as opposed to the late 1970s (Fang et al., 2001, Figure 3c and 3d).

4. Discussion

4.1. COMPARISON OF RESULTS AND METHODS IN FOREST BIOMASS AND C ESTIMATION

4.1.1. *Volume–Biomass Method With/Without Separating Ages in China's Studies*
We compared our results with Fang et al. (1998, 2001) who used a similar volume-to-biomass method and the same inventory data to estimate China's forest tree biomass. The main differences between the two studies are that we had 10-times more sample plots and developed the volume–biomass equations for different age groups.

The estimates of C in forest biomass (excluding woodland and bamboo, and using the same carbon conversion factor) by Fang et al. (2001) for the same inventory periods (1973–1976, 1977–1981, 1984–1988, and 1989–1993) are greater by 26.5, 21.7, 20.8, and 15.2%, respectively, than our estimates (Table IV). These differences are caused primarily by using different volume–biomass equations that were developed separately in the two studies. We compared the volume–biomass curves developed for most of the main forest types in China (Figure 4) in the two

TABLE V

Biomass densities (Mg ha^{-1}) by forest type (n = number of sample plots) and total biomass estimated using the mean biomass-density method based on the forest areas for different age classes from the inventory data of 1989–1993 (FRSC, 1994)

Forest type	Biomass	Area	Young		Middle		Premature		Mature		Overmature		Fang's data[1]	
	Pg	Mha	Mg/ha	*n*	Mg/ha	*n*	Mg/ha	*n*	Mg/ha	*n*	Mg/ha	*n*	Mg/ha	*n*
Abies-Picea	1.716	7.56	86.74	72	144.57	226	223.33	111	221.64	240	281.67	357	135.9	19
Larix	1.247	9.68	76.18	80	128.00	87	131.46	13	173.91	31	244.27	67	139.5	13
P. sylvestris var. *mongolica*	0.047	0.63	40.42	20	93.01	13	113.37	6	122.9	9	130.93	14	49.3	11
P. tabulaefomis	0.234	3.03	62.71	201	81.92	92	82.05	59	93.76	25	108.47	3	88.7	90
P. armandii, P. densata	0.473	3.77	76.71	70	134.22	41	169.25	25	191.87	28	170.48	30	71.8	10
P. koraiensis	0.372	2.25	74.91	81	171.89	2	214.46	4	245.52	17	246.14	30	65.4	19
P. massoniana	1.827	15.40	70.53	265	126.31	52	322.20	16	319.49	9	406.52	4	81.1	12
P. yunnaensis, P. khasya	0.545	4.19	58.79	84	108.87	74	197.11	10	219.99	15	268.60	38		
Cunninghamia lanceolata	0.660	9.39	40.06	50	85.95	234	93.97	78	117.91	79	281.36	41	86.3	74
Cypress	0.125	1.63	59.79	30	70.67	10	135.34	2	155.04	5	172.64	17	213.1	19
Broadleaf deciduous forests	2.030	20.67	80.49	146	103.99	123	110.69	66	110.44	29	157.38	13	89.2	6
Populus-Betula	1.161	15.75	54.72	15	67.12	23	92.48	21	97.06	72	134.59	274	*113.1	22
Populu-Robinia plantation			76.85	60	87.24	53	119.70	37	152.67	65	161.73	18	109.1	16
Subtropical broadleaf evergreen	2.387	12.60	118.98	363	181.98	213	243.07	64	303.46	53	549.73	8	178.3	11
Subtrop mixed deciduous-evergreen			91.17	69	171.96	20	250.89	18	250.88	20	348.39	11	313.6	19
Subtropical evergreen *Quercus*	0.285	1.55	132.65	2	154.63	12	182.92	19	232.28	42	291.80	7	163.7	21
Tropical forests	0.143	0.58	117.79	17	316.88	8	328.76	3	414.67	3	476.59	3	324.3	12
Total	13.250	108.63												

[1] From Fang et al. (1998).

*The data of *Populus* and *Betula* were separated in Fang et al. (1998). The value here is the weighted mean value based on the original data.

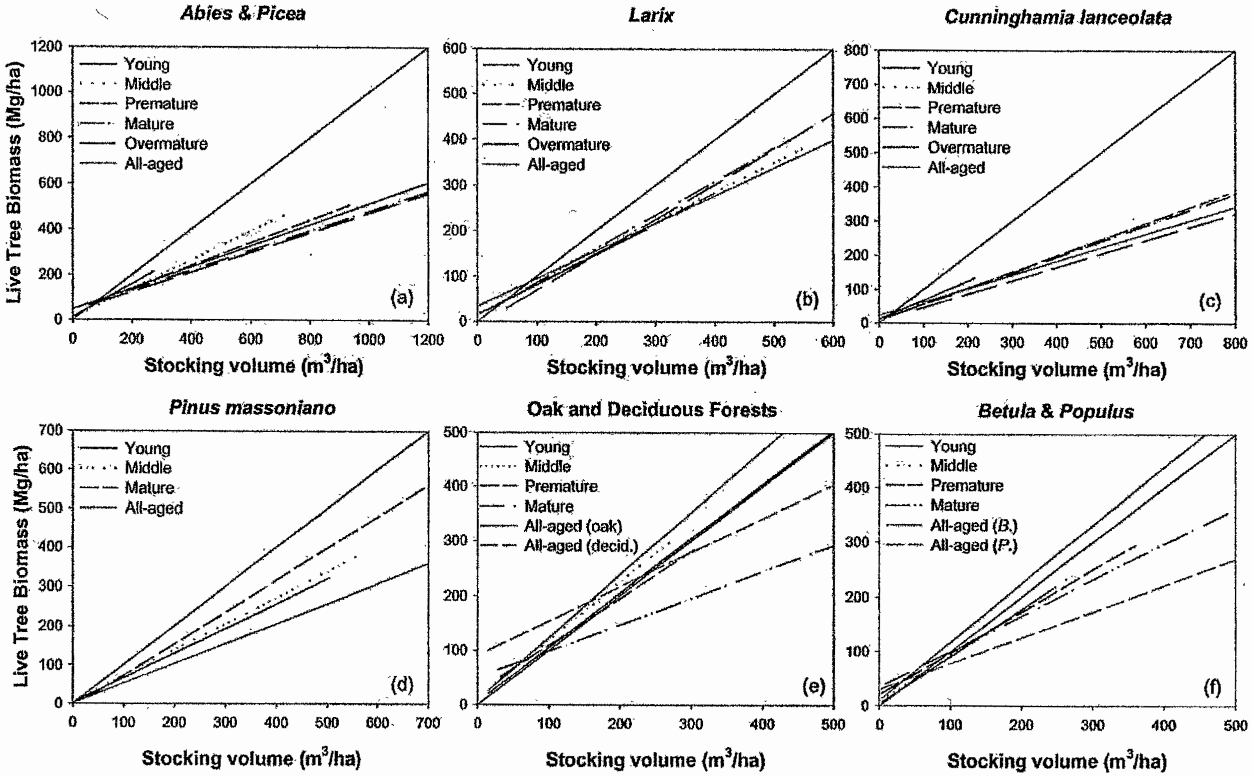

Figure 4. Comparison between the volume–biomass equations of different age groups (current study) and all-aged equations (Fang et al., 2001).

studies. The regression curves developed by Fang et al. (2001, 1998) show that the curves for most forests types are close to the curves of middle- and young-aged stands in our studies (Figure 4). The estimated biomass densities for the sample plots in Fang's study also indicate this phenomenon (Table V). By our estimation, with data from 793 field plots derived from the Chinese literature that include most information used in Fang et al. (1998, 2001), 83% of the plots are classified as young- and middle-aged stands. This percentage is higher than shown by the data in the FRSC (1977, 1982, 1989, 1994), which range from 68 to 71% (Table IV), and may indicate a skewed age distribution in the sample plots.

The regression curves that we developed for age groups show that the relationship between biomass and volume varies with age (Figure 4). However, within an age group, the volume–biomass relationship appears to be linear (Figure 5). The range of stem volume in an age group can be wide and reflects the effects of diverse growth conditions (Figure 5). The ratios of biomass to growing stock are often lower in older forests except *Pinus massoniano* and *Larix* that have higher ratios in more mature stands (Figures 4b and 4d). Both stem volume and tree biomass are no doubt the functions of age, and the relationships appear to be nonlinear (Figures 6a and 6b). The relationships demonstrate an intrinsic biological relationship between growth and aging (Waring and Schlesinger, 1985). The data show that the relationship between volume and biomass is more likely to be linear (Smith et al., 2002, also see Figures 5 and 6c), and that the ratios (biomass/volume) decline as trees grow bigger (Figure 4, referring to one-to-one lines). Such a phenomenon is determined by the characteristics of tree morphology, described by the pipe-model theory (Shinozaki et al., 1964 a, b), that the amount of foliage is related to the surface areas of sapwood under tree crowns that remain relatively constant as trees grow. Trees at different ages, however, have different strategies for allocating carbon to different tree components, which reflect the changing biological traits with age, and affect the volume–biomass relationship (comparing Figures 6a and 6b). The linear volume–biomass equations should be represented by a set of curves to address this trait (Figure 4) and the patterns of the curve sets could be different for various life forms (Figure 6d). Thus, separating age groups for developing linear volume–biomass equations, if extra age information is available, will improve the accuracy of the models (Figure 5). The age-based volume–biomass equations will improve the accuracy of prediction for *Abies and Picea* forests, *Pinus massoniano* forests and Oak and deciduous forests in our case (Figures 4a, 4d and 4e).

It is possible that the volume–biomass equations by Fang et al. (2001) overestimate biomass for mature or all-aged forests, such as spruce-fir, oak, deciduous, and birch forests (Figures 4a, 4e and 4f). Generally, mature and overmature spruce-fir forests constituted 80% of the spruce-fir forest type, which occupied more than 6.5% of the total forest area in the country (FRSC, 1977, 1982, 1989, 1994). The deciduous forests of oak and birch generally occupied more than 49% of the total forest area. Consequently, we believe that Fang et al. (2001) overestimates forest tree biomass in more than 54% of the forests in China.

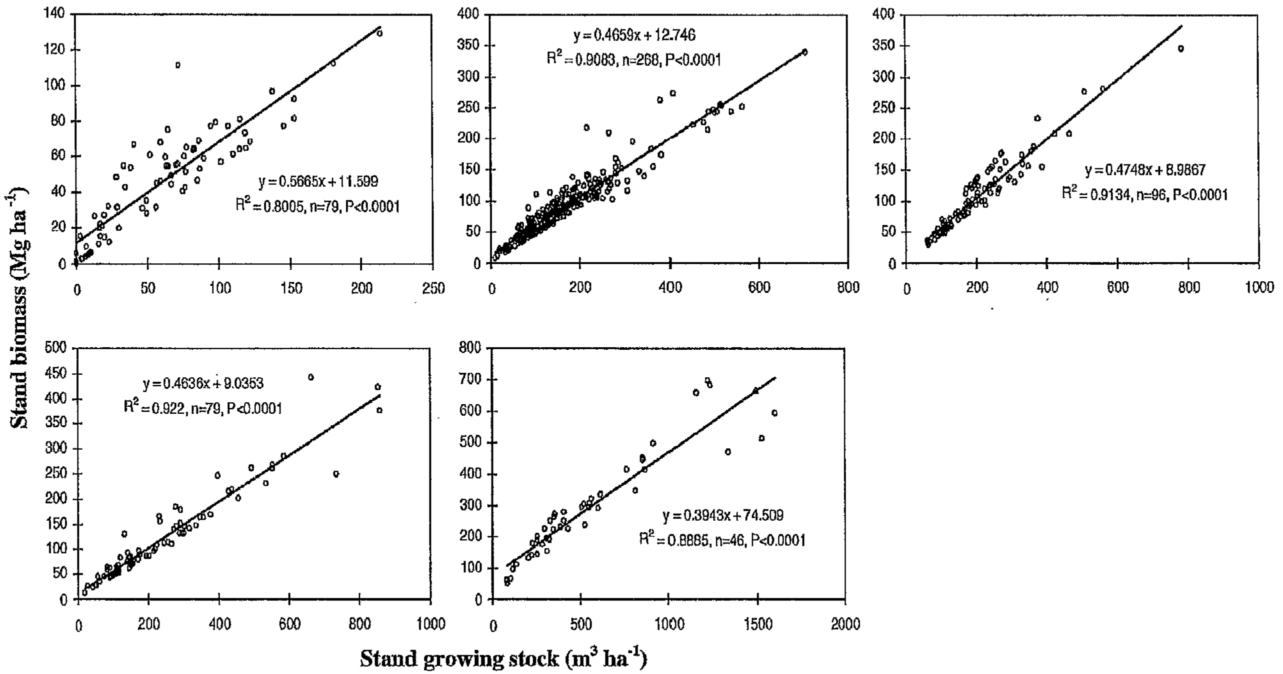

Figure 5. Linear regressions between growing stock and stand biomass within age groups in Chinese fir forests (*Cunninghamia lanceolata*).

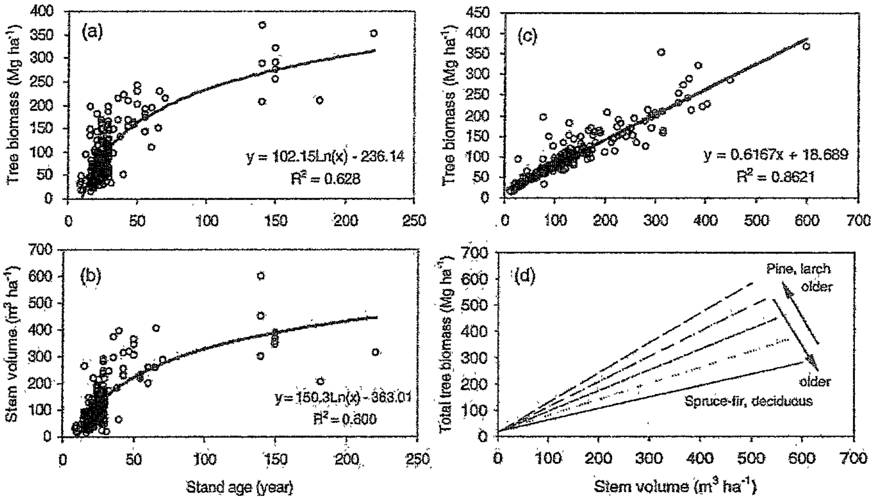

Figure 6. Total tree biomass (a), tree stem volume (b), and the relationship between stem volume and tree biomass (c). The data collected by Luo (1996) include 243 plots of even-aged temperate pine forests in China with measurements of tree biomass and wood volume. The theoretic pattern of a set of volume–biomass curves for age classes (d).

Cases also exist where the all-aged equations in Fang et al. (2001) underestimate forest biomass in *Pinus massoniano* and poplar forest types for all-aged stands (Figures 4d and 4f). *P. massoniano* and poplar forests occupy approximately 18% of the total forest area, which means that Fang et al. (2001) could underestimate biomass in less than 20% of the forests. Overall, Fang et al. (2001) could overestimate forest tree biomass in more than 35% of the forested lands. The comparison indicates that all-aged volume–biomass equations developed with small datasets and a skewed age distribution of sample plots toward younger ages may lead to biased estimates and, in this case, overestimates of live tree biomass.

4.1.2. *Biomass Expansion Factor Method*

In addition to the volume–biomass method, the Biomass Expansion Factor (BEF) method is mentioned often and used in inventory data-based biomass and carbon research (Schroeder et al., 1997; Kauppi et al., 1992; Brown and Schroeder, 1999). BEF converts growing stock volume to mass, accounting for noncommercial components. Essentially, the BEF method is the same as the volume–biomass method (Figure 1), especially when a continuous function is developed (usually an exponential function) for BEF to convert growing stock volume to total tree biomass. Sometimes the biomass expansion factors are estimated as individual conversion parameters for different size classes of trees. The study by Schroeder et al. (1997) indicates that there is a general pattern between BEF and stand volume for temperate broadleaf forests. The BEF declines from stands of lower growing stock volume to stands of higher growing stock volume. The one-to-one lines in Figure 4 illustrate a general pattern between live tree biomass and growing stock volume that can be explained as declining ratios with increasing growing stock volume. Even with this general pattern, age is another factor that affects this ratio (Figures 4 and 6d). The information implies that using sample data from either young stands or stands with low stocking to develop the volume–biomass equations or BEFs could cause overestimates of biomass, and the opposite is true, also.

4.1.3. *Mean Biomass Density Method*

In early International Biosphere Program and biomass studies, the mean biomass-density method was often used to estimate forest biomass (Lieth and Whittaker, 1975). This method estimates a mean biomass density (Mg ha^{-1}) using datasets for a certain forest type and then multiplies the mean biomass density by the forest area derived from the inventory statistics (Figure 1). We used the inventory data of 1989–1993 to compare this method with ours. The mean biomass-density method estimates 13.25 Pg of forest tree biomass, which is 65% higher than the volume–biomass method (8.04 vs. 13.25 Pg, see Table III and V). A much lower biomass estimate using the volume–biomass method implies that the mean biomass densities estimated from the inventory of growing stock volume are much lower than those directly estimated from the sample plot datasets.

Inconsistency in the mean biomass densities used in the two methods reflects statistical biases in the reference datasets that cannot cover the full range of forest conditions represented in the inventory information. Forest inventories are based on the systematic plot networks designed to represent the broad range of forest conditions actually present. Therefore, inventories are more likely representative of the true average values of stem volumes, which can be further transformed to biomass (Birdsey, 1992). The lower mean biomass densities based on the volume–biomass equations and inventory data indicate that forests across heterogeneous regions could, on average, experience very different growth conditions than represented by a small number of reference plots. Because volume–biomass equations represent continuous relations between a wide range of values of volume and biomass (Figure 4), this method should be more reliable statistically to convert growing stock to biomass than the mean biomass-density method.

4.1.4. *Biomass Estimation Methods Used in the U.S.A. and Russia*

The biomass estimates based on inventory data were developed in the U.S. (Birdsey 1992; Birdsey and Heath, 1995; Jenkins et al., 2001) and Russia (Alexyev et al., 1995). In the U.S., allometric equations developed from empirical data are used to calculate biomass in different forest components including growing stock, tops, branches, foliage, rough and rotten trees, small trees, standing dead trees, stump section, roots, and bark (Cost, 1990). The ratios of total forest biomass to the biomass in growing stock (for different regions and species groups) were calculated and used as the ratios of total tree volume to growing stock (Birdsey, 1992). These ratios were then applied to Forest Inventory Analysis (FIA) data (growing stock volume) to calculate total tree volumes based on regions. The mean specific gravities of wood for different tree species were used to convert total tree volume to total tree biomass (Figure 1).

Initially, estimation of forest tree biomass in the U.S. depended on the ratios of total tree volume to merchantable wood volume, and average specific gravity, to develop the relationship between growing-stock volume and total forest biomass (Birdsey, 1992). This method averages and does not consider a functional relationship between volume and biomass. The updated studies for the U.S. carbon biomass estimates give full consideration to the effects of stand volume on live tree biomass and develop the volume–biomass equations (exponential functions) based on large amounts of forest inventory plot data (Smith et al., 2002; Jenkins et al., 2003). The advantage in the U.S. approach is that a great amount of inventory data at both tree and plot levels are available for analysis and developing models, which are not accessible for either Russian or Chinese inventory databases. From a statistical point of view, the volume–biomass equations in the updated U.S. forest carbon study could be more precise and less biased than those linear equations developed in the carbon studies of China's forests that had limited plot data available.

National Forest Inventory data in Russia include information about forest age groups similar to the FRSC. The data from 2290 sample plots across Russia for tree species, age classes, and ecoregions were used to estimate forest tree biomass, and the ratios of bark, crown, and root biomass to under-bark wood biomass (Alexeyev and Birdsey, 1996). The ratios that convert the growing stock volume (i.e. inventory data including under-bark wood and bark) to total tree biomass were developed dependent on the biomass ratios of tree components to under-bark wood and the specific gravities of wood and bark. Except for separating age groups and using different specific gravities to calculate bark biomass, the method in the Russian study is similar to the methods in the U.S. biomass estimates. Both depend on biomass (or volume) ratios of tree components and wood/bark specific gravities (the gravity method, Figure 1).

4.1.5. *Differences Inherent in Estimation Methods*

All the methods we mention, except the mean biomass-density method, take steps to develop relations or ratios between growing stock volume and total tree biomass. However, the volume-to-biomass and the BEF methods establish the functional relations or ratios between the growing stock and total tree biomass based on data from sample plots (Figure 1). The specific gravity methods determine ratios of total tree biomass to stem biomass (as the ratios of total volume to stem volume) using data from sample plots, but then convert wood volume to wood biomass by using specific wood or bark gravities usually derived from measurement handbooks and laboratory studies that represent independent data sources (Figure 1). Whether such a difference in methods could cause considerable variations in the final estimates of forest biomass is unclear. The volume-to-biomass and BEF methods rely exclusively on sample data for the volume–biomass relationship and may involve more statistical errors and biases related to selection of sample plots and their variability.

4.2. EFFECT OF AGE STRUCTURE CHANGES ON ESTIMATES OF CARBON SEQUESTRATION IN FOREST TREES

On average (over the four inventories between 1973 and 1993), our estimates of C storage in China's forests are approximately 21% lower than those in the earlier study by Fang et al. (2001). However, the C accumulation rates in our estimates are higher than the estimates in Fang et al. (2001) (Table IV). The major differences in the results of these two studies include:

(1) We estimated China's forests from 1973–1976 to 1977–1981 to be a C sink (0.02 Pg C yr^{-1}), which is consistent with the change of wood volume in the inventory data during the period. Fang et al. (2001) estimated the forests at the same period were a source (−0.013 Pg C yr^{-1}), which is not consistent with the increase in wood volume that appeared in the inventory data (Figures 3c and 3d). Our estimates indicate that the forests in China initially became a C sink in the early '70s rather than the late '70s.

(2) From 1984–1988 to 1989–1993, the forest C accumulation rate (0.066 Pg C yr^{-1}) we estimated is almost twice (89% higher) the earlier estimate (0.035 Pg C yr^{-1}) by Fang et al. (2001) (Table IV). A significantly greater C sink in China's forests from the middle 1980s to early 1990s is likely related to the changing age structure in China's forests that reached more productive stages, reflecting the effects of reforestation and afforestation programs from the 1960s (Figure 3a). This C sink may also be attributed to climate variability and strong El Niño/La Niña events during the period (Schimel et al., 2001).

Comparing the inventory-based forest carbon estimates of China, the conterminous U.S., and Russia for 1988–1993, we may further recognize the effect of age structure on forest C sequestration (Table VI). During this period, the areas of forest lands were 130.5, 245.9, and 771.1 M ha, and C stored in forests was 4.34, 13.78, and 25.6 Pg C for China, the conterminous U.S., and Russia, respectively. The area-weighted carbon density in forests is 33.3, 56.0, and 33.2 Mg ha^{-1} for China, the conterminous U.S., and Russia. China and the conterminous U.S. are at similar latitudes, but carbon density in China's forests is only approximately 60% of U.S. forests. This difference may be associated with more intensive human disturbances and younger forests in China. The annual C sequestration rate is 0.066, 0.10, and 0.058–0.429 Pg C yr^{-1} (Table VI) for China, the conterminous U.S., and Russia respectively (Birdsey and Heath, 1995; Liski and Kauppi, 2000; Nilsson et tal., 2000). The area-weighted sequestration rate (i.e. Mg C $ha^{-1}yr^{-1}$), however,

TABLE VI
Inventory-based estimates of forest tree carbon for the early 1990s in some Northern Hemispheric countries

Country	Forest lands (Mha)	C storage in forest trees (Pg C)	Area-weighted C density (Mg C ha^{-1})	C sequestration rate for country (Pg C yr^{-1})	Area-weighted C sequestration rate (Mg C $ha^{-1}yr^{-1}$)	Percent of mature forests (%)
China	130.5	4.34	33.3	0.066	0.51	29
The U.S.[1]	245.9	13.78	56.0	0.100	0.41	41
Russia[2]	771.1	25.60	33.2	0.058–0.429	~0.26	67
Canada[3]	244.6	11.89	48.6	0.093	0.38	50
Europe[4]	195.0	7.70	39.5	0.090	0.46	na

Data sources:

[1] Birdsey and Heath, 1995.

[2] Alexeyev et al., 1995; Liski and Kauppi, 2000; Nilsson et al., 2000.

[3] Liski and Kauppi, 2000.

[4] Goodale et al., 2002.

is 0.51, 0.41, 0.08–0.52 for China, the conterminous US, and Russia (Birdsey and Heath, 1995; Liski and Kauppi, 2000; Nilsson et al., 2000). China has the highest and Russia the lowest area-weighted sequestration rates in forests if the average rate of 0.26 Mg C/ha/yr is taken from the variable estimates of Russian sink (Liski and Kauppi, 2000; Nilsson et al., 2000). During 1988–1993, mature forests were approximately 29, 41, and 67% for China, the U.S., and Russia respectively (FRSC, 1994; Myneni, 2001). Because younger forests sequester C at higher rates than mature forests, this may explain why the area-weighted C sequestration rate in China is higher than the conterminous U.S. and Russia. In addition, we included the C data of Canada and Europe in our comparison table (Table VI), which also shows a consistent pattern for C sequestration. Although the total forested lands and forest carbon pool in China is small in comparison to the U.S. and Russia, the relatively younger forests in China may have great potential for storing additional carbon in the system.

4.3. UNCERTAINTIES IN THE INVENTORY-BASED FOREST C ESTIMATION

Forest inventory data are recognized as valuable resources in global carbon cycle research. Aside from using the data to directly estimate carbon storage and changes in forests, the data are also used to compare and/or validate the estimates based on other methodology, such as eddy-flux covariance, remote sensing, and ecosystem modeling (Myneni et al., 2001; Jenkins et al., 2001). However, in those related carbon studies, many uncertainties in the inventory-based C estimates were ignored or lacked appropriate description. Here, we list several sources of errors that cause uncertainties in the inventory-based C estimates, although we may not be able to quantify all of these uncertainties:

1. *Definition of forests.* Different definitions for forests are often used in different studies, which affects comparison between studies (IPCC, 2000). For example, the “forests” used in our study in C estimation methods include stocked forests, woodlands, and bamboo forests. Fang et al. (2001) included only natural and plantation forests. Additionally, the China Forest Administration has changed the minimum threshold of canopy cover for forests from 0.3 to 0.2, beginning with the inventory period of 1994–1998, which generally increases the forest area by approximately 9% (i.e. 145.2 M ha including forests, woodlands, and bamboo forests). This change does affect total forest C estimates and area-weighted C densities and makes it difficult to evaluate historical changes in forest carbon storage. However, the forest area in China under the new definition is close to the result by the remote sensing study that estimated 142.6 M ha of forest in China in the 1990s (Myneni et al., 2001).
2. *Inventory methods.* Forest inventory methods have changed with new technology and knowledge. These changes may cause inconsistency when estimating

the historical change of forest carbon but are rarely evaluated (Birdsey and Schrueder, 1992). For example, in China the forest inventories for some remote areas, such as Tibet, were based on ground surveys and measurements before 1989 and switched to remote sensing after 1989 (Luo, 1996). This situation happens in other countries, such as Russia's Siberian region and in the U.S. where sampling procedures have evolved over time (Nilsson et al., 2000; Birdsey and Schrueder, 1992). The changes in forest inventory methods should be documented in historical data analysis. The relevant uncertainties associated with changes in the inventory methods should be evaluated to make accuracy adjustments in the data.

3. *Carbon estimation methods and sample data.* As discussed earlier, different procedures, methods, and statistical errors can affect the inventory-based C estimates. Insufficient sample data to develop statistical equations or ratios may cause great biases in estimation. The comparison between Fang et al. (2001) and the current study shows that the skewed age distribution of biomass measurements in sample plots that cannot represent all age classes may cause a 15–27% difference in the forest carbon estimate, but will cause a –254 to 89% difference in estimated C sequestration rates even when using the same estimation method (Table IV, Figure 3d). The studies by Smith and Heath (2000) and Smith et al. (2002) show that where an adequate sample of forest inventory data exists, if representative biomass equations are available, C stock change can be estimated with a precision of about ±10%. Additionally, our analysis indicates that the different estimation methods, such as the volume–biomass method and mean density method, may cause a 65% difference in C stock, although the same sample plot data are used.
4. *Retrospective analysis.* Various environmental processes, such as land-use change, climate anomalies, elevated atmospheric CO_2, ozone, and N deposition can affect forest C sequestration rates. The inventory-based C estimates are used to diagnose the change in growth trend associated with those processes (Casperson et al., 2000). Such analyses should be done with caution because the C estimates for different time periods often use the same statistical equations or ratios derived from the same group of sample data. The underlying hypothesis is that the biological/morphological characteristics of trees do not change with time, and therefore, allometric equations, ratios of tree components, or volume–biomass relations do not change either. However, changes in atmospheric chemistry, such as CO_2 and N deposition, or silviculture and forest management, may alter C allocation patterns in trees (Delucia et al., 1999; McGuire et al., 1995). Therefore, the forest C estimates for different inventory periods, but using the same equations or ratios, may fail to diagnose changes in growth attributable to the changed processes.

5. Conclusion

The carbon pool in China's forests is relatively small compared to the U.S. and Russia, amounting to 4.34 Pg C in the early 1990s. This pool has increased approximately 13% since the early 1970s, reflecting the impact of reforestation and afforestation programs in China since the 1960s. The carbon sequestration rate from the late 1980s to the early 1990s was significantly higher, which was approximately four- to five-times higher than in the 1970s and 1980s, and amounted to 0.068 PgC (forests including woodlands and bamboo). The large carbon sink during the late 1980s to early 1990s was likely related to a change in forest age structure and higher productivity at the time, which may be a response to large climate variability as reported by other studies (Schimel et al., 2001). Although China has less forested land and a smaller forest carbon pool than the U.S. and Russia, the area-weighted C sequestration rate was highest from the late 1980s to early 1990s. This was due to younger age structure and greater C sequestration potential in China's forests.

The comparison of methods reveals the impact of separating age groups to estimate forest carbon. Separation may cause a 15–27% difference in estimated pool sizes for China's forests and much higher differences in estimated C sequestration rates. Generally, the biomass to volume ratio declines as trees age and growing stock volume increases. The volume-to-biomass, BEF, and gravity methods all can incorporate the effect of sizes on the ratio. In China's studies, because the field data derived from the literature include relatively higher percentage of young and middle-aged stands, a skewed distribution of sample data towards younger ages may lead to overestimates for forests with older age structure. Considering that currently China's forests have relatively young age structure (only 29% of the forests reach more mature stages), the age impact on C sequestration estimates will be more prominent in the near future.

The comparison of the estimation methods indicates that using different methods may cause approximately 65% of the discrepancy in China's forest carbon estimates. Although the inventory-based forest carbon estimates all rely on simple statistical methods, those methods could create statistical biases of different magnitudes. We should evaluate and choose the method that is likely to introduce the fewest statistical errors.

Many issues may cause uncertainties in the inventory-based forest carbon estimates. For most of those uncertainties, we could not provide quantified evaluations because of a lack of available data to evaluate errors. Although inventory-based forest carbon estimates rely on real ground measurement data, we still need more evaluation and comparison studies to improve estimation and reduce uncertainty. Inventory-based forest carbon research should also be combined with other independent methods and data, such as remote sensing and eddy covariance data, to make more reliable carbon estimates.

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