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Managing reforestation to sequester carbon, increase biodiversity potential and minimize loss of agricultural land

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ABSTRACT

Reforestation will have important consequences for the global challenges of mitigating climate change, arresting habitat decline and ensuring food security. We examined field-scale trade-offs between carbon sequestration of tree plantings and biodiversity potential and loss of agricultural land. Extensive surveys of reforestation across temperate and tropical Australia ($N = 1491$ plantings) were used to determine how planting width and species mix affect carbon sequestration during early development (< 15 year). Carbon accumulation per area increased significantly with decreasing planting width and with increasing proportion of eucalypts (the predominant over-storey genus). Highest biodiversity potential was achieved through block plantings (width > 40 m) with about 25% of planted individuals being eucalypts. Carbon and biodiversity goals were balanced in mixed-species plantings by establishing narrow belts (width < 20 m) with a high proportion (>75%) of eucalypts, and in monocultures of mallee eucalypt plantings by using the widest belts (ca. 6–20 m). Impacts on agriculture were minimized by planting narrow belts (ca. 4 m) of mallee eucalypt monocultures, which had the highest carbon sequestering efficiency. A plausible scenario where only 5% of highly-cleared areas (<30% native vegetation cover remaining) of temperate Australia are reforested showed substantial mitigation potential. Total carbon sequestration after 15 years was up to 25 Mt CO_2-e year^{-1} when carbon and biodiversity goals were balanced and 13 Mt CO_2-e year^{-1} if block plantings of highest biodiversity potential were established. Even when reforestation was restricted to marginal agricultural land (<$2000 ha^{-1} land value, 28% of the land under agriculture in Australia), total mitigation potential after 15 years was 17–26 Mt CO_2-e year^{-1} using narrow belts of mallee plantings. This work provides guidance on land use to governments and planners. We show that the multiple benefits of young tree plantings can be balanced by manipulating planting width and species choice at establishment. In highly-cleared areas, such plantings can sequester substantial biomass carbon while improving biodiversity and causing negligible loss of agricultural land.

1. Introduction

Reforestation of agricultural land has influences on the global challenges of mitigation of climate change through sequestration of biomass carbon, negating the decline in native habitat (and thus biodiversity) through deforestation, and ensuring food security (e.g. Nabuurs et al., 2007; Smith et al., 2013). Increased reforestation in response to emerging carbon markets provides valuable opportunities for improved biodiversity outcomes in degraded agricultural regions (e.g. Hatanaka et al., 2011; Kessler et al., 2012; Nguyen et al., 2012). It is therefore advocated that carbon certification schemes include assessments of biodiversity poten-

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tial (e.g. Montagnini and Nair 2004; Standish and Hulvey 2014). However, such land-use change needs to minimise impacts on agricultural food production as population and per capita food consumption increase (Smith et al., 2013; Godfray and Garnett 2014). Although maintaining agricultural production can be achieved partially through spatial planning at regional or national scales (e.g. Polglase et al., 2013), questions remain at field-scale about how to best integrate reforestation into farms to achieve multiple benefits of carbon and biodiversity with limited impact on land available for agricultural production.

Spatial planning has been useful for targeting reforestation at landscape (ca. 10 km^2) to national scales using scenarios of typical rates of carbon sequestration in generic types (carbon vs. environmental) of tree plantings (e.g. Bryan et al., 2014). Details of establishment and management of these plantings are often overlooked but may be equally as important as location in determining their potential to sequester carbon (Paul et al., 2013c). Plantings can vary in shape (i.e. narrow belts vs. wider blocks), tree density, species and structural complexity (e.g. proportion of trees vs. shrubs). Each of these establishment choices is likely to affect carbon sequestration, biodiversity potential (i.e. the range of habitats) and losses in land available for agricultural production. For example, narrow belts of monocultures of fast-growing trees may sequester more carbon per area than other types of plantings (e.g. Paul et al., 2014b). Furthermore, belt plantings may minimise losses in land for agricultural production (i.e. opportunity costs) because they can be spaced to allow agricultural production between belts (e.g. Paul et al., 2013c). Block plantings of a diverse mix of trees and shrubs are likely to provide habitat for a greater range of native taxa and thus have higher biodiversity potential (e.g. Wormald 1992; Lindenmayer and Hobbs 2004). Planting management options can favour one goal over another, making it unclear how to achieve multiple benefits from reforestation with limited trade-offs.

In Australia, about 78% of reforestation projects for carbon sequestration are mixed-species plantings (typically indigenous mixtures of tree and understory shrub species) and monocultures of mallee eucalypts (Mitchell et al., 2012; Stephens and Grist 2014). Variously, these plantings can improve degraded landscapes, increase native habitat and produce biomass products (e.g. Harper et al., 2005; Felton et al., 2010). Land managers can obtain payments for these plantings based on carbon sequestration following reforestation predicted by the national carbon accounting model, FullCAM (DotE, 2014a; Paul et al., 2014a,b). Modelling of above-ground biomass in the FullCAM model using categories of stand density, planting width, species composition and climatic regions (Paul et al., 2014a,b) provided moderate predictive power for environmental plantings ($R^2 = 0.46$) and mallee eucalypts ($R^2 = 0.63$) (Paul et al., 2014a,b). Incorporating continuous variables for stand density, planting width and species composition is likely to further improve the predictions of biomass carbon accumulation in these planting types.

Here, we determined typical rates of carbon sequestration for different planting strategies using extensive surveys ($N = 1491$ plantings) of a range of reforestation, including environmental and mallee eucalypt plantings, across Australia through the development of empirical models of above-ground biomass accumulation using continuous rather than categorical variables. These models were then used to: (i) explore field-scale trade-offs between carbon sequestration and either biodiversity potential or food production, and (ii) given the most favourable planting strategies identified through these trade-off assessments, predict potential reforestation opportunities across marginal and/or highly-cleared agricultural land of Australia.

2. Methods

2.1. Comparison of biomass carbon among planting types

A database of above-ground biomass estimates (AGB, Mg DM ha^{-1}, where AGB is above-ground biomass, and DM is dry matter) had been previously developed for tree plantings, based on inventory surveys of stem diameter (measured at breast height (1.3 m) for trees, and at 10 or 30 cm above the ground for shrubs, most mallee eucalypts and some multi-stemmed trees), and application of allometric equations, from low to high rainfall (265–4600 mm year^{-1}) regions of Australia (Paul et al., 2013a,b). This database included: (i) monocultures of mallee eucalypt plantings (subsequently termed ‘mallee plantings’; $N = 744$ plantings), (ii) temperate mixed-species environmental plantings (subsequently termed ‘temperate plantings’; $N = 583$ plantings), and (iii) tropical mixed-species environmental plantings (subsequently termed ‘tropical plantings’; $N = 164$ plantings, Table 1, Fig. 1). The surveyed plantings covered a wide geographical range, including the agricultural regions throughout Australia (−42.8 to −16.5° S and 115.1 to 152.7° E).

An analysis of covariance (ANCOVA) that accounted for stand age was used to determine whether these biomass estimates differed significantly among the three planting types. As the model derived from this statistical analysis had stand age as one of the explanatory variables, typical rates of AGB accumulation were estimated for mallee, temperate and tropical plantings for a stand age of 15 years, and the prediction errors reported. Stand age (mean ± SD) of mallee, temperate and tropical plantings was 5.6 ± 4.7 years, 12.6 ± 6.7 years and 9.1 ± 5.3 years, respectively, thereby providing highest confidence of prediction of AGB accumulation for developing stands (i.e. <15 years old; Paul et al., 2014a,b). In the absence of below-ground biomass or carbon concentration measurements, typical rates of sequestration of carbon in total biomass (and their prediction errors) were estimated in Mg $\mathrm{CO_2}$-e ha^{-1} year^{-1} using the standard assumptions that root-to-shoot ratios were 0.25 and that carbon fractions of biomass were 0.50 (IPCC, 2006). However, new allometric equations have recently become available for prediction of root biomass of trees and shrubs in environmental and mallee plantings (Paul et al., 2014c). Work is therefore currently underway to further improve estimates of total biomass carbon sequestration at each of our study sites using improved estimates of root biomass. Given preliminary results indicate root-to-shoot ratios of trees in environmental, and particularly mallee plantings, are generally higher than the 0.25 assumed here, our estimates of sequestration of biomass carbon are likely to be underestimated, particularly for mallee eucalypts.

2.2. Empirical models of aboveground biomass

Following the approach used by Paul et al. (2014a,b), multiple linear regressions for tropical and temperate plantings, and ANCOVA for mallee plantings, were used to derive empirical models predicting AGB. For mallee plantings, an ANCOVA analysis was used, rather than regression, because there were three categories of species planted: (i) *Eucalyptus polybractea* (mallee-P), (ii) *E. loxophleba* ssp. *lissophloia* (mallee-L) and (iii) other key species of mallee (mallee-O), which comprised mostly *E. kochii*. For all analyses, AGB and stand age were log-transformed to ensure data were normally distributed, and step-wise model selection was used, with only factors that had significant main effects or interactions ($P < 0.05$) included in the final empirical model. Explanatory variables considered were stand age, site productivity index (FPI, Kesteven et al., 2004), stand density (number of planted individuals per hectare), proportion of individuals in the plantings that were eucalypt trees (PropEuc), planting width, diversity of planted