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Timber production assessment of a plantation forest: An integrated framework with field-based inventory, multi-source remote sensing data and forest management history

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ABSTRACT

Timber production is the purpose for managing plantation forests, and its spatial and quantitative information is critical for advising management strategies. Previous studies have focused on growing stock volume (GSV), which represents the current potential of timber production, yet few studies have investigated historical process-harvested timber. This resulted in a gap in a synthetical ecosystem service assessment of timber production. In this paper, we established a Management Process–based Timber production (MPT) framework to integrate the current GSV and the harvested timber derived from historical logging regimes, trying to synthetically assess timber production for a historical period. In the MPT framework, age-class and current GSV determine the times of historical thinning and the corresponding harvested timber, by using a “space-for-time” substitution. The total timber production can be estimated by the historical harvested timber in each thinning and the current GSV. To test this MPT framework, an empirical study on a larch plantation (LP) with area of 43,946 ha was conducted in North China for a period from 1962 to 2010. Field-based inventory data was integrated with ALOS PALSAR (Advanced Land-Observing Satellite Phased Array L-band Synthetic Aperture Radar) and Landsat-8 OLI (Operational Land Imager) data for estimating the age-class and current GSV of LP. The random forest model with PALSAR backscatter intensity channels and OLI bands as input predictive variables yielded an accuracy of 67.9% with a Kappa coefficient of 0.59 for age-class classification. The regression model using PALSAR data produced a root mean square error (RMSE) of 36.5 $m^3\ ha^{-1}$. The total timber production of LP was estimated to be $7.27 \times 10^6\ m^3$, with $4.87 \times 10^6\ m^3$ in current GSV and $2.40 \times 10^6\ m^3$ in harvested timber through historical thinning. The historical process-harvested timber accounts to 33.0% of the total timber production, which component has been neglected in the assessments for current status of plantation forests. Synthetically considering the RMSE for predictive GSV and misclassification of age-class, the error in timber production were supposed to range from −55.2 to 56.3 $m^3\ ha^{-1}$. The MPT framework can be used to assess timber production of other tree species at a larger spatial scale, providing crucial information for a better understanding of forest ecosystem service.

1. Introduction

Timber production is the most important ecosystem service of plantation forests (Costanza et al., 1997). With development of human society, the demand of timber increases sharply. Timber production of natural forest hardly meet timber demand of human society due to deforestation of primary forest across the world, thus plantation forests are planted as a substitution for natural forests (Mason and Zhu, 2014; Zou et al., 2015). As reported by Food and Agriculture Organization (FAO) in 2010, the total area of planted forest is estimated to be 264 million ha, corresponding to 6.6% of the world’s forest area. During the past half century, China possesses the largest area of planted forests in the world, accounting

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for 36% (69 million ha) of the country's total forested area. whereas only accounting for 17% (2.48×10^9 m^3) of the total growing stock volume (GSV), with an average of 35.8 m^3 ha^{-1} (Chinese Ministry of Forestry, 2014). The low productivity weakens the expected function of plantation forests for timber production. In this context, accurate estimations of timber production and its spatial distribution are required for a better understanding of ecological service functions and further improving timber production of plantation forests, which services for the strategic goals of plantation forest resource management (Alkemade et al., 2014; Mason and Zhu, 2014; Fu and Forsius, 2015).

The GSV is defined as stem volume of living trees in a given area of forest, including bark but excluding branches and stumps. The GSV represents directly the amount of current timber in a stand, which is a key indicator in the context of forest management. GSV is also a major predictor for assessing biomass of forest, which plays an important role in carbon cycle and global change issues (Fang et al., 2001; Pan et al., 2011). The GSV is traditionally estimated from field-based measurements of the diameter at breast height (DBH) collected at sample plots (Santoro et al., 2011). Alternatively, the satellite-based approach aided by forest inventory can up-scale observed extent and has thus been widely used to estimate GSV or biomass for a continuous spatial distribution (Bijalwan et al., 2010; Gao et al., 2013a). Satellite optical images have been used to estimate biomass and GSV at different scales (Houghton et al., 2007; Anaya et al., 2009; Zheng et al., 2013; Gao et al., 2013b). However, passive optical data can only sense the canopy in two dimensions, thereby making it be insensitive to sub-canopy structure, such as basal area and height of tree (Almeida Filho et al., 2007; Morel et al., 2011). Satellite-based synthetic aperture radar (SAR) data have been examined for handling this issue, due to their sensitivity to the geometric properties of forests (Liesenberg and Gloaguen, 2013; Chowdhury et al., 2014; Galeana-Pizaña et al., 2014; Santoro et al., 2015). Comparing to SAR data acquired at shorter wavelengths (e.g., X and C-bands), L-band (23.5 cm) SAR is particularly useful in mapping forest areas because of its better ability to penetrate into forest canopies. The L-band backscatter from forested terrain consists primarily of backscatter from stem volume (Way et al., 1994; Karam et al., 1995), thus showing a greater sensitivity to the woody components. In current studies, L-band SAR data have also been proved to be more useful for GSV estimation (Imhoff, 1995; Simard et al., 2002; Rosenqvist et al., 2007), although a saturation effect (L-band backscatter does not increase with GSV) has been observed. Previous literatures reports that L-band SAR data appears well adapted to estimate the relatively low GSV of boreal forest (Peregon and Yamagata, 2013; Suzuki et al.,2013), temperate forest (He et al., 2011; Cartus et al., 2012) and savanna woodlands (Carreiras et al., 2012; Mermoz et al., 2014). However, these studies on L-band SAR data-based GSV estimations are specific to each study site that caused by various environment conditions and forest structures. Considering that low GSV and structure of plantation forests in China, L-band SAR data are supposed be rather useful for the GSV estimation of plantation forests, but little attention has been paid to the issue.

Timber production of plantation forests is a historical process, closely relating to forest managements. In addition to current GSV, thinning operation (or selective logging), which is considered as a component of near-natural forest management (Luo et al., 2014; Li et al., 2014a), also harvests considerable biomass, including non-timber and timber biomass. For an efficient forest management, successive thinning should be implemented as a stand growing, providing timber throughout a rotation of plantation forest. During this stand age-related process, additionally, non-timber biomass of plantation, including branches and leaves, is returned to soil or collected for fuelwood. These forest management practices have been recognized to play an important role in the terrestrial carbon cycle and the potential contribution to climate change mitigation efforts for plantation forests (Ray et al., 2009). Nevertheless, due to the extensive area of plantation forests and the long-term history of forest management, our current knowledge about the timber production of historical process is rather limited. Previous studies have reported the effects of thinning on carbon storage (Davis et al., 2009; Nunery and Keeton, 2010) and structure (Forshed et al., 2008; Zhu et al., 2010) at a stand-scale, however, these studies mainly focused on the responses of forest to management practices. Yet few studies have investigated the historical contribution of successive thinning operations to timber production at a continuous spatial scale. Although a long-term field-based inventory that recording management practices can represent the historical timber production for a given stand, it is insufficient for a large spatial scale assessment of production timber. This resulted in a gap in a synthetical ecosystem service assessment of timber production of plantation forests.

In order to obtain timber production for a period, the timber harvested by historical management practices is supposed to be quantitated. In this study, timber is defined as stem volume of trees, and timber production includes harvested timber and current timber (GSV). We established a Management Process–based Timber production (MPT) framework to integrate historical logging process and current potential of timber production, trying to synthetically assess timber production for a historical period at a continuous spatial scale. In the MPT framework, age and current GSV of plantation forests are the two key parameters, and a space-for-time substitution was used to define historical process-harvested timber. To test and apply this framework, we conducted an empirical study on a larch plantation (LP) in Saihanba Forestry Center, which is the largest plantation forest center of larch in Asia. Multi-source remote sensing data and field-based inventory were employed to estimate age and GSV of plantation forests. These two key parameters are input to the MPT framework to assess the timber production for a period of approximate 50 years.

2. Data and methods

2.1. Study area

Larix spp. is one of the most important planted timber tree species of China (Zhu et al., 2010; Yan et al., 2013; Gao et al., 2015). Since the 1950s, about 3.06 million ha of LP have been planted in North China. This study location is Saihanba Forestry Center (SFC), which is the largest plantation forest center of larch in Asia (116°52–117°39′ E, 42°04′–42°36′ N; *ca.* 93,000 ha; Fig. 1). SFC is located in a typical forest-steppe ecotone between the Inner Mongolian Plateau and North Hebei Mountain, with an elevation ranging from 1042 m to 1936 m. The climate of SFC is semi-arid and semi-humid, with a short growing season of May to September. Annual mean air temperature and precipitation were −1.2 °C and 452 mm, respectively. SFC is consisted of six sub-forestry centers, by the names of Sandaohekou (SDHK), Qiancengban (QCB), Beimandian (BMD), Yinhe (YH), Sanxiang (SX), Dahuanqi (DHQ), from west to east, respectively. Since 1960s, SFC has been planted over 74,000 ha of plantation forest. Currently, the forest cover of SFC reaches as high as 80%. The total extent of LP (*Larix principis-rupprechtii*, a principal tree species for forestation) is approximately 44,000 ha, accounting for 58% of forest land area of SFC. Most of LPs in SFC are a single species monoculture. The other forest types are *Pinus sylvestris var. mongolica* plantations and *Betula platyphylla* natural secondary forest, accounting for 27% and 11% of total forest area, respectively.