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Forest biomass patterns across northeast China are strongly shaped by forest height

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ABSTRACT

The emergency of satellite-borne light detecting and ranging (LiDAR) technology in recent years have provided a promising way to monitor worldwide patterns of forest biomass and carbon sources/sinks. However, few studies have examined the roles of various abiotic and biotic factors in modulating the relationship between forest biomass and height at a large scale. This is important given the growing dependence on LiDAR derived forest height as a predictor of forest biomass. In this analysis, we used 529 plots across northeast China to examine this question, and to explore the method to estimate forest biomass from height. Our results showed that, while forest height and average tree height showed close relationships with stand biomass or mean biomass per stem (R^2 between 0.57 and 0.78), stand biomass could not be reliably predicted with two methods based on average tree height. In contrast, when the effects of climate and forest groups were included in the models, forest height could predict biomass patterns with a R^2 between 0.74 (belowground) and 0.91 (total biomass), which was comparable to the widely accepted biomass expansion factor method (R^2 between 0.72 and 0.98). We also showed that the ratio of both aboveground and belowground biomass to forest height (B/H ratio) was roughly similar at a large scale, suggesting that forest biomass patterns are strongly shaped by forest height. However, B/H ratio showed significant difference between deciduous and evergreen forests across northeast China. The life form of canopy trees was the major factor modulating the relationships between stand biomass and forest height, while climate, forest type and forest origin played a secondary role. Our results strongly support the use of LiDAR to monitor the large-sale patterns of both above and belowground forest biomass. Our analysis also found that the lack of forest height information in previous literatures has caused most of the biomass data could not be utilized to estimate biomass patterns from height, and we advocate future analyses to report forest height together with field-observed biomass.

1. Introduction

Forest ecosystems accounted for a majority of global terrestrial carbon pool (over 80% of aboveground carbon, Dixon et al., 1994), and might become a major carbon source as a result of rapid land use change and climatic warming (Houghton, 2005; IPCC, 2007). Consequently, estimating the large scale biomass patterns accurately is crucial for monitoring forest carbon source and sink dynamics worldwide (e.g. Fang et al., 2001; Schimel et al., 2001).

It is widely accepted that estimating forest biomass from stock volume (the biomass expansion factor method) is the most accurate method for large scale biomass estimation (e.g. Fang et al., 2001; Brown, 2002). However, this method also has some limitations: (1) it involves intensive investigations of large amount of widely-distributed field plots, which is time and efforts consuming. (2) Many countries or regions have not conducted forest inventory yet (Houghton, 2005; Massada et al., 2006) and thus this method cannot be applied. (3) The time and spatial resolutions of forest inventory data were generally coarse. For instance, forest inventory data were reported on the province (or county) basis every 5 years in China (Fang et al., 2001). However, forest biomass is strongly affected by disturbances (e.g. Wang et al., 2008; Simard et al., 2011). To capture the effects of disturbance and tree growth on spatial biomass patterns (for a more accurate monitoring of carbon sink/source), Houghton (2005) suggested that forest biomass are better to be monitored at a resolution of 25–250 m. Consequently, a more time and efforts saving method is needed to map forest biomass at finer time and spatial resolutions, especially when some important forest regions in the world (e.g. tropic and temperate forests) are undergoing rapid deforestations (Kauppi et al., 2006; IPCC, 2007).

The progresses of light detecting and ranging (LiDAR) techniques in the last two decades have provided a promising approach for this purpose. Studies with airborne LiDAR have shown that various forest structure parameters (e.g. forest height, stem density, and average tree height), as well as stand biomass and volume,

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could be estimated with LiDAR satisfactorily (e.g. Dubayah and Drake, 2000; Lefsky et al., 2002; Drake et al., 2003; van Leeuwen and Nieuwenhuis, 2010). Recently, satellite-borne LiDAR data are also available, and have promoted the mapping of forest height from regional (Lefsky et al., 2005) to global scales (Lefsky, 2010; Simard et al., 2011; Los et al., 2012). These forest height maps provided an ideal opportunity for estimating large-scale forest biomass patterns based on the relationship between biomass and forest height (e.g. Dubayah and Drake, 2000; Lefsky et al., 2005; Fang et al., 2006). However, because most previous LiDAR studies were based on airborne LiDAR at relative small scales, the large scale biomass–height relationships have seldom been examined in details.

We believe that such an examination is critical for monitoring the large-scale dynamics of forest biomass. If biomass–height relationships showed great differences both across environmental gradients and among forest types, then it is not only necessary to construct biomass–height relationships for each forest type by each region (e.g. Drake et al., 2003), but also required to monitor the distribution of each forest type (e.g. with remote sensing data). On the other hand, it might be that not all the factors affecting biomass–height relationship are really important for large-scale biomass estimations. For instance, if biomass–height relationship differed only between some coarsely classified forest groups (e.g. conifer vs. broadleaf, or deciduous vs. evergreen forests) at a large scale, and did not differ significantly among forest types within these coarse-defined forest groups (e.g. Drake et al., 2002; Chen, 2010), then the efforts in classifying forest types from remote sensing images could be greatly reduced (which should be conducted regularly to monitor forest distribution). As a result, identify the major factors modulating biomass–height relationship is especially important for monitoring forest biomass with LiDAR technologies at the large to global scales.

In this study, we used 529 forest plots (either measured by us or complied from literatures) across northeast China to explore the large-scale relationship between forest biomass and height. There are many data on field-observed biomass and tree height in literatures (e.g. Cannell, 1982; Fang et al., 2006; Wang et al., 2008). If these data can be utilized to develop models for estimating biomass patterns from height, then a great amount of efforts in the field investigation of forest biomass can be avoided. Consequently, we also tested which kind of literature data could be utilized for this purpose. Specifically, we examined four questions as follows.

(1) What are the major factors regulating the large-scale biomass–height relationship (see above)?
(2) Can belowground stand biomass be well predicted from forest height? Belowground biomass is a major source of uncertainties in large-scale biomass estimation, and has long been a great challenge (Cairns et al., 1997; Brown, 2002). Previous studies have shown that forest biomass belowground are closely related with aboveground biomass (e.g. Mokany et al., 2005; Wang et al., 2008), while aboveground biomass is closely related to forest height (e.g. Dubayah and Drake, 2000; Lefsky et al., 2002, 2005; Fang et al., 2006). Thus we hypothesized that biomass belowground may also be closely related to forest height. If estimating belowground biomass from forest height is possible, then the satellite-borne LiDAR will provide an unprecedented opportunity for monitoring global forest carbon belowground.
(3) Can forest biomass be well estimated from average tree height? Forest height and maximum tree height are the most easy parameters that could be retrieved from LiDAR data (Drake et al., 2003; Lefsky, 2010; van Leeuwen and Nieuwenhuis, 2010; Simard et al., 2011). However, most literatures on filed-observed stand biomass reported only average tree height (for both canopy trees and trees under canopy). This situation will greatly reduce the data available for constructing large scale biomass–height models. Recent studies have shown that estimating average height for both canopy and under-canopy trees from LiDAR data is possible (Maltamo et al., 2004; Lee and Lucas, 2007). Consequently, we also tested the possibility to estimate stand biomass from average tree height. If this is possible, then the abundant biomass data in the literatures could also be utilized by LiDAR studies.
(4) Why stand biomass can be estimated from forest height? While previous studies have focused on predicting forest biomass from LiDAR retrieved forest height (Lefsky et al., 2005; van Leeuwen and Nieuwenhuis, 2010), the biological bases for estimating biomass from height remains less attentions. Fang et al. (2006) showed that the ratio of aboveground biomass to forest height (i.e. biomass per cubic meter of forest space) is similar in East Asia, Europe, USA and Canada, and proposed that the differences in biomass per area among continents was largely caused by difference in forest height. Here we tested whether this hypothesis could be applied to explain the geographic forest biomass patterns within a huge region in East Asia, using forest plots well distributed across northeast China.

2. Materials and methods

2.1. Study area and data

The northeast part of China is defined here using the same definition as our previous study (Wang et al., 2008), i.e. including Heilongjiang, Jilin and Liaoning provinces, eastern Inner Mongolia Autonomous Region, and northern Hebei province, covering an area of *ca.* 1,600,000 km^2. The topography, climate and forest vegetations of the study area have been described in Wang et al. (2008) and thus not detailed here.

We constructed a database for forest biomass, which consist of 641 plots across northeast China. In Wang et al. (2008) there were 515 plots, and 126 plots were appended into the database since then. Our database documented the following information for each plot: (1) stand biomass (total, above and belowground); (2) geographic ordinations (latitude, longitude and altitude); (3) climate variables, including mean annual and growing season (months with mean temperature $\geqslant 5$ °C) temperature and precipitation, etc.; (4) forest structure parameters, including diameter at breast height (DBH), forest height (or maximum tree height) and average tree height, stem density and stand volume, etc.; (5) forest type, dominant tree species, and forest origin (primary/secondary/planted forest). Most of the plots (475) were compiled from literatures and thus some of the stand structure or biomass variables might be not available. Methods for data compilation, estimation of climate variables have been reported in Wang et al. (2008) and thus not described here. Another 166 plots across all the major mountain ranges (Changbai Mountains, Zhangguangcai Mountains, Xiaoxing'an Mountains, Daxing'an Mountains and Yanshan–Taihang Mountains) and forest types in northeast China were sampled by us using the method described in Wang et al. (2008) (in that analysis 85 plots were sampled by ourselves). In a few Chinese literatures, the average tree height of a plot is calculated as the tree height corresponding to the geometric mean of DBH (estimated with DBH–height relationship of the plot) (e.g. Meng, 2006). However, for the literatures where our biomass data came from, none of them have stated that the average heights were calculated in that way. Because the arithmetic mean of tree height is a far more commonly used statistic in ecological studies (e.g. Cannell, 1982; Fang et al., 2006), we assumed that all these literatures documented