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Estimating temporal changes in carbon sequestration in plantings of mallee eucalypts: Modelling improvements

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ABSTRACT

Establishment of mallee eucalypt plantings on cleared agricultural land is currently the predominant method of reforestation for carbon sequestration in Australia. Investment in establishing and maintaining such plantings relies on having a cost-effective approach for providing un-biased estimates of yield in biomass and carbon sequestration. The Australian Government's forest carbon accounting model (FullCAM) had not previously been calibrated for mallee eucalypt plantings and, in many circumstances, substantially under-estimated of biomass for these plantings. Our objective was to improve model applicability and reliability of estimates of carbon sequestration. To achieve this, we first collected and analysed above-ground biomass data from 257 mallee eucalypt plantings (or 744 observations, when including the multiple measurements made at some planting sites) to determine the key factors influencing growth. Plantings were categorised according to species, planting configuration (block or belt plantings) and stand density. Each category of planting had significantly different rates of growth, with the rates of sequestration of above-ground biomass carbon being relatively high when established in densely-stocked, two-row belts. These categories of plantings then provided the basis for calibration (estimation of appropriate modifiers) of FullCAM growth curves. Overall model efficiency was 63%, and there was no apparent bias when the model was applied to the various planting categories. Thus, modelled estimates of biomass accumulation will be reliable on average but at any particular location will be highly uncertain, with either substantial under- or over-prediction possible. For some categories of mallee eucalypt plantings, and for plantings with access to ground-water or established in non-productive soils, there were insufficient observations to provide confidence in new calibrations specific for these circumstances. Moreover, application of the calibrations provided here are applicable for prediction of sequestration of biomass carbon of relatively young (<15-year-old) stands, with more data needed for prediction of longer-term rates of growth.

1. Introduction

Mallee eucalypts have multiple woody stems arising from an underground lignotuber which readily coppices, and therefore are well adapted to grow in infertile soils and arid climates, and to recover from disturbances such as fire or harvesting. Consequently, land managers in Australian dryland agricultural regions (250–850 mm year^{-1} rainfall) have often preferred planting mallee eucalypts over other woody species. Such plantings can readily be integrated with existing agriculture, often established in narrow belts with cropping or grazing between belts, and may provide

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possible salinity mitigation and biodiversity benefits as well as options for harvesting of biomass (e.g. Bartle et al., 2007; Polglase et al., 2008). Relatively low land values (and thus opportunity costs) in these regions can also make the generation of carbon offsets through reforestation viable (Yu et al., 2009), resulting in mallee eucalypt plantings currently being the most common form of carbon plantings in Australia (Mitchell et al., 2012; Stephens and Grist, 2014).

Land managers in many Australian dryland agricultural regions are now assessing the economics of growing mallee plantings for carbon sequestration, which may or may not include harvesting. A key determinant of economic viability is the estimated rates of carbon accumulation. To obtain cost-effective predictions of biomass accumulation, forest carbon accounting models such as the Full Carbon Accounting Model (FullCAM) may be applied (Brack and Richards, 2002; Richards and Brack, 2004; Waterworth and Richards, 2008). The FullCAM model is used in Australia's National Inventory System (DOTE, 2014a) to estimate rates of carbon sequestration caused by changes in land use or management across Australia, including reforestation with mallee eucalypt plantings. FullCAM is utilised for estimating net greenhouse gas emissions for both Australia's international reporting obligations and for its domestic carbon market (Carbon Farming Initiative, ComLaw, 2011).

FullCAM has a Tree Yield Formula (TYF) which can be calibrated for different planting types (Waterworth et al., 2007). The TYF is used to predict current annual increments in above-ground biomass (AGB, on an oven-dry mass (DM) basis), with growth potential being driven spatially by a Forest Productivity Index (FPI). The FPI is a dimensionless measure of site productivity determined by soil, sunlight, rainfall, evaporation, and frost, with higher values of long-term average FPI (FPI_{ave}) resulting in higher net primary productivity through a non-linear relationship (Kesteven et al., 2004; DOTE, 2014a). The FPI varies temporally and spatially, with estimates available across Australia from an online FullCAM database (DOTE, 2014a).

Although the TYF has already been calibrated for many traditional plantation species (Waterworth et al., 2007) and, recently, for mixed-species environmental plantings (Paul et al., 2014), it had not been calibrated for mallee eucalypt plantings. Previous TYF calibrations, as well as other studies using large forest productivity datasets (e.g. Hui et al., 2012) have shown that both the scaling and slope components of tree growth curves may need to be adjusted in accordance with management (i.e., species, density, planting geometry, etc.) and environmental (i.e. location and elevation, etc.) factors.

Water availability is a major constraint to biomass production of mallee eucalypt plantings in dryland agricultural regions, resulting in trees being established in belts to potentially allow the capture of some water (and nutrients) from adjacent land (Brooksbank et al., 2011). Thus, planting configuration is likely to be an important factor influencing AGB (Cooper et al., 2005; Carter et al., 2011; Paul et al., 2013a) as is stand density and species selection (e.g. Polglase et al., 2008; Paul et al., 2008, 2014; Preece et al., 2012). Some mallee eucalypt plantings in dryland agricultural regions have access to groundwater, resulting in increased growth rates (e.g. George et al., 1999). However water availability is only one component contributor to tree growth, and responses of AGB to additional water will be dependent on salinity and nutrient supply in the surface soil (Carter et al., 2011). Also, coppice re-growth after harvesting shows accelerated rates of AGB accumulation in the short-term compared to newly-planted stands of the same age (Peck et al., 2012). All of these factors require investigation to determine which statistically significantly influence AGB of mallee eucalypt plantings, and therefore whether separate TYF calibrations are required to account for them.

This study had two objectives, to: (i) collate new and existing inventory data from mallee eucalypt plantings to identify the key factors influencing growth, and (ii) develop FullCAM TYF calibrations for un-biased estimation of the pattern of AGB accumulation, and thus carbon sequestration, at regional and national scales for a range of different types of mallee eucalypt plantings.

2. Methods

2.1. Database

A database was developed from 257 mallee eucalypt plantings (or 744 observations, including repeat measurements at some sites over time) distributed largely across south-eastern, and particularly south-western, Australia (Fig. 1, Table 1). Most plantings in the dataset were relatively young, with a mean (and standard deviation, SD) stand age of 5.6 years (and 4.6 years), respectively, with 95% of plantings aged 1–14 years. Plantings were generally from regions of relatively low rainfall (mean and SD of 383 and 80 mm $year^{-1}$, respectively) and, therefore, low productivity as characterised by the long-term average Forest Productivity Index (FPI_{ave}). The FPI_{ave} varies from 1 to 27 across Australia (DOTE, 2014a), yet across the mallee plantings studied, average FPI_{ave} was only 4.20 (SD 1.02).

Plantings were grouped into three categories of mallee eucalypt species; (i) 'Polybractea' (28% of dataset): (ii) 'Loxophleba' (49% of dataset), and (iii) 'Other' (23% of dataset). Polybractea and Loxophleba categories comprised of *Eucalyptus polybractea* R.T. Baker (blue mallee) and *Eucalyptus loxophleba* ssp. *lissophloia* L.A.S. Johnson & K.D. Hill (smooth bark york gum) plantings, respectively. In contrast, the Other category of mallee plantings was mostly (86%) *Eucalyptus kochii*, but including the sub-species of ssp. *kochii* Maiden & Blakely, ssp. *borealis* C.A. Gardner, and ssp. *plenissima* C.A. Gardner (oil mallee), and 1–5 plantings of *Eucalyptus horistes*, *Eucalyptus ucalyptus calycogona*, *Eucalyptus cneorifolia* (Kangaroo Island CS20275), *Eucalyptus cyanophylla* (Loxton cult.), *Edumosa*, *Eucalyptus gracilis* (Loxton cult.), *Eucalyptus incrassata*, *Eucalyptus leptophylla*, *Eucalyptus oleosa*, *Eucalyptus plenissima*, *Eucalyptus porosa*, and *Eucalyptus socialis*. These generally multi-stemmed species of eucalypts differed in their growth form, with Other tending to produce the most stems, and Loxophleba tending to produce the least stems. There were also differences between species in terms of the inherent qualities of the sites at which they were established, with Polybractea tending to be established at sites of higher site quality. In terms of FPI_{ave}, 95% of the plantings in the Polybractea, Loxophleba and Other categories were established at sites of between 3.56–5.93 (mean 5.20), 2.76–5.31 (mean 3.94), and 2.95–4.10 (mean 3.50), respectively.

All plantings were established with tube-stock and in rows generally spaced 2 m apart. There were three different types of planting configurations sampled: block (8% of dataset), wide belt (49% of dataset), and narrow belt (43% of dataset). The block, wide belt and narrow belt configurations corresponded to plantings with edge trees comprising <25%, 25–50% (generally three to eight rows), or 100% (two tree rows) of trees measured, respectively. For belt plantings, the recommended distance between adjacent plantings is about 40 m as the zone of hydrological influence of mature roots extends up to about 20 m from the edge row of belts (Harper et al., 2010; Peck et al., 2012; Brooksbank et al., 2011).

There was large variation in stand densities, the mean being relatively high at 2241 trees per hectare (tph) of planted area (SD 695 tph). Two categories of stand density were derived to effectively divide the datasets into two sub-sets; low (<2300 tph) and high (>2300 tph).