

OVERESTIMATED BIOMASS CARBON POOLS OF THE NORTHERN MID- AND HIGH LATITUDE FORESTS

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Abstract. The biomass carbon (C) stock of forests is one of key parameters for the study of regional and global carbon cycles. Literature reviews shows that inventory-based forest C stocks documented for major countries in the middle and high northern latitudes fall within a narrow range of 36–56 Mg C ha⁻¹ with an overall area-weighted mean of 43.6 Mg C ha⁻¹. These estimates are 0.40 to 0.71 times smaller than those (61–108 Mg C ha⁻¹) used in previous analysis of balancing the global carbon budget. A statistical analysis, using the global forest biomass database, implies that aboveground biomass per hectare is proportional to forest mean height [biomass in Mg/ha = 10.63 (height in m)] in closed-canopy forests in the study regions, indicating that forest height can be a proxy of regional biomass C stocks. The narrow range of C stocks is likely a result of similar forest height across the northern regions. The lower biomass C stock obtained in this study strongly suggests that the role of the northern forests in the global carbon cycle needs to be re-evaluated. Our findings also suggest that regional estimates of biomass could be readily made from the use of satellite methods such as lidar that can measure forest canopy height over large regions.

1. Introduction

There is clear evidence that forests of the mid- and high latitudes in the Northern Hemisphere significantly contribute to the terrestrial carbon (C) sink (e.g., Houghton and Hackler, 2000; Fang et al., 2001, 2005; Myneni et al., 2001; Pacala et al., 2001; Schimel et al., 2001; Goodale et al., 2002; Janssens et al., 2003; Liski et al., 2003; Nabuurs et al., 2003; Piao et al., 2005). However, the magnitude of the C sink is still controversial, partly due to uncertainties in the estimation of forest biomass carbon and its increment (Holland et al., 1999; Houghton et al., 2001; Jenkins et al., 2001; Houghton, 2003, 2005; Kauppi, 2003; Liski et al., 2003). For instance, biomass estimates of Russian forests varied from 28.0 Pg C to 35.1 Pg C by different authors (Alexeyev et al., 1995; Isaev et al., 1995) although the same forest data sources but different methods were used. In Brazil's Amazonian forests, estimates of forest biomass varied by more than a factor of two from 39 Pg C to

93 Pg C (Houghton et al., 2001). This disagreement in biomass C estimates for large regions of the world suggest a need to develop an improved method for accurately estimating regional and global forest biomass carbon stocks. Forest inventory-based estimation with improved allometric regression equations is a way to accomplish such an accurate estimation (Houghton et al., 2001; Goodale et al., 2002; Houghton, 2003; Fang et al., 2005). Recently, Kauppi (2003) and Liski et al. (2003) used an inventory-generated global forest resource database to reevaluate the biomass C stocks of the global forests, and found a much lower estimate for the forests than that used for the previous assessment of the global carbon budget.

The realistic estimate of forest biomass stocks is critical for balancing the global carbon budget as it is associated with estimates of the vegetation net primary production and the amount of carbon released by clearing forests (Botkin and Simpson, 1990; Jenkins et al., 2001; Brown, 2002; Kauppi, 2003). Its time series can also be a way to validate other methods for estimating the net carbon flux such as inverse modeling (Goodale et al., 2002; Kauppi, 2003).

Early global estimates of the C pools in forests used the average biomass density (half of which is carbon) derived from direct field measurements of biomass (e.g., Whittaker and Likens, 1975; Ajtay et al., 1979). The biomass carbon map for the world's vegetation (updated version of Olson et al., 1983), which is commonly used in global carbon models, is also based on such direct measurement studies. These global estimates have been further used to calculate or assess global carbon budgets (e.g. White et al., 2000; IPCC, 2001; Saugier et al., 2001). However, as a non-random sampling approach, the direct measurement of biomass on a local level does not accurately represent the average biomass within a region or country because it is often biased towards plots with large diameter trees, resulting in an overestimation of biomass (Brown et al., 1989; Botkin and Simpson, 1990; Dixon et al., 1994; Schroeder et al., 1997; Fang et al., 1998; Jenkins et al., 2001; Kauppi, 2003). Other approaches have used well-designed and statistically sound regional or national forest inventories available for many countries as a key data source to calculate forest biomass and account for the C budgets at regional scales (e.g., Brown et al., 1989; Kauppi et al., 1992; Birdsey, 1992; Birdsey and Heath, 1995, 2001; Alexeyev et al., 1995; Isaev et al., 1995; Turner et al., 1995; Brown and Schroeder, 1999; Fang et al., 2001, 2005; Jenkins et al., 2001; Goodale et al., 2002; Kauppi, 2003; Liski et al., 2003; Nabuurs et al., 2003; Smith et al., 2003, 2004).

Most forest inventories record detailed information on forest area and timber volume by forest type. However, only the commercial portion (such as stem volume) of forest biomass is usually considered. To use inventory data to estimate total and/or aboveground forest biomass, a biomass expansion factor [BEF, defined as the ratio of all stand biomass to growing stock volume or mass (Brown et al., 1989; Schroeder et al., 1997; Fang and Wang, 2001)], which converts stem volume or stem biomass to total and/or aboveground forest biomass and accounts for noncommercial components, must be calculated first. This was called the BEF method (Brown

et al., 1989; Fang and Wang, 2001; Fang et al. 2005). In the current study, we (1) present estimates of the biomass C pools in the northern latitude forests by reviewing recent publications that report national forest biomass estimates derived from inventory data sources and the BEF methods, (2) compare these inventory-based estimates with those used in the analysis of global carbon cycle, and (3) explore the possible cause of the discrepancy between these two estimation approaches. In addition, this work also provides insights into the development of future methods for carbon inventory based on remote measurements of mean forest height. Because the area of the northern forests differs considerably in the various literature sources, we focus our analysis on biomass C density (living vegetation mass per hectare in C unit) rather than on total C pools.

2. Forest Biomass Estimates of the Northern Latitudes

2.1. INVENTORY-BASED FOREST BIOMASS ESTIMATES

Using forest inventory data and BEFs, forest biomass has been estimated for major countries in the Northern Hemisphere by different authors (Table I). The methods used in these estimations were basically the same, and the data sources were all from statistically sound regional or national forest inventories.

In Canada, the age class versus forest area relationship and age class versus biomass relationship were developed to estimate forest biomass for each region. The forest inventory datasets used include forest area, age classes (regeneration, immature, mature and overmature), and aboveground biomass data (Bonnor, 1985; Kurz et al., 1992; Kurz and Apps, 1999). China's forest biomass was estimated from the variable function equations of BEF versus stem volume that were derived from a number of direct field-biomass measurements. Using these variable BEF equations, timber volume was converted to total vegetation biomass for each forest type for each region (Fang et al., 1998, 2001). European forest vegetation carbon was calculated by using different BEFs by each forest group (coniferous and deciduous) and each country (UN-ECE/FAO, 2000; Nabuurs and Schelhaas, 2003). Japan has well-documented forest inventory datasets from 1960s to 1995 (Matusmoto, 2001). The estimates of the country's forest biomass were based on different BEFs for major tree species (Matusmoto, 2001). To estimate biomass of Russian forests, 2700 sample plots from more than 200 regional studies were used to develop nonlinear regression equations of BEF versus forest features (age group, site index, and relative stocking) (Nilsson et al., 2000). Then these equations were used to calculate forest biomass for each age group and site index for each dominant species in each ecoregion. In the United States (Alaska and conterminous USA), whole-tree biomass carbon was converted from growing-stock volume in a specific forest area in two steps: (1) growing-stock volume was converted to total forest volume using a ratio that accounts for the volume of additional tree components such as tops,

TABLE I
Forest carbon pools in major regions of the middle and high latitudes in the Northern Hemisphere

| Region | Forest area (10 ⁶ ha) | Time period | Total C (Pg) | C density (Mg.ha ⁻¹) | Methods | Reference |
|---------------------|-------------------------------------|----------------|-----------------|-------------------------------------|--|--|
| Alaska | 52.2 | 1987–92 | 2.2–2.3 | 41.3–43.8 | BEF for each species group | Birdsey (1992), Birdsey and Heath (1995) |
| Canada | 404.2 | 1989 | 14.5 | 35.9 | Using age class versus area relationship and age class versus biomass relationship | Kurz and Apps (1999) |
| China ^a | 102.2–108.6 | 1988–93 | 4.5–4.6 | 42.6–43.5 | Continuous BEF | Fang et al. (2001) |
| Conterminous U.S. | 243.8–245.9 | 1987–92 | 13.8–13.9 | 56.0–56.8 | BEF for each region and each species group | Birdsey (1992), Birdsey and Heath (1995) |
| Europe ^b | 182.0 | 1990 | 7.3 | 40.1 | BEF for each country and for each tree species group | UNECE/FAO (2000) |
| Japan | 23.9–25.0 | 1990 | 1.2 | 46.0–50.4 | A BEF value of 1.7 and 1.8 for coniferous and deciduous forests | Matsumoto (2001), Fang et al. (2005) |
| Russia | 763.5 | 1990 | 32.9 | 43.0 | BEF for each age group, site index, and relative stocking for each dominant species in different ecoregions | Nilsson et al. (2000) |
| Total in 1990 | 1777 | | 77.6 | 43.6 | | |

All estimates are based on forest inventory data. Only biomass (above- and below-ground) of living vegetation is shown. Biomass is converted to carbon content using a factor of 0.5.

^aCanopy coverage is more than 30%.

^bParameter of total forests (forest and other wooded lands). Parameters of forest only were given in 1990 in the original publication (UNECE/FAO, 2000). Parameters of the total forests are estimated based on proportion of those to 1990.

branches and roots, and (2) total forest tree volume was converted to biomass carbon using different BEFs for softwoods and for hardwoods (Birdsey, 1992).

The area-weighted mean C density of the northern forests estimated from the above approaches falls within the narrow range of 36 Mg C ha⁻¹ (Canada) to 56 Mg C ha⁻¹ (the USA) in around 1990, with an overall average of 43.6 Mg C ha⁻¹ (Table I). Compared to this narrow range, a previous study (Dixon et al., 1994) obtained a wider variance of 28 Mg C ha⁻¹ (Canada) to 114 Mg C ha⁻¹ (China), with an average of 63 Mg C ha⁻¹. The overall average that we obtained (Table I) is smaller by 69% than that reported by Dixon et al. (1994), but close to a recent estimate based on remote sensing combined with forest inventory [42.9 Mg C ha⁻¹ by Myneni et al. (2001)], and the estimates derived from an inventory-based global forest resource database by Kauppi (2003) and Liski et al. (2003).

Compared to the forest biomass estimates in Table I, those used for many modeling studies of the global carbon cycle are 1.4 to 2.5 times larger (Table II). The estimates in Table II, ranging from 61 to 108 Mg ha⁻¹, have been commonly used to develop regional and global carbon budgets. This suggests that the previous forest biomass C stocks in the northern mid- and high latitudes may be overestimated, and thus the role of the Northern Hemisphere forests in global C budget may need to be re-evaluated.

These downward estimates have also been documented by several previous studies. For instance, Botkin and Simpson (1990) used field measures of tree dimensions to estimate the C stocks of North American boreal forests and found they were smaller than previous estimates. Nilsson et al. (2000) pointed out that previous global database approaches and global vegetation models have overestimated total biomass C stocks of Russian boreal forests by a factor of 1.5–2.0. In a review paper, Fang and Wang (2001) present biomass C densities for major northern countries and suggested possible overestimates. Goodale et al. (2002) and Liski et al. (2003) reviewed the C sink and stocks of temperate and boreal forests. Kauppi (2003) re-analyzed the global forest C stocks and argued that a lower estimate (300 Pg C) of the global C pool is more realistic. This recent research suggests that the lower C stock estimates are likely more reasonable.

2.2. FOREST HEIGHT CAN BE A PROXY OF FOREST BIOMASS CARBON AT LARGE SCALE

To address the question of why a small biomass density range occurs in the northern forests (Table I), we have reviewed the relationships between forest biomass and tree dimensions (diameter at breast height, tree height, number of stems, and forest age) for the northern regions, using a global forest biomass database that was developed from field measurements of tree dimensions during the IBP (International Biological Programme, 1965–1974) across the world (Cannell, 1982). We found that forest biomass was most closely related to forest height at the large scale. This suggests

TABLE II
Biomass carbon density (above- and below-ground) estimates in the mid- and high latitudinal zone of the Northern Hemisphere, based on different authors

| Vegetation zone/ latitudinal belt ^a | Forest area (10 ⁶ ha) | Total C (PgC) | C density (MgCha ⁻¹) | Time period | Methodology or data source | Reference |
|---|-------------------------------------|------------------|-------------------------------------|----------------|---|------------------------------|
| 1 | 3250 | 338 | 104 | 1960s | Field direct measurements | Whittaker and Likens (1975) |
| 2 | 1850 | 200 | 108 | 1960s | Field direct measurements | Ajtay et al. (1979) |
| 3 | 3180 | 306 | 78 | 1970s | Field direct measurements | Olson et al. (1983) |
| 4 | 4700 | 376 | 80–94 | 1970s | Simulation study | Prentice and Fung (1990) |
| 5 | 2010 | 129 | 63 | 1987–90 | Most data sources are from inventory, but some are not (e.g. China) | Dixon <i>et al.</i> (1994) |
| 6 | 3210 | 225 | 70 | 1990 | Predicted from a global carbon model (CEVSA) | Cao and Woodward (1998) |
| 7 | 2020 | 126 | 62 | 1980s | Predicted from a global vegetation model (Hybrid v4.1) | White <i>et al.</i> (2000) |
| 8 | 2410 | 147 | 61 | 1980s | Field measurements combining with inventory | Watson (2000); IPCC (2001) |
| 9 | 2410 | 196 | 104 | 1980s | Field measurements combining with inventory | Saugier <i>et al.</i> (2001) |
| 10 | 1865 | 80 | 43.1 | 1990s | Forest inventory | Liski <i>et al.</i> (2003) |
| 11 | 1777 | 78 | 43.6 | 1990 | Forest inventory | In this study |

^aVegetation zone/latitudinal belts are: (1) Temperate evergreen forest, temperate deciduous forest, boreal forest, woodland and shrubland; (2) Temperate forests and boreal forests; (3) Mediterranean forest and woodland, cold-deciduous broadleaf forest and woodland, cold-deciduous needle-leaved forest and woodland, and evergreen needle-leaf forest and woodland; (4) Mediterranean forest and woodland, temperate evergreen broadleaf forest and woodland, cold-deciduous needle-leaved forest and woodland, evergreen needle-leaf forest and woodland, temperate evergreen broadleaf forest, and dry broadleaf forest; (5) High latitude: Alaska, Canada, and Russia; Middle latitude: China, Europe, and USA; (6) Boreal woodland, boreal forest, temperate coniferous forest, temperate mixed forest, temperate deciduous forest, and temperate broadleaf evergreen forest; (7) High-latitude zone: coniferous forest, temperate forest, and temperate/mixed forest; (8) Temperate forests and boreal forests; (9) Temperate forests and boreal forests; (10) Including counties in the Commonwealth of Independent States (CIS), Europe, and North America; (11) Including Canada, China, Finland, Japan, Russia, Sweden, United States and other European countries.

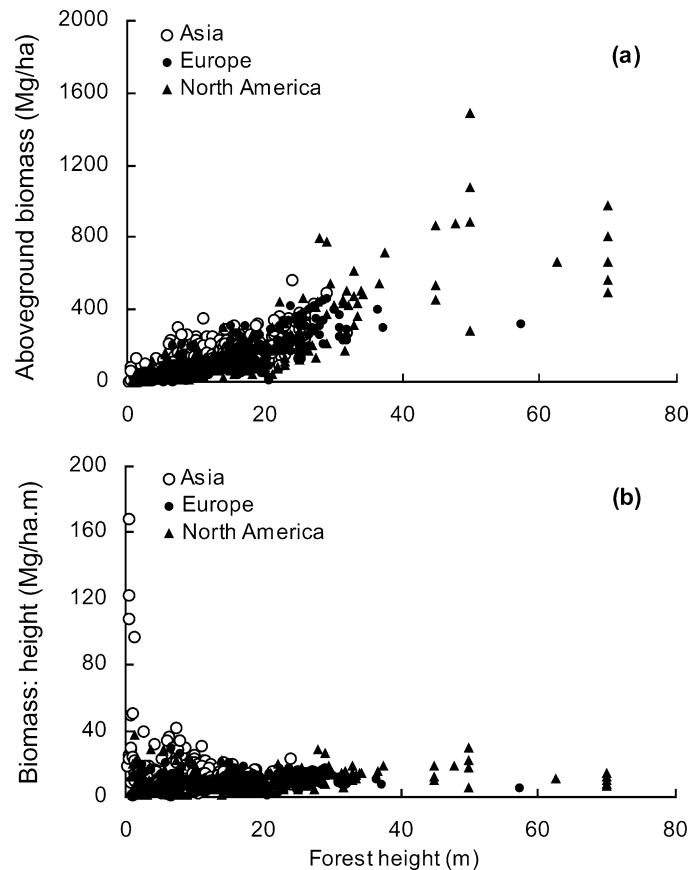


Figure 1. Pattern in (a) aboveground biomass and (b) aboveground biomass per forest space (BPS) with forest height for forests in three continents: East Asia, Europe and North America. With an increase of forest height, aboveground biomass increases and the BPV remains almost a constant when forests are relatively closed canopied. Data for China are based on Fang and Chen (2000), and others from Cannell (1982). Number of data points available is 643, 227 and 294 for Asia, Europe and North America, respectively.

that forest height is a critical factor for controlling the magnitude of regional biomass density.

It is well known that forest height is an indicator of site quality and growth potential, and in fact the site-quality index is usually derived from the forest age-height relationship (Kimmis, 1987; Kira, 2001). For this reason, we plotted the aboveground biomass versus mean tree height of forests in three continents, East Asia (China and Japan), Europe (Russia and countries of European Union) and North America (Canada and United States) (Figure 1A), based on the global forest biomass database (Cannell, 1982). These data are not from forest inventories but rather from studies that used fewer numbers of plots and thus may tend to

TABLE III
Mean forest height, aboveground biomass and aboveground biomass per forest space (BPS) in main regions of the northern middle and high latitudes

| Continent | Sample size | Forest height (m) | | Aboveground biomass (Mg.ha ⁻¹) | | BPS (kg.m ⁻³) | |
|------------------------|-------------|-------------------|-------|--|--------|---------------------------|------|
| | | Mean | SD | Mean | SD | Mean | SD |
| East Asia | 306 | 15.4 | 4.30 | 163.4 | 78.50 | 1.05 | 0.37 |
| Europe | 153 | 19.9 | 6.80 | 190.6 | 100.21 | 0.94 | 0.34 |
| North America | 166 | 21.9 | 12.90 | 230.1 | 233.10 | 0.94 | 0.49 |
| Conterminous U.S. only | 132 | 23.3 | 13.98 | 257.4 | 248.49 | 1.00 | 0.50 |
| North Hemisphere | 625 | 18.2 | 8.50 | 187.8 | 143.60 | 0.99 | 0.40 |

Only data with forest height taller than 10 m were used for calculations. Data for China were based on Fang and Chen (2000), and the others from Cannell (1982).

overestimate the biomass density at large scales but tend to be accurate at the scale for which they were designed. Despite this limitation in the database, they are useful for providing insights into the cause of the similarity of biomass densities across a wide region of the world.

The results show that biomass density increases with an increase in forest height as might be expected (Figure 1A). However, it is also clear that the ratio of aboveground biomass to forest height (termed as the aboveground biomass per forest space, BPS) shows a small difference for the three continents when forests are relatively tall and closed canopied (Figure 1B). For clarity, we used data for forests that were taller than 10 m to calculate the mean BPS for the three continents. We found that the BPS was almost constant, with a range of 0.93–1.05 kg m⁻³ and an overall average of 1.0 kg.m⁻³ (Table III), regardless of forest type and forest height. In other words, biomass density of a closed-canopy forest depends mainly on its height. The relationship of aboveground biomass (y , Mg/ha) to forest height (x , m) was expressed as $y = 10.63 x$ (Figure 2, $R^2 = 0.603$, $p < 0.0001$) for 625 plots with a canopy taller than 10 m across the three continents, suggesting that forest biomass density was proportional to forest height. At the continental scale, the correlation between these two parameters was very high ($R^2 = 0.94$, $p < 0.0001$, Table III). This explains not only why biomass densities fall within a narrow range for most northern countries – forest height varies little (15.4–19.9 m), but also helps us interpret why there are difference in the biomass density in the different regions. A larger biomass density in the conterminous USA than the mean for the northern countries is because its forests are tall (mean height of 23.3 m), suggesting that the USA forests have higher site quality than other northern regions. Figure 3, which depicts the correlations of forest height to forest age by Asia, Europe, and North America (but separated into USA and Canada) further confirms this inference. As shown in this figure, the USA forests have the highest overall site quality, followed

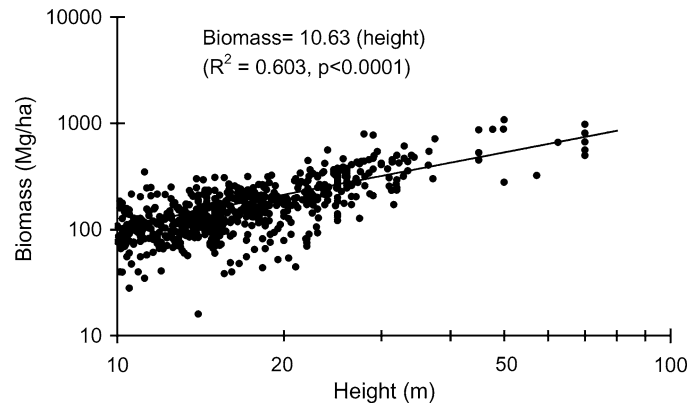


Figure 2. Relationships between aboveground biomass and height for forests taller than 10 m across the main countries of mid and high latitudes in the Northern Hemisphere. The data sources are the same as Figure 1.

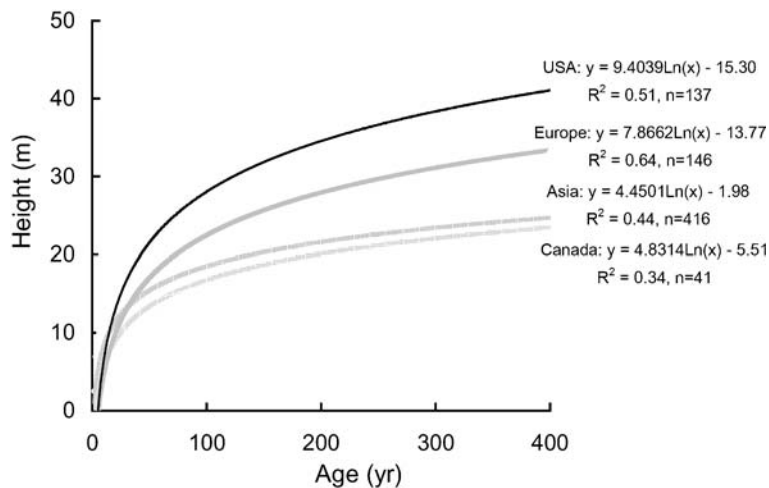


Figure 3. Relationships between mean forest age and forest height for the northern regions (USA, Canada, East Asia, and Europe), suggesting the highest overall site quality is in USA forests, followed by European, Asian, and Canadian forests. The data sources are the same as Figure 1.

by Europe, Asia, and Canada. This is consistent with mean forest height in different regions (Table III). This further shows that forest height can be an effective proxy of regional biomass stock, and therefore used for explaining regional differences in forest site quality and biomass density.

Although forest height is an important parameter for prediction of regional forest biomass, biomass is also impacted by human-induced (e.g., land-use pattern and logging regimes) and natural disturbances (e.g., wild fire patterns), as well as site quality. Generally, human and natural disturbances lead to a decrease in mean forest

height, especially for the case of managed forests (personal communication with P. E. Kauppi, 2005). Therefore, these disturbances also need to be taken into account in the relationship between forest biomass and height.

3. Conclusions

Biomass density represents a stock of organic carbon accumulated over time, which is associated with both the accumulation rate of organic carbon and forest age, and therefore influences calculations of net primary production (NPP) and net ecosystem production (NEP). Both NPP and NEP are used to estimate the magnitude of the forest carbon budget. Previously overestimated forest biomass stocks could have led to an over-valuation of NPP, NEP, and the amount of C released by clearing forests at large scale because they are usually derived from living biomass estimates (Botkin and Simpson, 1990; Jenkins et al., 2001; Brown, 2002). Therefore, downward correction of the estimates of the northern forest C stocks has major implications for balancing the global carbon budget and would challenge our current understanding of the role of vegetation in the global carbon cycle (Kauppi, 2003).

Our results reveal a small range of forest biomass density in the northern regions due primarily to a small difference in forest height at the large scale. The relatively constant BPS for the northern hemisphere forests is even more surprising, considering that the forests in each of these regions have been subject to different disturbance regimes and are at various ages and stages of recovery. For example, most forests of the eastern USA are in various stages of recovery and have biomass densities that are considerably lower than for mature forests (Brown et al., 1997). In Europe, a large area of forests is in recovering stages and accumulating a substantial amount of carbon (Nabuurs et al., 2003). Similarly, in China where most forests are planted or secondary, forests are relatively short with low biomass. In east and central south China where forests are almost all from afforestation, for instance, the forest biomass densities range between 23 and 30 MgC ha⁻¹, about a half of that in other regions of China (Fang et al., 2001).

A smaller, inventory-based forest C density estimate provides a reasonable basic parameter for the studies of the mid- and high latitude forests and the global carbon budget, and suggests that the role of the mid- and high latitude forests in the global carbon budget may need to be re-evaluated. A low forest biomass also reflects younger stands that are more vigorously growing and that are far from their potential biomass, suggesting that the most northern forests have not reached carbon saturation, but could continue to sequester carbon from the atmosphere if conserved.

We have shown that forest height can be a proxy of regional biomass C stocks in the mid to high latitude forests. This has important implications for using remote methods to estimate forest biomass over large regions. Using the more conventional multi-spectral remote sensing data (e.g. Landsat data) to estimate forest biomass

over large regions has met with limited success. However, our findings suggest that regional estimates of biomass could be readily made from the use of remote methods such as lidar that can measure forest canopy height directly over large regions (Zimblea et al., 2003; Hopkinson et al., 2004, Matthew et al., 2004; Brown et al., 2005).

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