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Inventory-based estimation of aboveground net primary production in Japan's forests from 1980 to 2005

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Abstract. Recent studies based on remote sensing and carbon process models have revealed that terrestrial net primary production (NPP) in the middle and high latitudes of the Northern Hemisphere has increased significantly; this is crucial for explaining the increased terrestrial carbon sink in the past several decades. Regional NPP estimation based on significant field data, however, has been rare. In this study, we estimated the long-term changes in aboveground NPP (ANPP) for Japan's forests from 1980 to 2005 using forest inventory data, direct field measurements, and an allometric method. The overall ANPP for all forest types averaged $10.5\,\mathrm{Mg\,ha^{-1}\,yr^{-1}}$, with a range of 9.6 to $11.5\,\mathrm{Mg\,ha^{-1}\,yr^{-1}}$, and ANPP for the whole country totaled $249.1\,\mathrm{Tg\,yr^{-1}}$ (range: 230.0 to $271.4\,\mathrm{Tg\,yr^{-1}}$) during the study period. Over the 25 years, the net effect of increased ANPP in needle-leaf forests and decreased ANPP in broadleaf forests has led to an increase of $1.9\,\mathrm{Mg\,ha^{-1}\,yr^{-1}}$ (i.e., $0.79\,\%\,\mathrm{yr^{-1}}$). This increase may be mainly due to the establishment of plantations and the rapid early growth of these planted forests.

1 Introduction

Net primary production (NPP) is defined as the rate of accumulation of organic matter by vegetation and equals the difference between carbon assimilated by plants through photosynthesis and the carbon consumed by plant autotrophic respiration (Chapin et al., 2002). NPP therefore represents the efficiency of CO_2 fixation by plants, determines the amount of materials and energy available for heterotrophic organisms, and represents the activity of vegetation in the global carbon cycle (Jenkins et al., 2001). Recent results from satellite remote sensing and carbon process models have suggested that NPP has increased in the middle and high northern latitudes since the 1980s (Myneni et al., 1997, 2001; Hicke et al., 2002; Fang et al., 2003; Nemani et al., 2003; Piao et al., 2005) and that this increase was crucial for explaining the increased terrestrial carbon sink. However, regional NPP estimates based on significant field data are rare, especially over long time scales (Turner et al., 1999; Fang et al., 1996; Brown and Schroeder, 1999; Kurz and Apps, 1999; Jenkins et al., 2001; Brown, 2002).

Biomass-based NPP estimation has been considered an effective method to assess NPP variations on a national scale (Whittaker and Marks, 1975; Fang et al., 1996; Jenkins et al., 2001; Brown, 2002). Whittaker and Marks (1975) detected a linear relationship between biomass and NPP for the first time, and Fang et al. (1996) developed this method by establishing several allometric biomass-NPP relationships for major forest types and using the allometries to estimate NPP for China's forests. Jenkins et al. (2001), using plot-level forest inventory data, also reported a linear relationship between

biomass and NPP for the mid-Atlantic region of the United States. A positive biomass-NPP relationship is useful for estimating NPP because biomass can be easily obtained from forest inventory data, which have become increasingly complete and available for many countries and regions in recent decades.

Japan has a typical marine climate with abundant rainfall, and two-thirds of its land area is covered with forest (Kira, 1991). Since the International Biological Program (IBP, 1965 to 1974), biomass and NPP have been measured extensively for the main forest types in Japan (Fang et al., 2005). In addition, a systematic forest inventory has been conducted in Japan at about 5 yr intervals since 1947, and the surveys have intensified since the 1980s (Fang et al., 2005). These direct field measurements and systematic forest inventories make it possible to investigate the historical changes in NPP for Japan's forests.
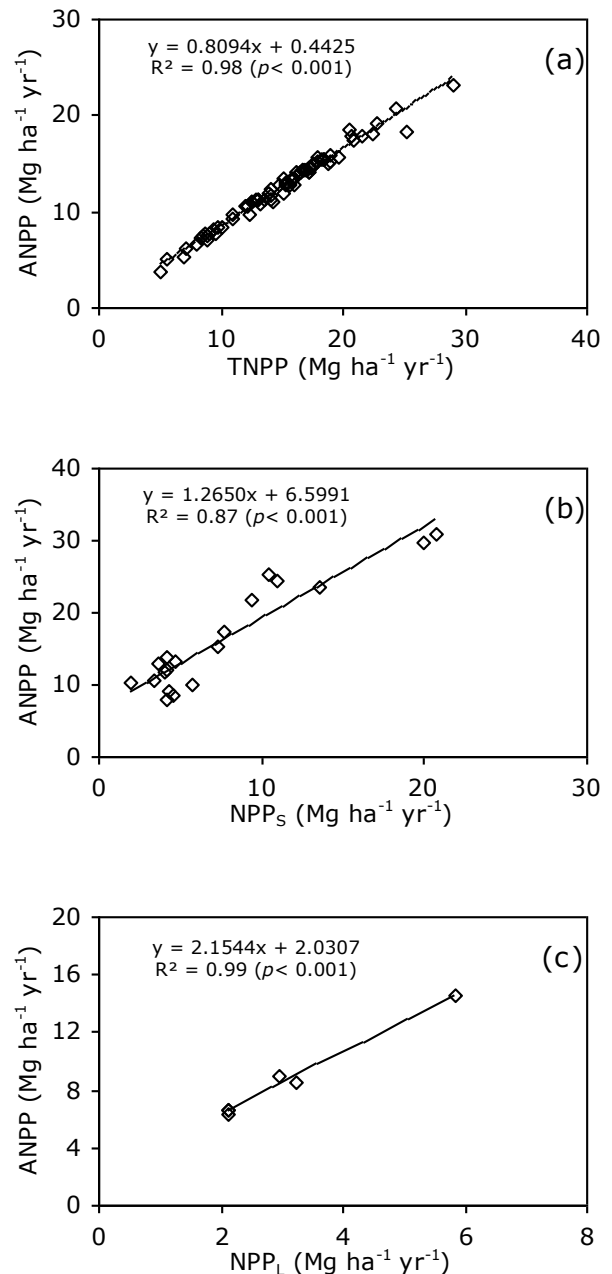
In order to estimate changes in biomass in Japan's forests over time, we reviewed the research literature on Japan's forests and compiled a database for Japan's forest biomass (Fang et al., 2005). Based on this database and forest inventory data, we investigated changes in the biomass of Japan's forests from 1947 to 1995 in the previous study (Fang et al., 2005). In this study, we further complemented the database with NPP datasets, developed allometric relationships between aboveground biomass (AB) and aboveground NPP (ANPP) for Japan's major forest types, and investigated the changes in ANPP in Japan's forests from 1980 to 2005.
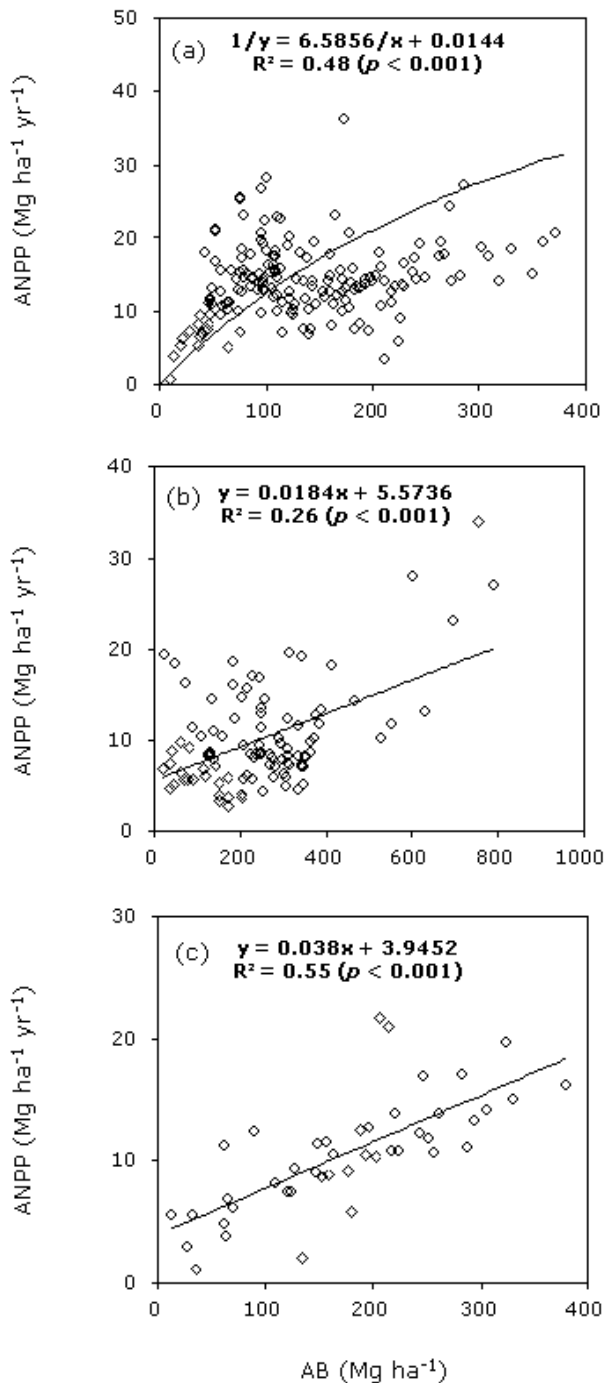
2 Data and methods

We estimated the ANPP of Japan's forests based on biomass-NPP relationships and data from forest inventories. Therefore, we used two datasets in this study: direct field measurements, including both biomass and NPP, and data from forest inventories.

2.1 Field measurement data

Since the IBP, studies of biomass and NPP have been conducted for Japan's major forest types. Cannell (1982) compiled a global database of forest biomass and NPP, including some data from Japan. Fang et al. (2005) developed a database of Japan's forest biomass that included 945 sets of data. We started with this database, then collected additional NPP data for Japan's forests from all the available literature to establish a new database. This new database contains the forest type, stand age, stand density, total basal area, stand volume, stem biomass, AB, belowground biomass, biomass of forest-floor vegetation, and 572 sets of NPP data. The NPP data generally included stem NPP (NPP_S), branch NPP (NPP_B), and leaf NPP (NPP_L), and some of them also include root NPP (belowground NPP, BNPP) or total NPP (TNPP = ANPP + BNPP). Unfortunately, there

Fig. 1. Examples of the relationships between the components of net primary production (NPP) and aboveground net primary production (ANPP). **(a)** The relationship between total net primary production (TNPP) and ANPP for *C. japonica* forests. **(b)** The relationship between stem net primary production (NPP_S) and ANPP for evergreen broadleaf forests. **(c)** The relationship between leaf net primary production (NPP_L) and ANPP for needle-leaf and broadleaf mixed forests. The relationships between these NPP components and ANPP for other forest types are shown in Table 1.

Fig. 2. Examples of the relationships between aboveground biomass (AB, $Mg\,ha^{-1}$) and aboveground net primary production (ANPP, $Mg\,ha^{-1}\,yr^{-1}$) for three of the main forest types in Japan. **(a)** *C. japonica* forests, **(b)** other deciduous broadleaf forests, and **(c)** *Abies* and *Picea* forests. Table 2 presents details of the regression analysis for all forest types.

was insufficient longer-term BNPP data for us to reconstruct BNPP changes during the study period. We defined ANPP as the sum of NPP_S, NPP_B, and NPP_L. All the NPP data were estimated by means of destructive sampling and were defined as the difference in biomass and litterfall between two survey years divided by the number of years between measurements, thereby providing the net biomass and litterfall change per year. In this study, we defined "biomass" as the standing crop ($Mg\,ha^{-1}$). In this study, biomass and ANPP are all dry-matter based.

2.2 Calculation of ANPP from other NPP components

Since some of the original sets did not provide ANPP data and instead presented only data on NPP_S, NPP_L, or TNPP, we estimated the ANPP for each dataset using allometric relationships between the various NPP components and ANPP. We developed three allometric relationships to perform this analysis: (1) the TNPP-ANPP relationship, (2) the NPP_S-ANPP relationship, and (3) the NPP_L-ANPP relationship. Figure 1 shows typical examples of these relationships, and Table 1 lists the regression results for the sets of data that required this allometric approach. As shown in Table 1 and Fig. 1, strong and significant linear correlations were found between the NPP components (such as NPP_S, NPP_L) or TNPP and ANPP, suggesting that our approach is an acceptable way to obtain ANPP data from studies that presented only NPP components.

2.3 Relationship between biomass and ANPP

Biomass is generally considered to represent the accumulation of plant organic matter during a plant's life cycle. During a forest's growth stages, ANPP tends to increase with increasing AB (Whittaker and Marks, 1975; Fang et al., 1996; Jenkins et al., 2001; Brown, 2002). Therefore, previous studies established the biomass-NPP relationship based on field measurements and used biomass to estimate the changes in NPP (Whittaker and Marks, 1975; Fang et al., 1996; Jenkins et al., 2001). In the present study, we used our new database to establish a series of relationships between AB and ANPP for Japan's main forest types. To document the contribution of various forest types to Japan's total ANPP, we classified the country's forests into 10 major types: *Cryptomeria japonica* forests, *Chamaecyparis obtusa* forests, *Pinus* forests, *Larix leptolepis* forests, *Abies* and *Picea* forests, other needle-leaf forests, *Quercus* forests, other deciduous broadleaf forests, evergreen broadleaf forests, and needle-leaf and broadleaf mixed forests (For the details of the dominant species in each of the forest types, see Table S1). Figure 2 presents typical examples of the relationships between AB and ANPP, and Table 2 presents the regression results for all of these forest types. Table 2 and Fig. 2 both show strong and significant ($p < 0.05$) relationships between AB and ANPP for most forest types, with the exception of evergreen

Table 1. Regression parameters for the relationships between aboveground net primary production (ANPP) and total NPP (TNPP), stem NPP (NPP_S), and leaf NPP (NPP_L) for Japan's major forest types, where a and b are the regression constants for each forest type. The units of all NPP components are $Mg\,ha^{-1}\,yr^{-1}$. All regressions were statistically significant ($p < 0.001$).

Forest type	ANPP = a TNPP + b				ANPP = a NPP_S + b				ANPP = a NPP_L + b			
	a	b	R^2	n	a	b	R^2	n	a	b	R^2	n
Cryptomeria japonica forests	0.8094	0.4425	0.98	74	1.2927	3.7627	0.91	107				
Chamaecyparis obtusa forests	0.8800	−1.0011	0.98	12	1.2635	3.6640	0.86	48				
Other deciduous broadleaf forests	0.8703	0.2064	0.98	27	1.2072	3.3053	0.87	10				
Other needle-leaf forests					1.9424	0.7924	0.88	12				
Evergreen broadleaf forests					1.2650	6.5991	0.87	19				
Needle-leaf and broadleaf mixed forests									2.1544	2.0307	0.99	6

Table 2. Relationships between aboveground biomass (AB, x) and aboveground net primary production (ANPP, y) for the major forest types in Japan. SD = standard deviation.

Forest type	AB ($Mg\,ha^{-1}$)			ANPP ($Mg\,ha^{-1}\,yr^{-1}$)			AB-ANPP relationship			
	Range	Mean	SD	Range	Mean	SD	Equation	n	R^2	p
Cryptomeria japonica forests	10.5 to 371.0	136.8	75.9	0.7 to 36.3	14.3	5.2	$1/y = 6.5856/x + 0.0144$	172	0.48	< 0.001
Chamaecyparis obtusa forests	25.3 to 308.2	161.3	69.0	4.9 to 20.6	12.4	3.6	$y = 0.0152x + 9.9770$	85	0.08	0.007
Pinus forests	24.7 to 222.1	96.5	51.4	5.6 to 20.3	11.8	3.8	$1/y = 2.5151/x + 0.0582$	26	0.56	< 0.001
Larix leptolepis forests	13.3 to 210.3	88.6	60.0	5.6 to 17.1	12.2	3.2	$y = 0.0416x + 8.5101$	26	0.61	< 0.001
Abies and *Picea* forests	12.6 to 378.7	176.2	91.1	1.2 to 21.7	10.7	4.7	$y = 0.038x + 3.9452$	44	0.55	< 0.001
Other needle-leaf forests	13.6 to 396.4	119.2	89.1	3.3 to 18.1	10.2	4.4	Mean = 10.2	16		
Quercus forests	27.4 to 265.0	117.0	69.5	4.7 to 23.6	11.8	4.9	$y = 0.0489x + 6.1131$	26	0.48	< 0.001
Other deciduous broadleaf forests	18.4 to 787.4	250.7	151.4	2.8 to 34.0	10.2	5.5	$y = 0.0184x + 5.5736$	101	0.26	< 0.001
Evergreen broadleaf forests	19.5 to 377.6	99.8	87.9	7.8 to 30.8	15.4	5.4	Mean = 15.4	67		
Needle-leaf and broadleaf mixed forests	86.1 to 559.7	308.5	203.4	6.4 to 16.2	9.4	3.6	Mean = 9.4	9		

Table 3. Forest area, mean aboveground biomass (AB), mean aboveground net primary production (ANPP), and total ANPP for Japan's major forest types from 1980 to 2005. CRYJAP, *C. japonica*; CHAOBT, *C. obtusa*; Larix, *L. leptolepis*; ABI & PIC, *Abies* and *Picea*; OtherN, Other needle-leaf forests; OtherB, Other deciduous broadleaf forests and Evergreen broadleaf forests.

Item	Period	Needle-leaf forest							Broadleaf forest			Total
		CRYJAP	CHAOBT	*Pinus*	*Larix*	ABI & PIC	OtherN	Subtotal	*Quercus*	OtherB	Subtotal	
Forest area (10^3ha)	1980	4416	2177	3746	1129	3627	1104	16198	1140	6500	7640	23839
	1985	4522	2392	2382	1100	5536	627	16560	1906	5315	7221	23781
	1990	4590	2513	2592	1097	2638	814	14244	1890	7657	9546	23791
	1995	4574	2600	2411	1084	2267	777	13713	2362	7609	9971	23685
	2000	4545	2626	1998	1060	1820	1039	13087	3197	7222	10419	23506
	2005	4528	2633	1903	1034	1617	767	12482	2946	8210	11156	23637
Mean AB ($Mg\,ha^{-1}$)	1980	71.5	66.3	46.1	52.7	34.7	63.8	54.9	70.3	101.2	96.6	68.2
	1985	84.8	74.2	70.7	68.8	30.1	102.7	62.7	53.5	134.6	113.2	77.9
	1990	95.0	80.9	69.9	78.9	45.3	82.1	76.8	50.1	98.7	89.1	81.7
	1995	108.2	91.7	78.4	89.4	51.5	82.9	87.5	22.9	108.2	88.0	87.7
	2000	129.8	108.4	94.8	103.6	66.7	75.6	104.9	55.4	123.1	102.3	103.8
	2005	144.9	121.2	106.6	112.0	74.2	113.3	120.2	53.3	116.7	100.0	110.7
	Mean*	105.7	90.4	77.8	84.2	50.4	86.7	84.5	50.9	113.7	98.2	88.3
Mean ANPP ($Mg\,ha^{-1}\,yr^{-1}$)	1980	9.4	11.0	8.9	10.7	5.3	10.2	9.2	9.6	12.3	10.9	9.6
	1985	10.9	11.1	10.7	11.4	5.1	10.2	9.9	8.7	12.3	10.5	10.0
	1990	11.9	11.2	10.6	11.8	5.7	10.2	10.2	8.6	12.3	10.4	10.3
	1995	13.3	11.4	1.1	12.2	5.9	10.2	10.7	7.2	12.3	9.7	10.4
	2000	15.4	11.6	11.8	12.8	6.5	10.2	11.4	8.8	12.3	10.5	11.2
	2005	16.7	11.8	12.2	13.2	6.8	10.2	11.8	8.7	12.3	10.5	11.5
	Mean*	12.9	11.4	10.9	12.0	5.9	10.2	10.5	8.6	12.3	10.4	10.5
Total ANPP ($Tg\,yr^{-1}$)	1980	41.4	23.9	33.2	12.1	19.1	11.2	149.6	10.9	79.6	83.3	230.0
	1985	49.1	26.6	25.4	12.5	28.2	6.4	163.6	16.6	65.1	75.7	238.6
	1990	54.8	28.2	27.5	12.9	15.0	8.3	145.8	16.2	93.8	99.3	244.5
	1995	60.8	29.6	26.7	13.3	13.4	7.9	146.4	17.1	93.2	97.1	247.3
	2000	69.8	30.5	23.6	13.6	11.8	10.6	148.9	28.2	88.5	109.8	262.5
	2005	75.6	31.1	23.3	13.6	10.9	7.8	147.4	25.7	100.6	117.0	271.4
	Mean*	58.6	28.3	26.6	13.0	16.4	8.7	150.3	19.1	86.8	97.0	249.1

*Mean value of data from 1980 to 2005.

broadleaf forests, other needle-leaf forests, and needle-leaf and broadleaf mixed forests. For these three forest types, we used the mean value from the field data for our further analysis of ANPP.
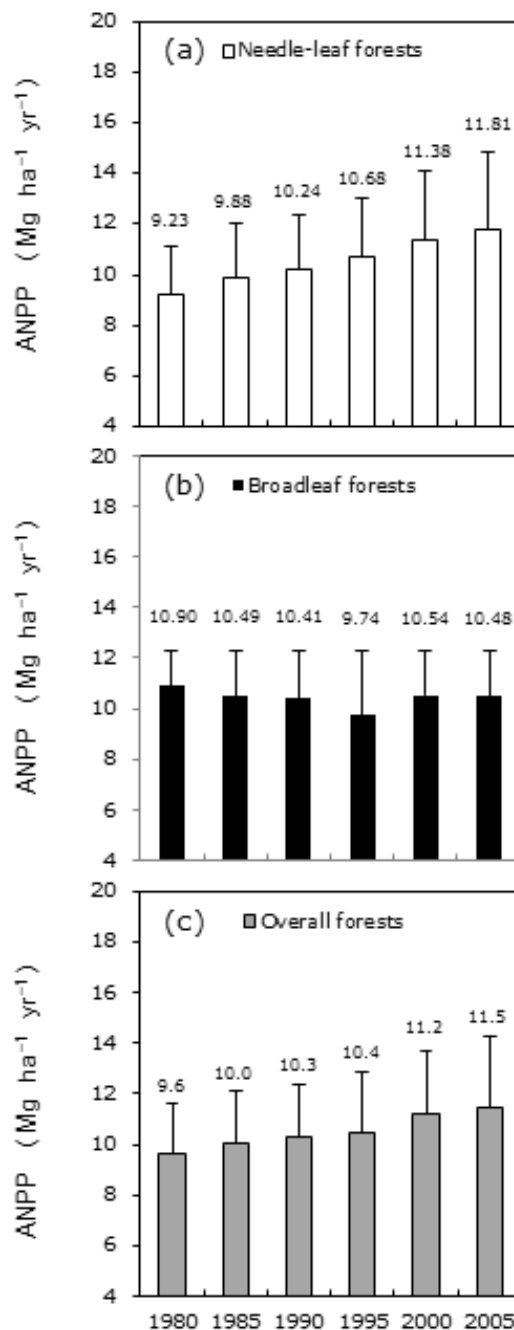
2.4 Forest inventory dataset

Although Japan's Forest Resources Statistics are available from 1947 to 2005, only those since 1980 are complete and report both the forest area and total timber volume for each age class and each major forest type by prefecture (for the 47 prefectures in Japan). The data were compiled from 10 000 statistically representative, adequately replicated, permanent sample plots across the country. The area of each plot is 1000 m^2. In the present study, forest was defined as land with 20 % or more crown cover of government-owned forests and more than 30 % crown cover of community and privately owned forests. The data recorded included the forest group (planted and natural forests), owner, dominant tree species, age class, diameter at breast height, tree height, and stem volume. Biomass was estimated for each kind of forest from the timber volume. For a detailed description of forest inventories in Japan and the methods of biomass estimation, see Fang et al. (2005).

3 Results

Because of limitations in the earlier data from Japan's Forest Resources Statistics, we have focused on the changes in ANPP of Japan's forests only from 1980 to 2005. Table 3 summarizes the mean and total ANPP of Japan's forests for this period. The mean ANPP for all forest types combined averaged 10.5 Mg ha^{-1} yr^{-1} during the 25 yr, and ranged from 9.6 to 11.5 Mg ha^{-1} yr^{-1} (Table 3, Fig. 3). From 1980 to 2005, the mean ANPP increased markedly, by 1.9 Mg ha^{-1} yr^{-1}, with a mean annual increment of 0.076 Mg ha^{-1} yr^{-1} (0.79 %).

The mean ANPP of needle-leaf forests increased steadily throughout the study period (Fig. 3), with a mean annual increment of 0.10 Mg ha^{-1} yr^{-1} (1.12 %), giving a total increment of 2.6 Mg ha^{-1} yr^{-1} (Table 3). In addition, the mean ANPP of most types of needle-leaf forest increased. The largest increase was for *C. japonica* forests, with a total increase of 7.3 Mg ha^{-1} yr^{-1} over the 25 yr, followed by *Pinus* forests, *L. leptolepis* forests, *Abies* and *Picea* forests, and *C. obtusa* forests, with increases of 3.3, 2.5, 1.5, and 0.8 Mg ha^{-1} yr^{-1}, respectively (Table 3). Because the AB-ANPP relationship for other needle-leaf forests was not significant (Table 2), we used the mean value of the field data in Table 3. Therefore, it is difficult to determine the changes in mean ANPP of this forest type during the study period.

In contrast, the mean ANPP of broadleaf forests showed a more complex pattern of changes. ANPP declined from 10.9 Mg ha^{-1} yr^{-1} in 1980 to 9.7 Mg ha^{-1} yr^{-1} in 1995, then

Fig. 3. Changes in mean aboveground net primary production (ANPP) of Japan's forests from 1980 to 2005: **(a)** needle-leaf forests; **(b)** broadleaf forests; **(c)** overall forests. The vertical lines extending from the top of boxes indicate standard errors of the means for different forests.

recovered to 10.5 Mg ha^{-1} yr^{-1} in 2000 and remained at this level until 2005 (Table 3, Fig. 3). Overall, the mean ANPP of broadleaf forests decreased slightly (by 0.4 Mg ha^{-1} yr^{-1}) during the study period, with a mean annual decrement of 0.02 Mg ha^{-1} yr^{-1} (0.15 %). Because the data for other

Table 4. Estimates of mean aboveground net primary production (ANPP) for Japan's forests and those of other northern countries or regions.

Country or region	Period	Forest type	Mean ANPP (Mg ha^{-1} yr^{-1})	Reference
Japan	1980 to 2005	All	10.5	This study
		Broadleaf	10.4	This study
		Needle-leaf	10.5	This study
China	1984 to 1988	All	4.4*	Fang et al. (1996)
United States (Mid-Atlantic region)		All	8.5	Jenkins et al. (2001)
		Broadleaf	8.6	Jenkins et al. (2001)
		Needle-leaf	7.9	Jenkins et al. (2001)
United States (eastern region)	1980s to 1990s	Broadleaf	9.7	Brown and Schroeder (1999)
		Needle-leaf	8.7	Brown and Schroeder (1999)
Europe	1995 to 2000	All	3.2 (1.2 to 8.0)	Karjalainen et al. (2003)

* Including belowground NPP.

broadleaf forests in Table 3 represent the mean values for other deciduous broadleaf forests and evergreen broadleaf forests (Table 2), the changes in this forest type were not visible during the study period. Therefore, the majority of the change of mean ANPP of broadleaf forests resulted from changes in the mean ANPP of *Quercus* forests. Moreover, we noticed that the forests in two categories, "other needle-leaf forests" and "other broadleaf forests", did not show a clear trend in temporal variation both in area and other variables, compared with other forests. A possible error may exist in the inventory data due to land-surface classification differing in different periods. Further attention to the two forest types should be paid in the future because of their significant area, biomass, and productivity.

The total ANPP of Japan's forests (all types combined) averaged 249.1 Tg yr^{-1} during the study period and ranged from 230.0 to 271.4 Tg yr^{-1} (Table 3). Simultaneous with the increase of mean ANPP, the total ANPP of Japan's forests increased by 41.4 Tg yr^{-1} over the 25 yr, representing a mean annual increase of 1.66 Tg yr^{-1} (0.72 %). However, in contrast with the trends for mean ANPP, the total ANPP of needle-leaf forests decreased by 2.2 Tg yr^{-1} from 1980 to 2005 (a mean annual rate of 0.06 %), whereas the total ANPP of broadleaf forests increased by 33.7 Tg yr^{-1} (a mean annual rate of 1.62 %) during the same period (Table 3). For specific forest types, the total ANPP increased most for the *C. japonica* forests, followed by other broadleaf forests, *Quercus* forests, *C. obtusa* forests, and *L. leptolepis* forests, which increased by 34.2, 21.0, 14.8, 7.2, and 1.5 Tg yr^{-1} over the 25 yr, respectively (Table 3). The reductions in total ANPP were greatest for *Pinus* forests, followed by *Abies* and *Picea* forests and by other needle-leaf forests, with decreases of 9.9, 8.2, and 3.4 Tg yr^{-1} over the 25 yr, respectively (Table 3).

4 Discussion

Our analysis revealed different patterns of change in the mean ANPP between needle-leaf and broadleaf forests (Fig. 3). This can be attributed to differences in the ratio of planted and natural forests for needle-leaf and broadleaf forests. In Japan, most of the planted forests are needle-leaf forests. Moreover, due to the economic benefits and the pinewood nematode, the large area of deforestation of natural needle-leaf forests happened in recent decades, making the ratio of planted to natural forests increase from 1.5:1 to 4.1:1 (Table S2). Compared to natural forests, the well-managed plantations exhibited rapid early growth, resulting in a significant ANPP increment in needle-leaf forests from 1980 to 2005. Conversely, more than 97 % of the broadleaf forests were natural forests (Table S2). The area of old natural forests with high biomass density decreased rapidly, accompanied by a rapid increase in the area of young secondary forests with low biomass density, thereby decreasing the mean ANPP of broadleaf forests.

Interestingly, the directions of mean ANPP change for needle-leaf and broadleaf forests were the opposite of the directions for total ANPP. Because total ANPP was estimated by combining the mean ANPP with the total forest area, the forest area did play an important role in this difference. During the study period, the area of needle-leaf forests declined by 3.716×10^6 ha (22.9 %), whereas that of broadleaf forests increased by 3.516×10^6 ha (46.0 %) (Table 3).

To compare mean forest ANPP in Japan with values from elsewhere, we summarized the mean forest ANPP for several key northern countries or regions in the Northern Hemisphere (Table 4). The overall mean ANPP of Japan's forests averaged 10.5 Mg ha^{-1} yr^{-1} from 1980 to 2005, and those of broadleaf forest and needle-leaf forest were 10.4 and 10.5 Mg ha^{-1} yr^{-1}, respectively. The mean ANPP of Japan's forests was more than two times the mean TNPP of China's forests (4.4 Mg ha^{-1} yr^{-1}; Fang et al., 1996). Because TNPP equals the sum of ANPP and BNPP, the actual ANPP

difference between Japan and China would be even greater. The mean ANPP of Japan's forests was also higher than that of forests in the eastern United States (ranging from 8.7 to $9.7 \, \mathrm{Mg \, ha^{-1} \, yr^{-1}}$; Brown and Schroeder, 1999) and the mid-Atlantic region of the United States ($8.5 \, \mathrm{Mg \, ha^{-1} \, yr^{-1}}$; Jenkins et al., 2001). Europe had the lowest ANPP, with a mean of only $3.2 \, \mathrm{Mg \, ha^{-1} \, yr^{-1}}$ (ranging from 1.2 to $8.0 \, \mathrm{Mg \, ha^{-1} \, yr^{-1}}$; Karjalainen et al., 2003). These results were consistent with those for the forest biomass carbon density of northern countries and regions reported by Fang et al. (2005). In their study, Japan's carbon sink was higher than that of other countries or regions, and this large carbon sink was mainly due to the rapid regrowth of plantations. Actually, high ANPP have been reported in some plantations in the southern United States (e.g., McNulty et al., 1996) and Europe (e.g., Xiao et al., 2003). It is note that, however, the NPP distinguished heavily not only depend on forest types, but also depend on site conditions, making it difficult to give reasonable judgment on plantation level all over the world. Therefore, in this study, we just roughly classified the forest to "Needle-leaf forest" and "Broadleaf forest" and pay attention on the studies reported on countries or regions level using the similar analysis method.

The large ANPP estimated in this study may also imply a large belowground net primary productivity (BNPP), since BNPP often vary proportionally with ANPP (Gower et al., 1997; Kajimoto et al., 1999; Xiao et al., 2003; Tateno et al., 2004; Hertel et al., 2009). However, these studies also indicate that the ratio of ANPP to BNPP can vary largely depending on physical environment, forest stand age and plant species composition etc. Therefore, the exact BNPP of the forests in Japan remains to be further explored in the future.

It is noteworthy that compared with other countries or regions, the mean ANPP of needle-leaf forests was comparable with that of broadleaf forests in Japan. Compared to other countries or regions, the selection of fast-growing types of needle-leaf forest (such as *C. japonica*) and the intensive forest management practiced in Japan are probably responsible for the higher ANPP of the needle-leaf forests.

All the equations of NPP and biomass in this present study were established basing on a review and analysis of field data on forest biomass and NPP (945 sets of biomass data and 572 sets of NPP data) from the five decades before 1995. All the NPP data were estimated by means of destructive sampling, so the results can be expected to be accurate.

Kira (1976) calculated NPP using the following equation:

$$\Delta P_n = \Delta Y + \Delta L + \Delta G, \tag{1}$$

where ΔP_n is NPP, ΔY is the net change in standing biomass per unit time (year), which represents the amount of growth, ΔL is the loss due to tree mortality, and ΔG is the biomass loss due to herbivory. Because the herbivory loss is difficult to estimate, it was not included in our sets of NPP data. Based on the results of Kira (1976) and Clark et al. (2001),

the loss of biomass due to the herbivory makes the underestimation the NPP of canopy trees by about 7 %. Thus, the value of NPP based on the field data used in our study was slightly underestimated.

Because we used the AB-NPP relationship to estimate the forest's NPP, the quality of our allometric equations determines the precision of our ANPP estimates. Since the stand age and stand density (crown cover) varied greatly among the field data, the simulation results are not very satisfactory, even though the relationships between AB and ANPP were generally strong and statistically significant. For the other broadleaf forests and evergreen broadleaf forests, which include many species, we could not develop a single statistically significant equation for the relationship between AB and ANPP, but instead had to use the mean values from the field data to estimate ANPP for these forest types. Given the above limitations, it should be possible to improve the precision of our estimates by (1) collecting more field data in these forests to increase the sample size, (2) using more suitable statistical equations that account for variations in stand age and density, and (3) dividing these forests into specific subtypes based on their species composition or other factors when developing future AB-NPP equations.

In summary, we used direct field measurements and forest inventory data to establish a new database of forest biomass and NPP in Japan, and we established allometric relationships between AB and NPP for Japan's major forest types. Based on these allometric relationships and forest inventory data, we assessed the long-term changes in ANPP for Japan's forests from 1980 to 2005. The results indicated that the mean and total ANPP of Japan's forests have increased markedly over the past 25 yr. Moreover, as was the case for Japan's carbon sink size in previous research, the ANPP of Japan's forests was higher than that of other countries or regions in the Northern Hemisphere. Afforestation based on planting of fast-growing trees and intensive forest management was the major factors responsible for Japan's higher ANPP.

Supplementary material related to this article is available online at: http://www.biogeosciences.net/8/2099/2011/ bg-8-2099-2011-supplement.pdf.

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