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Allometric relationships of stem volume and stand level carbon stocks at varying stand density in *Swietenia macrophylla* King plantations, Bangladesh

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ABSTRACT

Estimation of biomass carbon per unit area of forests or woodlands is of great concern to ecologists and forest managers considering global climate change scenarios. In the framework of this study, we intend to develop allometric models to predict stem volume and stand level carbon stocks in monoculture mahogany (*Swietenia macrophylla* King) plantations. It was also investigated that how stand density would influence stem volume allometric equations as well as carbon stocks per unit area. Results show that the two-variable model having less than 3% mean prediction errors (MPEs) is suitable for stem volume allometric equation, and two-variable or combined-variable models having less than 2% MPEs are equally suitable for allometric equations of stand level carbon stocks. It was also found that in *S. macrophylla*, stem volume allometric equations are not significantly influenced by stand density. We found that mean tree carbon (kg tree^{-1}) in *S. macrophylla* decreases at a rate of −1.58 with increasing stand density and stand level carbon stocks (Mg ha^{-1}) decreases at a rate of −0.58 with increasing stand density (trees ha^{-1}). The biomass carbon stocks (aboveground + belowground) in *S. macrophylla* varried between 34.4 and 351.9 Mg ha^{-1} having a mean of 120.2 Mg ha^{-1}. The allometric equations of stand level carbon stocks show influence of density, which is particularly prominent in the one-variable models, in contrast to the two- or combined-variable models. High precision estimate of stand level carbon stocks can be obtained using stand basal area multiplied by mean or maximum tree height. Our work also has implications on stand density management and the use of allometric equations in estimation of stem volume and carbon stocks.

1. Introduction

Gradual rise in atmospheric carbon dioxide (CO_2) and widespread concern about global climate change has led to interest in reducing emissions of CO_2. It has been predicted that the average global temperature will increase by 2–4 °C by the year 2050 (Anderson and Bows, 2011). Combustion of fossil fuel and deforestation are the two main sources of CO_2 emission to the atmosphere (Woodwell et al., 1983; Detwiler and Hall, 1988). Climate change has been one of the major environmental issues in Bangladesh. Forestry sector is in the forefront of these issues as the country has only 2.52 million ha of forest land characterized with a high deforestation and forest degradation rate (Sadath et al., 2013). Carbon sequestration is a mechanism of capturing atmospheric CO_2 by storing it in the green plants through photosynthesis (Suwa et al., 2006; Khan et al., 2007). It has been recognized as a way to slow down the accumulation of CO_2 in atmosphere usually through combustion of fossil fuels. Although any living creature releases CO_2 through respiration and short living plants re-release CO_2 back to atmosphere after death and decomposition, trees however permanently store CO_2 in the form of wood in particular, thus forests serve as carbon reservoir on earth playing an important role in mitigating global climate change (Dixon et al., 1994; Stinson and Freedman, 2001; Adame et al., 2013). Reducing Emissions from Deforestation and Forest Degradation (REDD+) is a key in recent international climate agreements and relatively cost-effective option for mitigating climate change (Gardner et al., 2012). Here, the strategic aim is to maintain terrestrial carbon storage through financial incentives or carbon payments (Alongi, 2011) for forest conservation (Donato et al., 2011).

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Despite having high global deforestation rate (Dixon et al., 1994), in Bangladesh, the plantations are increasing during last two decades (Rahman et al., 2015). In addition, being a developing country, Bangladesh is one of the low CO_2 emitting countries in the world having a CO_2 emission rate of 0.5 Mg/capita while in USA and UAE the rates are 16.5 and 23.3 Mg/capita, respectively in 2014 (World Bank, 2017). For sustainable management of forests and enhancement of forest carbon stocks in developing countries (Gardner et al., 2012) as a requirement of global treaties, such as UN Framework Convention on Climate Change (UNFCCC, ratified in 1994), the Kyoto Protocol (2001) and Paris Agreement (2015), it is necessary for Bangladesh to assess the biomass or carbon stock not only in natural forests but also in plantations.

Estimation of total woody carbon or biomass per unit area of forests or woodlands is of great interest to many ecologists and forest managers (Cannell, 1984; Khan et al., 2007; Adame et al., 2013; Chanda et al., 2016). The gross aboveground forest biomass can be easily estimated using the simple expression (Cannell, 1984), $V_T = \rho \times F \times H \times BA$, where ρ is wood specific gravity of the species, F is a stand form factor, H is mean tree height, and BA is stand basal area at 1.3 m height. The value of F is assumed to be 0.5 for tropical rain forests (Edwards and Grubb, 1977) and to be 0.4–0.6 for a wide range of forests and woodlands (Dawkins, 1967). The BA can be estimated through inventory data from sample plots and plot-less methods such as PCQM (Cottam and Curtis, 1956; Khan et al., 2016) as well. However, the use of form factor (F) may pose uncertainty in biomass estimates because F varies from species to species (Colgan et al., 2014) and individual tree volume differs when planted in different densities (Hébert et al., 2016). Allometric relationships are known for reliable estimate of stand level carbon stocks through stem diameter at 1.3 m height (*dbh*) and tree height (H) (Chave et al., 2005; Khan et al., 2005; Khan and Faruque, 2010; Chave et al., 2014), basal area through multiplying the wood specific gravity of a species. Considering 47% carbon in woody biomass (IPCC, 2006; Hengeveld et al., 2015) forest carbon stocks can be estimated using it's correlation to basal area (Rahman et al., 2015) and to multiplication of stand level basal area and stand mean tree height (Cannell, 1984; Malhi et al., 2004).

The carbon stocks obviously depend on the age of the stands (Gong and Ong, 1995; Khan et al., 2007) and stocking density per unit area (Hébert et al., 2016; Dangal et al., 2017) and basal area (Cannell, 1984). Self-thinning rule (Yoda et al., 1963; Weller, 1987; Enquist et al., 1999; Enquist and Niklas, 2002) suggest reduction of individual tree mass with increasing tree density (trees ha^{-1}), which is known as −3/2 power law of self-thinning (Yoda et al., 1963) and latter suggested by Enquist et al. (1998) as −1.33, i.e., −4/3. This gives rise a question whether high stand density would reduce biomass or carbon stocks per unit area. The geometric model (Yoda et al., 1963) predicts an exponent of −1/2, which were later found as −0.379 by Lonsdale (1990) and −1/3 by Enquist et al. (1998), meaning that biomass per unit area would be reduced as density increases. Evidence suggests that there is a potential effect of stand density on various tree structural dimensions, such as *dbh*, height, crown shape (Akhtar et al., 2008; Copenhaver and Tinker, 2014; Taylor et al., 2016; Djomo and Chimi, 2017; Singnar et al., 2017; Andrews et al., 2018; Jagodziński et al., 2018) but such effects may not be found in all systems as observed in *Eucalyptus globulus* (António et al., 2007).

Here, we have explored the stem volume allometric relationships in *Swietenia macrophylla* King at variable stand density and we aim to identify determinants of stand level carbon stocks in monospecific plantations of the species. Specifically, we aimed to:

- describe the influence of stand density on stem volume allometric equations to *dbh* and height,
- investigate the allometric relationships of stand level carbon stocks to basal area and tree height,
- describe the effect of stand density on carbon stocks per unit area.

2. Materials and methods

2.1. Description of the study site

The study was made on pure stands of mahogany (*Swietenia macrophylla* King) having different ages, sizes and stand densities located in block plantations in Khulna and Jesssore districts in Bangladesh (Fig. 1) during 2016–17. The summer (March–May), rainy (June–October) and winter (November–February) are the three distinct seasons of the region. In the region during the period 1981–2010 the average monthly maximum temperature was 31.9 °C, average monthly minimum temperature was 22.7 °C and total annual rainfall was 1808 mm (BBS, 2016).

The tree species *S. macrophylla* belongs to the family Meliaceae. It is a large tropical tree, frequently over 30 m in height and up to 150 cm in diameter. It is one of the widely planted timber species in Bangladesh. It grows naturally in Belize, Panama, Bolivia and most of the Latin American countries (Gullison et al., 1996). It has been introduced in most tropical countries where it becomes reforestation species especially in the Philippines, India and Bangladesh (Troup, 1921; Zabala, 1990). It is planted all over Bangladesh along roadside, as block plantations in farmlands, marginal lands and agroforestry projects.

2.2. Design of experiment

A total of 80 plots (0.01 ha each) were selected following a purposive sampling in monospecific *S. macrophylla* block plantations in Khulna and Jessore (Fig. 1) from the sites having different stand densities (trees ha^{-1}) where the canopy was completely closed. In the study site, three gross density groups were observed, such as 1000–1500, 1500–2000 and 2000–2500 trees ha^{-1}. In each sample plot *dbh* (stem diameter at. 1.3 m height), H (height) of all the trees were recorded. In order to obtain the stem volume allometric equations, stem diameter at different stem height (at 2 m interval) of three purposively selected standing trees in each sample plot was recorded using a laser tool Criterion RD 1000 (Laser Technology Inc., USA, accuracy: *dbh* = ± 6 mm and H = ± 0.03 m) ensuring a wide range of tree sizes in each density class. The *dbh* and H of all individual trees in each sample plot were measured using diameter tape and the Criterion RD 1000, respectively. Table 1 shows the statistics of the samples on tree level stem volume allometric models and stand level carbon stocks models, which were used in this study.

2.3. Data analysis

2.3.1. Allometric models of stem volume and carbon stocks

In order to develop allometric equations of stem volume and carbon stock, whether tree level model or stand level model, two kinds of models are usually established, that is, one- and two-variable models (Zeng and Tang, 2012; Zeng, 2015; Zeng et al., 2017). For tree level model, the first variable is *dbh*, i.e., stem diameter at 1.3 m height (*D*), and the second is tree height (*H*), and for stand level model, the first variable is basal area (*BA*), and the second is mean height or maximum height (or dominant height). The general form of individual-tree biomass and stem volume models stands as (Zeng and Tang, 2012),

$$y = \beta_0 x_1^{\beta_1} x_2^{\beta_2} \cdots x_j^{\beta_j} + \epsilon \quad (1)$$

where *y* is biomass (kg) or volume (dm^3), β_j are parameters, ε is an error term and x_j are predictive biometric variables that reflect tree dimensions such as *D*, *H*, *BA* etc.

In this study, in addition to the widely used one- and two-variable models (Zeng, 2015; Zeng et al., 2017), the performance of a combined-variable model ($D \times H$, $BA \times \overline{H}$, $BA \times H_{max}$) was also explored. The Stem volume, aboveground carbon and belowground carbon models based on one-, two- and combined-variable models can be expressed,