Forest Ecology and Management 404 (2017) 84–99

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Rubber tree allometry, biomass partitioning and carbon stocks in mountainous landscapes of sub-tropical China

Xueqing Yang[a,b,c], Sergey Blagodatsky[a,d,*], Feng Liu[e], Philip Beckschäfer[f], Jianchu Xu[c], Georg Cadisch[a]

[a] Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institute), University of Hohenheim, Garbenstrasse 13, Stuttgart 70593, Germany
[b] Key Laboratory for Plant Diversity and Biogeography of East Asia, Kunming Institute of Botany, Chinese Academy of Sciences, Kunming 650201, China
[c] World Agroforestry Centre (ICRAF), China & East Asia Office c.o. Kunming Institute of Botany, Heilongtan, Lanhei Road No.132, Kunming 650201, China
[d] Institute of Physicochemical and Biological Problems in Soil Science, Russian Academy of Sciences, 142290 Pushchino, Russia
[e] Bureau of Naban River Nature Reserve, Yuanlin alley 19#, Jinghong, 666100, China
[f] University of Göttingen, Chair of Forest Inventory and Remote Sensing, Büsgenweg 5, Göttingen 37077, Germany

ARTICLE INFO

Keywords:
Forest plantations
Aboveground biomass
Belowground biomass
Root-to-shoot ratio
Carbon stock

ABSTRACT

Expansion of rubber plantations into sub-optimal environments has been a dominating land conversion in continental South-East Asia in the last decade. Regional evaluation of the carbon sequestration potential of rubber trees depends largely on the selection of suitable allometric equations and the biomass-to-carbon conversion factor. Most equations are age-, elevation-, or clone-specific, and their application therefore gives uncertain results at the landscape level with varying age groups, elevation ranges, and clone types. Currently, for rubber-based systems, none of the allometric equations takes environmental factors (e.g. climate, topographic condition, soil properties, and management scheme) into consideration to allow pan-tropical usage. Against this background, 30 rubber trees with a root profile of up to 2 m were destructively harvested and 882 rubber trees were measured non-destructively in 27 plots, covering rotation lengths of 4–35 years, elevation gradients of 621–1127 m, and locally used clone types (GT1, PRIM600, Yunyan77-4) in mountainous South Western China. Allometric equations for aboveground biomass (*AGB*) estimations considering diameter at breast height (*DBH*), tree height (*H*), and wood density were superior to other equations. A simpler model with similar performance ($AGB = 0.0419DBH^{2.316}H^{0.478}$) can be used if tree-specific wood density is not available. For belowground biomass (*BGB*) a model using only *DBH* can provide a robust prediction ($BGB = 0.207DBH^{1.668}$). We also tested goodness of fit for the recently proposed pan-tropical forest model, which includes a bioclimatic factor *E*, combining indices of temperature and precipitation variability and drought intensity. Prediction of *AGB* by the model calibrated with the harvested rubber tree biomass and wood density was more accurate than the results produced by the pan-tropical forest model adjusted to local conditions. The relationships between *DBH* and height and between *DBH* and biomass were influenced by tapping, therefore biomass and C stock calculations for rubber have to be done using species-specific allometric equations. Based on the analysis of environmental factors acting at the landscape level, we found that above- and belowground carbon stocks were mostly affected by stand age, soil clay content, aspect, and planting density. Increasing planting density to > 570 trees per ha according to the regional plantation management strategy had a negative impact on aboveground carbon stock of old rubber plantations. The integration of bioclimatic and regional management factors is a further approach to build widely applicable biomass models for pan-tropical rubber-based systems. The results of this study provide reference for reliable carbon accounting in other rubber-cultivated regions.

1. Introduction

In many tropical regions, land use change has caused uncertainties in global carbon stocks accounting. This has been mainly attributed to changes in plant and soil carbon stocks during conversion of natural forests into economic plantations, e.g. oil palm (*Elaeis guineensis*), rubber (*Hevea brasiliensis* Müll. Arg), and eucalypt (*Eucalyptus grandis)* (Houghton and Goodale 2004, Houghton, 2005). The dramatic expansion of monoculture plantations has been blamed for high rates of deforestation and forest degradation in South East Asian countries (Fox,

* Corresponding author at: Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institute), University of Hohenheim, Garbenstrasse 13, Stuttgart 70593, Germany.
E-mail address: sblag@mail.ru (S. Blagodatsky).

http://dx.doi.org/10.1016/j.foreco.2017.08.013
Received 9 April 2017; Received in revised form 5 August 2017; Accepted 8 August 2017

2000; Koh and Wilcove, 2008; Ziegler et al., 2009; Li and Fox, 2012; Brockerhoff et al., 2013). Several market-based mechanisms were proposed as guidance on reduction of emissions from deforestation and forest degradation (REDD), sequestration of carbon through reforestation, and maintenance of existing forests (REDD+, Clean Development Mechanism) in tropical regions (Myers, 2007; Angelsen et al., 2009). However, implementation of these programs has not been straightforward (Van Noordwijk et al., 2012; Murray et al., 2015). Particularly, analysis of substitution of traditional swidden land by rubber plantations in Montane Mainland Southeast Asia (MMSEA) reflected how land use change might pose varying impacts on carbon emissions, farmer livelihoods and regional environmental services (Fox et al., 2014). To make emission reduction incentives widely applicable, a reliable and efficient tree carbon stock assessment is required.

Rubber is a perennial tree originating from the Amazon basin in South America; its historical habitat is distributed in the equatorial zone between 10°N and 10°S. Suitable natural cropping climates for rubber in the mainland of South East Asia include portions of southern Thailand, southeastern Vietnam, and southern Myanmar, other new expansion regions mainly located in Montane Mainland Southeast Asia (Fox and Vogler, 2005). With increasing worldwide natural rubber consumption and economic development, in the 1950s, the Chinese government initiated the “Decision on Cultivating Rubber Trees” for national defense and industrial demands. This strategy promoted the cultivation of rubber plantations in non-traditional environments, expanding as far north as 22° latitude in China, with cooler winter temperatures and distinct dry seasons (Xu et al., 2005). Currently, rubber plantations mainly serve as an important source of natural latex (review by Venkatachalam et al., 2013). Rubber trees are also used for wood products and furniture (Zhang et al., 2009). Additionally, plant biomass provides a bioenergy source used for heating (Krukanont and Prasertsan, 2004) and seed oil, which is used in various industries (Zhu et al., 2014). The massive expansion of rubber plantations has also negative impacts, such as increased carbon emissions, decreased biodiversity, habitat loss, and food security threat (Hu et al., 2008; Ziegler et al., 2009; Fu et al., 2010; Song et al., 2014; Cotter et al., 2017). In tropical countries, the feasibility of promoting biodiversity co-benefits with high carbon stocks and the optimization of rubber’s economic benefit for local livelihoods have been tested through various carbon trading schemes (Yi et al., 2014a; Villamor et al., 2014). Considering that more than 2.1 million ha of montane mainland Southeast Asia are occupied by rubber plantations (Fox et al., 2014), precise tree biomass estimation in these mountainous regions is a premise for landscape level rubber-based system carbon stock quantification.

The most accurate method for tree biomass assessment is harvesting the whole tree, with further separation into its components. Then, each component needs to be oven dried and weighted to determine its biomass. The carbon content of each component can be determined to quantify the total carbon stock of the biomass (Ketterings et al., 2001). Nevertheless, this approach can be applied only to a limited extent because of the time and labor-consuming procedure of sampling and due to its destructive nature. Instead of direct harvesting, tree biomass could also be modeled using allometric equations, that link easily measurable tree parameters, such as diameter at breast height (*DBH*), tree height (*H*), crown area (*CA*) and wood density (ρ), with biomass through linear or non-linear model fitting (Picard et al., 2012). Most existing allometric equations for rubber trees use *DBH* for biomass prediction (Jia et al., 2006; Tang et al., 2009; Sone et al., 2014). Cross-sectional area of the rubber tree trunk at breast height (basal area, *BA*) (Schroth et al., 2002) and trunk circumference (girth, *G*) (Shorrocks et al., 1965; Dey et al., 1996; Wauters et al., 2008) are also commonly applied in allometric equations. Some studies tried to improve prediction through allometric equations by including additional parameters, e.g. tree height (Jia et al., 2006; Tang et al., 2009; Sone et al., 2014), crown area, and wood density (Wauters et al., 2008). However, the selection and application of allometric equations for rubber trees faces many challenges. The restricted geographic areas of studies on allometric equations limit a wider application because of the uncertain transferability of the estimated parameters (Yuen et al., 2013, 2016). Trunk circumference or diameter measurements made at different heights further hamper the comparison of allometric equations and the transferability of results. Previous studies used 1.2 m (Sone et al., 2014), 1.3 m (Schroth et al., 2002; Tang et al., 2009), 1.5 m (Shorrocks et al., 1965; Dey et al., 1996; Jia et al., 2006), or 1.7 m (Wauters et al., 2008) for stem diameter measurement. Evidence from existing studies showed that rubber tree stand age was the main predictive factor for tree biomass (Tang et al., 2009; Song and Zhang, 2010; Petsri et al., 2013; Song et al., 2014). Moreover, climatic conditions (wetness) (Wauters et al., 2008; Munasinghe et al., 2014), elevation, slope and aspect (Jia et al., 2006; Yi et al., 2014a; Zhai et al., 2014; Yang et al., 2016), soil fertility and texture composition (Samarappuli, 2000), tapping activities during the growing season (Silpi et al., 2006), planting density (Wauters et al., 2008), and tree clone type (Chaudhuri et al., 1995) also impact on tree biomass partitioning and girth development. The integrative relationship between rubber tree biomass and its surrounding environment (climatic conditions determined by topographic location, soil properties, and management scheme) has not yet been established systematically. Thus, application of allometric equations under environmental conditions that differ from the conditions in the region, where equations were derived, needs to be performed with caution. Besides, few allometric equations are available for belowground biomass (*BGB*). Root biomass comprises around 17% of total rubber biomass based on the root-to-shoot ratio; therefore, omission or incorrect estimation of root biomass will bias biomass and potential carbon stock assessments of rubber plantations (Yuen et al., 2013).

In the context of China, only few allometric equations are available for rubber tree *AGB* and *BGB* estimations (Jia et al., 2006; Cheng et al., 2007; Tang et al., 2009). Most of them were established for age-, elevation-, or clone-specific groups, so that applying these equations to uneven-aged multi-clone stands across various elevations is risky, and the upscaling of model results to heterogeneous landscapes with various environmental influences can be problematic. Against this background, we attempted to derive generic allometric equations for rubber tree *AGB* and *BGB*, with consideration of various stand ages, elevations, and mixed clone types in a rubber planting area located in a mountainous landscape. The specific aims of this study were: (1) to quantify rubber tree biomass production and partitioning in a chronosequence in a mountainous landscape of sub-tropical China; (2) to develop generic allometric equations for rubber tree *AGB* and *BGB*; and (3) to upscale tree level biomass to plot level carbon stocks and to explore the influence of environmental factors on them. The results will be useful for providing reliable rubber tree biomass evaluations in mountainous landscapes over a wide range of environmental conditions. Comparison of carbon stocks in rubber plantation with those in other land use types provides a basis for land management decisions and for selection of future mitigation strategies dealing with environmental changes.

2. Methods

2.1. Study area

The Naban River Watershed National Nature Reserve (Naban Reserve) is located in the Dai Autonomous Prefecture of Xishuangbanna, Yunnan, China. The total protected area is 26,660 ha (22°04′ - 22°17′N, 100°32′ - 100°44′E), with an elevation range from 539 to 2304 m. The reserve has distinct dry (November-April) and rainy seasons (May-October). Annual rainfall varies from 1200 to 1700 mm and annual mean temperature range is 18–22 °C (YEPB, 2006). The major soil types are Ferralsols (Apel, 1996), whereas minor soil types are Regolsols (FAO/UNESCO, 1998). The reported rubber plantation area in Naban Reserve increased from 338 ha in 1989 to 2858 ha in 2012 (Yang et al., 2016). Plantations are mainly smallholder-owned,