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Changes in forest biomass over China during the 2000s and implications for management

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ABSTRACT

By integrating the reflectance of 7 spectral bands of the MODerate-resolution Imaging Spectroradiometer (MODIS) and forest inventory data with an empirical statistical model, we mapped the spatial distribution of total forest biomass carbon density (BCD) at 1 km resolution in China during the past decade. The empirical statistical model can explain 75% of the variation in BCD across 29 provinces in China ($R^2 = 0.75$, $P < 0.001$), with a root mean square error of 9.3 Mg C ha^{-1}. The total forest biomass carbon storage was estimated as 6.4 ± 0.6 Pg C, with an average BCD of 42.6 ± 3.9 Mg C ha^{-1} during the period of 2001–2005, which is close to the estimates solely by forest inventory data. During the 2000s, the forests in China sequestered carbon by 80 ± 103 Tg C yr^{-1}. Our estimation is close to an independent forest biomass estimation (76 ± 10 Tg C yr^{-1}) derived from passive microwave satellites (Liu et al., 2015). Most of the forest biomass carbon sink was attributed to the growth of low- and medium-biomass forests in eastern, central, and southern China. The large area of currently low-biomass forests will retain as a large potential biomass C sink in the next few decades. This implicates that low-biomass forests (most of these forests are planted forests) need well management such as selected wood harvest to keep large forest biomass carbon sinks in China. Plans of sustainable afforestation and forests protection projects by Chinese government could also enhance the forest biomass carbon sinks in the future. Nitrogen deposition in China significantly correlates with forest biomass C sinks across 2392 $0.5° \times 0.5°$ grid cells ($R = 0.54$, $P < 0.001$), which indicate the positive impacts of nitrogen deposition on China's forest biomass carbon sinks. Our results suggest that China forests can continue to act as a large carbon sinks in the near future because of the contributions of management of low- and medium-biomass forests, afforestation and nitrogen deposition.

1. Introduction

During the past three decades, China has launched a set of large afforestation and reforestation projects. Currently China has the largest area of plantation forest (71 million ha, 27% of world's 264 million ha of plantation forest) in the world (FAO, 2010). By 2008, it was reported that China's forest area reached 195.45 million hectares, covering 20.4% of its total land area (State Forestry Administration, 2009). The rapid increase in planted forest biomass in China contributed to ~30% of carbon (C) sinks in China's terrestrial ecosystems (e.g. Fang et al., 2007; Piao et al., 2009b). Previous studies indicated that forests in China play an important role on C sequestration to mitigate anthropogenic C emission and might have large potential C sinks because of its growth potential (e.g. Fang et al., 2007; Pan et al., 2011; Xu et al., 2010; Guo et al., 2013). Thus, monitoring the forest biomass changes and accurately assessing forest C sinks are important to climate-mitigation (e.g. Fang et al., 2001; Pan et al., 2011).

China has highly diverse forest types, including major forest types in Northern Hemisphere, with tropical rainforests in the south and boreal forests in the north (e.g. Fang et al., 2001). Currently, the national wide forest inventory implemented every 5 years in China since the 1970s offers the most reliable regional statistics of forest biomass and its changes (e.g. Fang et al., 2001; Pan et al., 2011; Guo et al., 2013), but could not offer spatial details of such critical information. On the other hand, integrating large scale forest inventory data with remote sensing data has been employed to investigate the explicit spatial distribution of forest biomass and its changes (e.g. Myneni et al., 2001; Piao et al., 2005). For example of China, Piao et al. (2005) exhibited the spatial distribution of forest biomass and its changes during the period of 1984–1998, using the integrated approach of Normalized Difference Vegetation Index (NDVI) and forest inventory biomass from each province in China, which showed good consistence with national forest inventories. A fine resolution distribution map of

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forest biomass is a useful tool for forest management (e.g. Blackard et al., 2008; Gallaun et al., 2010). In addition, the spatial distribution of forest biomass could also be used to explicitly estimate C emission by land use change and to reduce the uncertainty in regional C budget (e.g. Houghton, 2003; Blackard et al., 2008).

The availability of satellite observations promotes study of large scale forest biomass distribution and its changes (e.g. Myneni et al., 2001; Dong et al., 2003; Piao et al., 2005). In early studies, satellite derived NDVI data have been widely applied to monitor the vegetation growth (e.g. Myneni et al., 2001; Peng et al., 2013). Recently, the reflectance of several bands of MODerate-resolution Imaging Spectroradiaometer (MODIS) also were used to make map of forest biomass (e.g. Houghton et al., 2007; Baccini et al., 2008; Gallaun et al., 2010; Saatchi et al., 2011). The reflectance of MODIS spectral bands has a stronger explanation on variation of forest biomass than NDVI (e.g. Baccini et al., 2008), which maybe relate to more information of the reflectance of 7 MODIS spectral bands could be fully used to constrain the forest biomass while NDVI only use 2 out of 7 bands information. Therefore, it is interesting to test whether there is any improvement for forest distribution map based on the reflectance of 7 MODIS bands. The MODIS Nadir Bidirectional reflectance distribution function Adjusted Reflectance (NBAR) products were applied to map the distribution of biomass C density (BCD) in many regions such as Russia, Africa and Pan-tropics in previous studies (e.g. Baccini et al., 2008; Houghton et al., 2007).

Here using the MODIS products and the recent national forest inventory data, we estimated China's forest biomass carbon stocks and their changes in 2000s. Our primary objectives include: (1) to construct a statistical ensemble method combining forest inventory data and the reflectance of 7 MODIS bands; (2) to map the spatial distribution of total forest BCD in China; (3) to investigate uncertainty of BCD from remote sensing data using statistical ensemble method; (4) to estimate the total size and the spatial distribution of China's forest biomass C sources/sinks in 2000s; and (5) to attribute the changes in forest biomass carbon to possible contributions (afforestation, forest growth, nitrogen deposition, etc.).

2. Datasets and methods

2.1. Datasets

2.1.1. The forest inventory data

The State Forestry Administration of China published statistics about forest resources in China including forest area, timber volumes for dominant species by age class in each province every 5 years during the past four decades (Fang et al., 2001; Guo et al., 2013). The details of area, volume for each dominant specie were provided by five age groups (young, middle-aged, premature, mature and over-mature) (Guo et al., 2013). One period (1999–2003) forest inventory data were used in this study. Natural and planted forests stands were included as stands forests, and economic and bamboo forests stocks are excluded in this study. The continuous biomass expansion factor method (Eq. (1)) is commonly used to estimate the total forest biomass C stocks (aboveground + belowground biomass) from forest inventory data (area, timber, etc.) in most regions and countries (e.g. Fang et al., 2001; Pan et al., 2011).

$$\text{Biomass} = \sum_{i}^{n} A_i \times x_i \times BEF_i \tag{1}$$

Where Biomass stands for total forest biomass for each province, n is the number of forest types in each province from national inventory data. A_i, x_i and BEF_i are the total area, volume per unit area, and mean biomass expansion factor of forest type i, respectively. The details of parameters value for continuous biomass expansion factor method were shown in Table 1 in Guo et al. (2013).

Here we used the average BCD for 29 provinces during the period of 1999–2003 in China from Guo (2011), which is derived from the sixth National Forest Inventory based on the continuous biomass expansion factor method (Fang et al., 2001, 2007; Guo et al., 2010, 2013).

2.1.2. MODIS data

The MODIS NBAR product (MCD43B4, version 5) was used as independent variables to predict BCD. The MODIS NBAR product (MCD43B4) is derived from combination of MODIS Terra and Aqua instruments which are sun-synchronous and image the entire Earth every 1–2 days. The MODIS NBAR (MCD43B3) product during 2000–2010 used in this study has 1 km spatial resolution and a 16 days composites temporal resolution and includes seven bands with wavelength from 459 to 2155 nm. The wavelength of bands 1–7 are 620–670 nm, 841–876 nm, 459–479 nm, 545–565 nm, 1230–1250 nm, 1628–1652 nm and 2105–2135 nm, respectively. The MCD43B4 product is corrected for solar and view geometry, atmospheric attenuation, cloud cover, the off-nadir characteristics of scanning sensors and atmospheric haze and aerosols (Schaaf et al., 2002).

2.1.3. Forest distribution map

A digitized vegetation map of China at scale of 1:1,000,000 (Editorial Board of Vegetation Map of China, 2001) was used to obtain the spatial distribution of China's forest, which was grouped into 5 types: evergreen broadleaf forests (EBF), deciduous broadleaf forests (DBF), broadleaf and needleleaf mixed forests (MF), evergreen needleleaf forests (ENF) and deciduous needleleaf forests (DNF). Based on this map, the total forest area is 149 million hectares, which is smaller than the number (169 million hectares) from the Sixth National Forest Inventory. The details of spatial distribution of forest in China are shown in Piao et al. (2005).

2.1.4. Nitrogen deposition data

A global annual nitrogen deposition map with spatial resolution of 0.5°, covering the period 1860–2010, were provided by The Multi-scale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP) project (Wei et al., 2014). This dataset was interpolated into annual map originally from Dentener (2006), which estimated atmospheric deposition of total inorganic nitrogen (N), NH_x (NH_3 and NH^{4+}), and NO_y (all oxidized forms of nitrogen other than N_2O) for the years 1860, 1993 and 2050 at a spatial resolution of 5° longitude by 3.75° latitude, by a three-dimensional chemistry transport model. The details of this dataset can be found in Wei et al. (2014).

2.2. Analysis

To avoid bias caused by snow, we used the growing season (April–October) MODIS NBAR product for each year from 2000 to 2010 as independent variables to estimate BCD. For each of the seven MODIS bands, we first averaged the growing season NBAR of forest pixels for each province during the period 2000–2003. We then applied a stepwise multiple linear regression with BCD from forest inventory data during 1999–2003 as dependent variable and the seven averaged growing season NBAR during 2000–2003 as independent variable in Eq. (2).

$$\begin{aligned} BCD = {} & a0 + a1 \times B1 + a2 \times B2 + a3 \times B3 + a4 \times B4 + a5 \\ & \times B5 + a6 \times B6 + a7 \times B7 + \varepsilon \end{aligned} \tag{2}$$