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Improved models for estimating temporal changes in carbon sequestration in above-ground biomass of mixed-species environmental plantings

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ABSTRACT

Plantings of mixed native species (termed 'environmental plantings') are increasingly being established for carbon sequestration whilst providing additional environmental benefits such as biodiversity and water quality. In Australia, they are currently one of the most common forms of reforestation. Investment in establishing and maintaining such plantings relies on having a cost-effective modelling approach to providing unbiased estimates of biomass production and carbon sequestration rates. In Australia, the Full Carbon Accounting Model (FullCAM) is used for both national greenhouse gas accounting and project-scale sequestration activities. Prior to undertaking the work presented here, the FullCAM tree growth curve was not calibrated specifically for environmental plantings and generally under-estimated their biomass. Here we collected and analysed above-ground biomass data from 605 mixed-species environmental plantings, and tested the effects of several planting characteristics on growth rates. Plantings were then categorised based on significant differences in growth rates. Growth of plantings differed between temperate and tropical regions. Tropical plantings were relatively uniform in terms of planting methods and their growth was largely related to stand age, consistent with the un-calibrated growth curve. However, in temperate regions where plantings were more variable, key factors influencing growth were planting width, stand density and species-mix (proportion of individuals that were trees). These categories provided the basis for FullCAM calibration. Although the overall model efficiency was only 39–46%, there was nonetheless no significant bias when the model was applied to the various planting categories. Thus, modelled estimates of biomass accumulation will be reliable on average, but estimates at any particular location will be uncertain, with either under- or over-prediction possible. When compared with the un-calibrated yield curves, predictions using the new calibrations show that early growth is likely to be more rapid and total above-ground biomass may be higher for many plantings at maturity. This study has considerably improved understanding of the patterns of growth in different types of environmental plantings, and in modelling biomass accumulation in young (<25 years old) plantings. However, significant challenges remain to understand longer-term stand dynamics, particularly with temporal changes in stand density and species composition.

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1. Introduction

Reforestation contributes to climate change mitigation through sequestration of carbon in biomass (IPCC, 2007). In Australia, plantings of mixed native species (termed environmental plantings) accounted for up to 20% of the 1.14 Mha of reforestation between 1990 and 2012 (DOTE, 2014b). These plantings are often targeted in temperate and tropical agricultural regions where opportunity costs associated with such land-use change are relatively low (e.g. Harper et al., 2007; Mitchell et al., 2012). This is anticipated to increase given recent Government policy incentives (e.g. DOTE, 2014a) encouraging land owners to establish such plantings for outcomes of both sequestration of carbon and improved natural resource management. Mixed-species plantings can provide additional environmental benefits such as enhancing biodiversity, erosion control and improving water quality (e.g. Bennett and Ford, 1997; Felton et al., 2010) and reclamation from dry-land salinity (e.g. Stirzaker et al., 2002).

There are few options for payments for the range of environmental services environmental plantings may provide, so the anticipated payment from developing carbon markets could be a vital source of revenue for investment in establishing and maintaining environmental plantings. Unbiased estimates of rates of biomass carbon sequestration are required to facilitate the accounting for carbon credits. However, because these plantings are often established on marginal land where sequestration of carbon and associated financial returns are relatively low, costs associated with field-based measurement of biomass carbon could be a significant proportion of the carbon credits likely to be obtained (Polglase et al., 2011; Paul et al., 2013a; van Oosterzee et al., 2014). It is therefore essential that biomass estimates are obtained as efficiently as possible to reduce costs while maintaining accuracy.

One solution is to calibrate carbon accounting models such as the Full Carbon Accounting Model (FullCAM; Brack and Richards, 2002; Richards and Brack, 2004; Brack et al., 2006; Waterworth et al., 2007; Waterworth and Richards, 2008). The FullCAM model is used in Australia's national inventory system (DOTE, 2014b) to spatially estimate rates of carbon sequestration through land-use change, including reforestation with environmental plantings. FullCAM forms the basis of both Australia's international reporting on greenhouse gas emissions and the domestic carbon market (Carbon Farming Initiative, ComLaw, 2011).

Calibrations of models such as FullCAM need to account for the key factors influencing growth and sequestration of carbon. For example, in regions where water supply is a major constraint to biomass production, this constraint may be partially negated by planting a small proportion of the land area with belt plantings thereby allowing roots of edge trees to utilise additional water from land adjacent to the planting (e.g. Cooper et al., 2005). Previous work has shown that, per planted area, rates of sequestration of biomass carbon in belt plantings are higher than those of plantings established in blocks (Henskens et al., 2001, 2008; Noorduijn et al., 2009; Carter et al., 2011). Stand density and species-mix are also likely to influence rates of carbon sequestration (e.g. Polglase et al., 2008; Paul et al., 2008; Preece et al., 2012). Clearly, environmental constraints on plant growth will vary greatly between tropical and temperate regions of Australia (Keith et al., 2009; Stegen et al., 2011), resulting in different mixes of species, and potentially other factors such as stand density. Presumably these differences will influence patterns of biomass accumulation between these two climatic regions.

One way to account for such growth-influencing factors is to calibrate growth modifying parameters of above-ground biomass (AGB) yield curves applied in FullCAM known as the Tree Yield Formula (TYF, Waterworth et al., 2007). The TYF is used to predict AGB growth increments, with AGB growth potential being driven by a Forest Productivity Index (FPI), where higher values of FPI result in higher net biomass potential from trees. The FPI is a dimensionless measure of site productivity due to soil, sunlight, rainfall, vapour pressure deficit, temperature and frost (Kesteven and Landsberg, 2004; DOTE, 2014b). The FPI varies temporally and spatially, and estimates are available from the online FullCAM database for both annual FPI and long-term average FPI (FPI_{ave}).

Reliable growth modifiers of FullCAM's TYF have been calibrated for many traditional plantation species (Waterworth et al., 2007) but not for environmental plantings apart from simple modifiers which could be applied to represent fertiliser application or weed control. In many locations, previous applications of the FullCAM model for environmental plantings resulted in under-estimation of AGB (Montagu et al., 2003; Wood et al., 2008; Lowson, 2008; Keith et al., 2010; Fensham et al., 2012; Preece et al., 2012). An extensive assessment of forest productivity and biomass in China (6153 records), found the scaling component and slope component of the relationship between tree productivity and biomass needed to be varied with both management (e.g. tree age, size, and density) and environmental (e.g. latitude/longitude and elevation) factors (Hui et al., 2012). Similarly, both the shape and scaling components were found to require adjustment during previous work on calibration of the TYF to industrial plantation species (Waterworth et al., 2007).

Here, our objectives were twofold: (i) to collect new and collate existing estimates of AGB in environmental plantings and statistically analyse these datasets to assess key factors influencing AGB accumulation, and (ii) to develop FullCAM TYF calibrations for estimation of the pattern of AGB accumulation by environmental plantings. The overall aim was to update FullCAM to provide, on a national- or regional-scale, un-biased and accurate predictions of carbon sequestration in AGB for a range of different types of environmental plantings, underpinned by robust data.

2. Methods

2.1. Database

A database was developed from 605 environmental plantings (or 737 AGB observations, including repeat measures at some sites over time) in temperate and tropical regions of Australia (Fig. 1) that comprised new and/or existing inventory (Table 1) and auxiliary data (Table 2; Paul et al., 2013d). Establishment of native mixed-species plantings has largely been confined to the last two decades and thus the plantings studied were relatively young. Mean age of the plantings was only 12 years, with 95% of plantings having a stand age between 4 and 22 years. Plantings were established at sites with a wide range of potential productivities. FPI_{ave} varies from 1 to 27 across Australia (DOTE, 2014b), and across the plantings studied, the mean FPI_{ave} was 8.5, but with 95% between 3.8 and 21.7.

The inventory data were measures of stem diameter of all individuals within measurement plots at each site, and were used to estimate biomass by application of allometric equations for individual tree or shrub above-ground biomass (Paul et al., 2013c). Stem diameter measurements were generally made at 10, 30 and 130 cm above the ground for shrubs, predominantly multi-stemmed trees and predominantly single-stemmed trees, respectively. Prior to the application of allometric equations, diameters for each stem of multi-stemmed individuals (D_i) were converted to a single value (equivalent stem diameter, $D_e = \sqrt{\Sigma D_i^2}$), so that the total basal area for all stems was equal to the basal area of a tree with this equivalent single diameter. For each individual tree or shrub in each inventory dataset, the most relevant allometric equation