Forest Ecology and Management 344 (2015) 53–62

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Soil-vegetation type, stem density and species richness influence biomass of restored woodland in south-western Australia

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ARTICLE INFO

Article history:
Received 31 October 2014
Received in revised form 7 February 2015
Accepted 11 February 2015
Available online 27 February 2015

Keywords:
Biodiverse carbon planting
Carbon sequestration
Carbon stock
Environmental planting
Eucalypt woodland
Functional diversity

ABSTRACT

Woody plantings are increasing across the globe to satisfy ecosystem service markets for carbon and ecological restoration. Assessments of these complex woody systems typically use coarse-scale parameters, based on the climate and soil type of a region, and/or remotely assessed vegetation cover, to estimate carbon in their above- and belowground biomass. However it remains poorly known what factors influence their biomass at finer scales. Here, we investigated biomass variability after five years across a 250 ha environmental planting on a former agricultural property in south-western Australia. We aimed to understand which factors may influence observed biomass variability. The dominant canopy tree, *Eucalyptus occidentalis*, was planted as seedlings, and other woody species were direct sown in vegetation associations, according to soil type and landscape position, to reflect historic native assemblages. Results from 42 survey plots stratified across these associations showed variable seedling establishment from the seed mix, and that the amount of above- and belowground biomass varied widely (Coefficient of variation = 60%). A site mean and standard error were inadequate to capture biomass distribution. Instead, two modes were evident within the distribution at approximately 5 Mg ha^{-1} and 15 Mg ha^{-1} with variation primarily associated with differential seedling establishment and growth across the vegetation associations. Additionally, multiple regression analysis showed that stem density explained a significant amount of biomass variation whilst greater species richness was associated with increased biomass once stem density had been accounted for – models combining soil-vegetation association, number of individuals, and species richness explained between 60% and 80% of biomass variation depending on the response variable (total or live biomass) and choice of allometric equations to predict biomass. There was some evidence for a role of nitrogen-fixing species in determining biomass variation. There was no evidence for biomass variation being explained by the proportional contribution of the dominant canopy tree (*E. occidentalis*) or eucalypts in general once number of individuals had been accounted for, despite their large contribution to plot biomass. The substantial variation we show across the site has implications for carbon accounting practices and cost-benefit analyses guiding investment and regulation of the sector. Our results add weight to emerging evidence that restoring woody plant diversity can be compatible with efforts to maximize biomass and show the potential for diverse restored woodland assemblages to meet developing market demands for carbon.

1. Introduction

Environmental plantings have been widely proposed for ecological restoration and to sequester carbon to mitigate climate change (Silver et al., 2000; Dwyer et al., 2009; Fensham and Guymer, 2009). In response to these proposals, there has been an increase in the number and scale of (woody) environmental

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http://dx.doi.org/10.1016/j.foreco.2015.02.012
0378-1127/

plantings, often as part of ecosystem service markets and government programs (Phelps et al., 2012; Bradshaw et al., 2013). The ability to determine carbon sequestration of these multi-purpose and large scale (>100 ha) environmental plantings is not well studied due to the limited number of complex restoration projects of this type (see e.g. Paul et al., 2013a, 2014, 2015). Methods to quantify standing biomass in mixed species plantings may take several forms, such as process models, empirical models and forest inventory methods. Quantification can be complex to determine through sampling and inventory, and current models are not necessarily suitable for site level carbon accounting given they are often at a coarse-scale (e.g. FullCAM, Reforestation Modelling Tool Paul et al., 2003, 2013a). These coarse scale methods will not account for variation that occurs within complex vegetation systems due to the identity and growth form of species planted (e.g. Firn et al., 2007), differential seedling establishment success (Hallett et al., 2014), and subsequent growth (Erskine et al., 2006; Kanowski and Catterall, 2010). Forest inventory methods require an understanding of the spatial variability that may occur both within and between different vegetation associations. Currently, data to assess this variation and its potential impact on carbon accounting are limited, and so too measurements of the underlying ecological factors that might help explain the variation. These factors could further inform stratification of restored woodland assemblages for the purpose of improving the efficiency of biomass measurements without compromising the accuracy of carbon estimates for a site. Here, we estimated standing biomass of woodland assemblages five years after the establishment of a large-scale revegetation project in an old-field in south-western Australia. We then determined the relationships among soil type, landscape position and seed mix on biomass variation together with other biotic attributes. We asked whether the incorporation of these additional factors significantly and parsimoniously improved the explanatory power of statistical models predicting biomass sequestration. We then discuss how this knowledge can inform the stratification of a restored woodland assemblage for the purpose of obtaining the greatest efficiency of measurement-based biomass carbon estimates across a property as a whole.

We hypothesized that there are multiple, hierarchical controls on growth of woody species in environmental plantings as intimated previously (Diaz et al., 2007) and that these controls will lead to standing biomass variation across a site. For instance, and regardless of species, climate and large-scale soil changes will broadly influence the amount of biomass sequestered, as shown for *Acacia harpophylla* (brigalow) and *Acacia aneura* (mulga) woodland regrowth in Queensland (Dwyer et al., 2010b; Fensham et al., 2012) and pine forests in Catalonia (Vila et al., 2003). Below the level of environmental variation at this coarse-scale, small-scale differences in topography, aspect and soil type may influence establishment and subsequent growth of individuals (Tajchman et al., 1996; Paul et al., 2008; Preece et al., 2012), especially in areas where depth to water table is an important determinant (e.g. Carter et al., 2008). Geometry may also be important; for instance, narrow linear plantings often have greater biomass than block plantings due to higher resource availability at their edges (Paul et al., 2013a). At a given site and topographic location, the diversity of plants, typically measured as species richness, has been shown to also influence above ground biomass (Hooper et al., 2005). However, most research supporting this relationship has been conducted in grasslands and microbial microcosms with fewer investigations of woody species assemblages in field settings (Cardinale et al., 2012). A recent meta-analysis, of the few published experimental studies of woody species growth, indicated that species richness had a positive effect on aboveground biomass, but noted that the identity and functional traits of the species involved are an important component of how much carbon will likely be sequestered (Hulvey et al., 2013). Furthermore, individual studies can show conflicting results (e.g. Potvin et al., 2011) suggesting context dependency is important. In addition to plant species number and identity, the density of established individuals potentially influences the amount of carbon sequestered by an environmental planting (Dwyer et al., 2010a; Paul et al., 2013a).

Surveys of recently established non-experimental environmental plantings (and old growth forest e.g. Jacob et al., 2010; Seidel et al., 2013), as compared to experimental approaches, provide an alternative avenue to investigate potential influences on biomass/productivity, especially if (1) the planting is large enough to capture spatial heterogeneity (e.g. >100 ha); (2) there are records of establishment practices and site conditions; and, (3) records include accurate identities and measurements of established individuals. The first two allow investigations of biomass relationships among and within soil-vegetation type associations while the latter provides important information so that suitable allometric relationships can be applied to estimate biomass and carbon (e.g. Jonson and Freudenberger, 2011). Peniup, a large-scale environmental planting established in south-western Australia in 2008, meets these criteria and it thus provided us the opportunity to identify *potential* drivers of variation in standing biomass. Although this environmental planting lacked experimental controls, the planting was large enough (250 ha) to explore possible relationships with topography, soil type, seed mix, plant density, species richness and species identity, but small enough to ignore large-scale variation in climate.

We therefore asked: What site factors are associated with the variation in total (above- and belowground) biomass across a 250 ha environmental planting? We hypothesized that there would be marked spatial variation among surveyed plots which can be explained, in part, by differences in soil-landscapes that were sown with different seed mixes. Within any one of these soil-landscape-seed mix associations (hereafter "*vegetation associations*"), we hypothesized that greater numbers of established individuals, higher species richness, and the differential proportional presence of particular functional and structural groups (e.g. nitrogen-fixing woody plants) will lead to more biomass accumulation at this early stage of growth. Disentangling the influence of each of these factors separately and attributing causation, given the constraints of the survey design, is not possible; however we can make inferences using the statistical approach adopted. Finally, we also investigated whether biomass relationships with potential drivers varied among the different vegetation associations. All our hypotheses were defined *a priori* and informed by (limited) previous studies of these relationships in smaller-scale environmental plantings elsewhere in Australia (e.g. Erskine et al., 2006; Dwyer et al., 2010b; Kanowski and Catterall, 2010; Paul et al., 2013a) as well as our local ecological knowledge, and observations of seedling establishment at Peniup (Jonson, 2010; Hallett et al., 2014). We researched this with the view that understanding fine-scale variability in woodland restoration plantings could be used to inform a stratified sampling approach for more accurate, and potentially cost-effective, estimates of carbon sequestration.

2. Site description, methods and statistical analyses

2.1. Site description

Peniup is a 2406 ha former agricultural property that was purchased by the non-governmental organisations Greening Australia and Bush Heritage in July 2007 as part of the Gondwana Link initiative (www.gondwananlink.org). It was one of the first carbon-funded ecological restoration projects in Australia (Jonson, 2010). Peniup is located in the south west of Western Australia