



Modelling the growth of young rainforest trees for biomass estimates and carbon sequestration accounting



Noel D. Preece^{a,b,c,*}, Michael J. Lawes^{b,1}, Allison K. Rossman^{d,e}, Timothy J. Curran^{e,f}, Penny van Oosterzee^{a,b,c,2}

^a Centre for Tropical Environmental & Sustainability Science, College of Marine & Environmental Sciences, James Cook University, Queensland 4811, Australia

^b Research Institute for the Environment and Livelihoods, Charles Darwin University, Darwin, Northern Territory 0909, Australia

^c Biome5 Pty Ltd., PO Box 1200, Atherton, Queensland 4883, Australia

^d School for Environmental and Forest Sciences, University of Washington, Seattle, Washington 98195, USA

^e The School for Field Studies, PO Box 141, Yungaburra, Queensland 4884, Australia

^f Ecology Department, Lincoln University, Christchurch, New Zealand

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ABSTRACT

Few measurements for carbon sequestration, ratio of above-ground to below-ground biomass and wood density exist for young trees. Current allometric models are mostly for mature trees, and few consider trees at the sapling stage. Over four years we monitored the growth rates, from seedling to the sapling stage, of 490 trees (five native species) in environmental plantings, in the Wet Tropics of north-eastern Australia. Our biomass estimates were greater by several orders of magnitude in the first year ($6 \times 10^{-3} \text{ Mg ha}^{-1}$ cf. $4 \times 10^{-6} \text{ Mg ha}^{-1}$), and two orders of magnitude less at four years than those derived from the national carbon accounting model ($5 \times 10^{-1} \text{ Mg ha}^{-1}$ cf. 13 Mg ha^{-1}). We destructively sampled 37 young trees to accurately estimate the variation in below-ground and above-ground biomass (AGB) with stem size, and to derive a best fit model for predicting sapling biomass: $\ln(\text{AGB}) = -5.092 + 0.786 \ln(\text{Diam}_{\text{base}})^2 \text{Height}$. Biomass expansion factors for young tree species ranged from 1.71 to 2.44, higher than average for tropical forests. Root:shoot ratios are consistent with mean estimates for mature rainforest. Stem wood densities ranged from 0.444 to 0.683 Mg m^{-3} for the five species measured, which was 6.5% lower than published estimates for three of the species, and 12% and 27% higher for two species. Relative growth rates were faster for species with lower wood density in the first four years, but these species also had the lowest survival over the same period. The findings are significant for a number of reasons. Ecologically, they indicate that young rainforest trees invest more in leaves and branches than in stem growth. From a survival perspective, in the context of rainforest restoration, it is best to invest in species with higher wood densities. From a carbon accounting point of view, refinements to the models used for national carbon accounting are required that include the contribution of the sapling stage. Sapling growth rates were significantly different from those assumed in the national model, requiring growth rates to be increased after four years (as opposed to after 2 years in the national model) before reaching an asymptote at some time in the future. This adjustment is essential to enable carbon farmers to judge the time it takes to receive returns from investment. Policies that encourage carbon plantings should take into account that young plantings grow slower than predicted by current national carbon accounting models.

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1. Introduction

Sinking atmospheric carbon dioxide into planted forests is an important component of climate change mitigation, and around the world 26.5 million hectares of forestry projects were financed in 2012, valued at \$216 million (Peters-Stanley et al., 2013). Despite the appeal of forestry projects, the costs of establishing forests can be prohibitively high (van Oosterzee, 2012; Matzek et al.,

* Corresponding author at: Biome5 Pty Ltd., PO Box 1200, Atherton, Queensland 4883, Australia. Mobile: +61 407 996953.

E-mail addresses: noel.preece@jcu.edu.au, noel@biome5.com.au (N.D. Preece), Michael.Lawes@cdu.edu.au (M.J. Lawes), akrossman@gmail.com (A.K. Rossman), timothy.curran@lincoln.ac.nz (T.J. Curran), penny.vanoosterzee@jcu.edu.au (P. van Oosterzee).

¹ Tel.: +61 8 8946 6527.

² Mobile: +61 408847564.

2014); therefore, it is important that carbon accounting models reflect carbon sequestered.

Estimates of carbon sequestered in forest stands are modelled using allometric relationships of tree dimensions that rely on several key parameters: diameter at set heights (e.g. breast height), wood density, an expansion factor to account for branches, foliage and below-ground mass, and total height (West, 2009). Difficulty measuring wood density and height in the field has promoted the use of tree diameter over density and height to estimate above ground biomass (Chave et al., 2005, 2014). However, the relationships between diameter, wood density and height can vary considerably among species, sites and tree age (Brown et al., 1989; Brown, 1997; Baker et al., 2004; Chave et al., 2005, 2014; Alvarez et al., 2012; Preece et al., 2012). While site- and species-specific allometrics have been investigated for some locations (e.g. Henry et al., 2010; Chaturvedi and Raghubanshi, 2013; Fayolle et al., 2013; Mugasha et al., 2013), tree age remains largely unaccounted for.

Historically, foresters and ecologists have not measured the early stages of growth, so established allometrics account only for sub-mature to mature trees. In the absence of information on young trees, the only available method to estimate biomass is to extrapolate allometric equations back to the origin. Although allometrics are assumed to be robust for a range of ages and sizes (e.g. Chave et al., 2005), they probably do not hold for seedlings and saplings because the architecture of trees changes with age (Claussen and Maycock, 1995).

In Australia, the government-approved method for estimating carbon stored in permanent environmental plantings is FullCAM (Department of Climate Change and Energy Efficiency, 2012). Young trees are excluded from FullCAM and other carbon models because the allometric equations used to derive tree volume and mass ignore stems below breast height (1.3 m above ground surface) and below 2.5, 5 or 10 cm diameter at breast height (dbh) (Brown, 1997; Baker et al., 2004; Chave et al., 2005, 2014; Alvarez et al., 2012; Preece et al., 2012).

Another poorly-studied measurement of young trees is the ratio of above-ground to below-ground biomass, because it requires destructive and intensive sampling (e.g. Mugasha et al., 2013). Data of root:shoot ratios are rare for Australian wet tropical species. The two studies we found (Osunkoya et al., 1994; Deines et al., 2011) investigated seedlings grown in pots in greenhouses for less than 100 days for the first and at 15 months for the second experiment, so they are not considered further in our analyses. Snowdon et al. (2000) were unable at the time to find any estimates of root biomass for Australian rainforests, but global literature suggests tropical trees world-wide have a mean of 24% of below-ground to above-ground biomass (Cairns et al., 1997). Likewise, the ratios of stems to leaves and branches, expressed as 'biomass expansion factors' (BEF) (West, 2009), are unavailable for both young trees and the Australian Wet Tropics in general. Young trees usually have an architecture different from older trees (Claussen and Maycock, 1995) and age provides important explanatory power for root:shoot (R:S) ratios (Cairns et al., 1997; Kenzo et al., 2010).

Wood density of juvenile trees has also been poorly studied (Chaturvedi et al., 2012b, 2012a). Nearly all published wood density data, such as the report on the state of knowledge of wood density in Australia (Ilic et al., 2000), report on mature trees only (we use the term 'wood density' (ρ ; Mg m^{-3}) but Chave et al. (2005) and others use the dimensionless wood specific gravity, the density of wood relative to the density of water (Williamson and Wiemann, 2010)). In allometric equations for young trees, it is assumed that their wood density is the same as mature trees, but this may be an erroneous assumption. Models such as those

developed by Chave et al. (2014) are likely to be unreliable for young planted forests.

Wood density also affects growth and survival rates of trees (Falster, 2006), and must be considered for young trees in planted forests (Larjavaara and Muller-Landau, 2010, 2012; Niklas and Spatz, 2010). In addition, mean stand-level wood density across forest regions can vary significantly, affecting estimates of biomass (Baker et al., 2004) for both mature and young trees. Consideration of the variation in wood density among species is important, and the default wood density values (Ilic et al., 2000) may be wrong for mature trees in different bioclimatic regions, and for young trees, for which there are virtually no data.

We examine the contribution of small stems to carbon stocks. Small stems are ignored in current carbon accounting models because of the complex nature of growth at this stage caused by changes in wood density with ontogeny, and the difficulty of measuring various growth parameters other than stem diameter. We demonstrate that sapling growth and survival are influenced by wood density and sapling physiognomy.

We explore the contribution of young trees to carbon sequestration in the Wet Tropics of north-eastern Australia. We sampled established experimental plots and monitored the growth of planted tree seedlings over their first four years. We determined the biomass of saplings in each plot on several occasions and from destructively sampled young trees from nearby forest, including the biomass of excavated roots. We assessed the effects of species (and consequently wood density) on species survival and growth. We derived a best-fit allometric model of growth using height, diameter at three heights, and stem biomass.

2. Methods

2.1. Study site

The study site is at 1000 m.a.s.l. on the southern Atherton tablelands in the wet tropical region of far north Queensland (17.43°S, 145.51°E). Mean annual rainfall at the nearest weather station (Evelyn SF, 12 km south of our site) is 1442 mm (range 792–2442 mm) and mean monthly temperatures range from 14 °C to 26 °C at Atherton (18 km N) (Bureau of Meteorology, <http://www.bom.gov.au>; accessed 26 February 2015). Seedlings were planted in pastures that, until a few months prior to planting, had been grazed by cattle for approximately 70 years. The pastures comprised tropical pasture grass species, dominated by *Melinis minutiflora*, *Urochloa decumbens* and *Setaria sphacelata* (Poaceae), none of which are native to Australia. Native vegetation adjacent to the planting area is described as remnant and regrowth, simple to complex notophyll vine forest of cloudy wet highlands on basalt (Regional Ecosystem 7.8.4) (Environmental Protection Agency, 2007).

2.2. Experimental design

The experimental design was described by Preece et al. (2013). We planted ten replicated plots in February 2010 along a ridge-line. The plots were each 24 m × 24 m and marked at spacings of 3 m × 3 m, giving a total of 49 trees per plot. Plots varied in their history, with plots 3 and 10 on an old road surface, the upper half of plot 4 located on a rehabilitating former farm track, and the remainder being on moderate to steep grassy slopes (10–30°). Plots were treated with the herbicide glyphosate to remove grass at least two weeks prior to planting. Spraying was limited initially to a one metre radius circle where each seedling was to be planted. Post-planting spraying was conducted in May and September 2010, and January 2011 using glyphosate and again in

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