Journal of Environmental Management 181 (2016) 279–288

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Models of reforestation productivity and carbon sequestration for land use and climate change adaptation planning in South Australia

Trevor J. Hobbs [a, *], Craig R. Neumann [a], Wayne S. Meyer [b], Travis Moon [c], Brett A. Bryan [c]

[a] Department of Environment, Water and Natural Resources – South Australian Government, GPO Box 1047, Adelaide, SA 5001, Australia
[b] University of Adelaide, PMB l, Glen Osmond, SA 5064, Australia
[c] CSIRO Ecosystem Sciences, PMB 2, Glen Osmond, SA 5064, Australia

A R T I C L E I N F O

Article history:
Received 20 November 2015
Received in revised form
15 June 2016
Accepted 25 June 2016

Keywords:
Carbon sequestration
Productivity
Reforestation
Biodiversity plantings
Climate change
Land use planning

A B S T R A C T

Environmental management and regional land use planning has become more complex in recent years as growing world population, climate change, carbon markets and government policies for sustainability have emerged. Reforestation and agroforestry options for environmental benefits, carbon sequestration, economic development and biodiversity conservation are now important considerations of land use planners. New information has been collected and regionally-calibrated models have been developed to facilitate better regional land use planning decisions and counter the limitations of currently available models of reforestation productivity and carbon sequestration. Surveys of above-ground biomass of 264 reforestation sites (132 woodlots, 132 environmental plantings) within the agricultural regions of South Australia were conducted, and combined with spatial information on climate and soils, to develop new spatial and temporal models of plant density and above-ground biomass productivity from reforestation. The models can be used to estimate productivity and total carbon sequestration (i.e. above-ground + below-ground biomass) under a continuous range of planting designs (e.g. variable proportions of trees and shrubs or plant densities), timeframes and future climate scenarios. Representative spatial models (1 ha resolution) for 3 reforestation designs (i.e. woodlots, typical environmental planting, biodiverse environmental plantings) × 3 timeframes (i.e. 25, 45, 65 years) × 4 possible climates (i.e. no change, mild, moderate, severe warming and drying) were generated (i.e. 36 scenarios) for use within land use planning tools.

1. Introduction

In many regions of Australia and the world, the diversity of landscapes, climates, people and land uses creates a complex setting for governments, policy makers and planners to make well-informed decisions about managing regional natural resources for multi-purpose use, now and into the future (Bryan and Crossman, 2008; Wei et al., 2009; Parrot, 2011; Parrott and Meyer, 2012). To assist planning with this uncertainty, considerable efforts have been made to gather comprehensive regional natural resource information, develop analysis tools and provide assessment of land use planning options with a range of possible future scenarios and timeframes (Selman, 2006; Bryan et al., 2008; Polglase et al., 2008; Crossman and Bryan, 2009; Hobbs, 2009; Hobbs et al., 2010, 2013; Bryan et al., 2011; Polglase et al., 2013; Wise et al., 2014; Summers et al., 2015; Connor et al., 2015; Gao et al., 2016).

In southern Australia, future land use planning is aware that the majority of suitable land is privately owned, cleared of native vegetation and developed for agricultural production. Food and fibre industries (e.g. cereals, meat, wool, horticulture and forestry) dominate this production that supports the economic activity of local communities. Government policies support the existence of these industries and recognise the need to manage the soil and water resources on which these industries are based. In addition, policies and markets have evolved to support biodiversity conservation (e.g. native vegetation management), encourage carbon sequestration of atmospheric carbon dioxide through revegetation and adapt to expected changes in climates (Suppiah et al., 2006; IPCC, 2013, 2014). The opportunities and limitations that these emerging land uses present have been studied (Bartle et al., 2007; Polglase et al., 2008, 2013; Hobbs, 2009; Bryan et al., 2013, 2014; Paul et al., 2013a, 2015), with the conclusions always dependant

* Corresponding author.
E-mail address: Trevor.Hobbs@sa.gov.au (T.J. Hobbs).

http://dx.doi.org/10.1016/j.jenvman.2016.06.049
0301-4797/

on the reliability and generality of the input information. Consideration of current and future blends of traditional agricultural industries and new carbon or environmental plantings is dependent on credible comparisons between land use options. While the productivity and profitability of most traditional food and fibre industries is underpinned by sound science and economics, the quality of such information for reforestation productivity and carbon markets is limited (Bryan et al., 2011; Parrott and Meyer, 2012). Refining estimates of carbon sequestration by reforestation at regional and local scales is a high priority.

Reforestation or revegetation is a land use option sanctioned by the Australian government to sequester carbon dioxide from the atmosphere and to generate a carbon credit commodity that has an economic value within domestic carbon markets (i.e. Emissions Reduction Fund, Carbon Farming Initiative, Australian Government, 2011a,b, 2015; DOTE, 2015a). Carbon stored in reforestation is included in Australian National Greenhouse Accounts and reported under international obligations (DOTE, 2015a). Natural forest and reforested area extent are regularly assessed using satellite data. The carbon stocks from these spatial assessments are estimated with carbon models based on the Forest Productivity Index (FPI, Kesteven et al., 2004; DOTE, 2015b).

Several forest productivity models exist which are used to estimate biomass and carbon stocks from reforestation in Australia including FullCAM (Brack and Richards, 2002; Richards and Brack, 2004; Richards and Evans, 2004; Brack et al., 2006; Waterworth et al., 2007; Waterworth and Richards, 2008; DOTE, 2015b), 3-PG (Landsberg and Waring, 1997; Landsberg et al., 2003; Landsberg and Sands, 2011) and CABALA (Battaglia et al., 2004). They are mostly based on research results from commercial forestry species in higher rainfall zones of Australia. In recent years, these forestry models have been adapted to also represent environmental plantings and carbon accumulation in medium to lower rainfall regions. The resultant estimates have often underestimated biomass yields in reforestation (Montagu et al., 2003; Paul et al., 2008; Wood et al., 2008; Hobbs et al., 2010; Keith et al., 2010; Landsberg and Sands, 2011; Fensham et al., 2012; Paul et al., 2013b, 2015). Reliable calibration of these models for environmental plantings has been constrained by the lack of data collected outside of high-rainfall forestry species and regions. Some recent and significant improvements have been made in early growth calibrations for environmental planting models within FullCAM (Paul et al., 2013b, 2015).

Australia's main carbon accounting methodology for environmental plantings (i.e. Reforestation by Environmental or Mallee Plantings - FullCAM Method; Australian Government, 2014) is based on a point-based FullCAM model that uses spatial FPI data to estimate current and future reforestation productivity and carbon stocks with historic climatic conditions. The current version of FullCAM only provide broad classifications of planting designs (e.g. low, moderate, high plant stocking rates; Richards and Evans, 2004; DOTE, 2015b) which prevents these models from estimating within-class variations in productivity and carbon stock resulting from differences in plant density and competition effects. The magnitude of these variations is greatest for environmental plantings with low to moderate plant densities (Paul et al., 2013b, 2015). The accuracy of local applications of FullCAM for carbon accounting for reforestation projects is very limited due to the coarse scale of the underlying FPI data used in the model. The extrapolation of soil fertility modifiers developed for the FPI in high-rainfall conditions is likely to produce errors in lower-rainfall regions, where water is a more dominant growth factor (Kesteven et al., 2004; Landsberg and Sands, 2011). Process-based models (e.g. 3 PG, CABALA) have the potential to reliably estimate reforestation productivity and carbon stocks but insufficient data exists to provide reliable species (or mixed species) model calibrations or site parameterisations for models in many regions (Landsberg and Sands, 2011; Song et al., 2012).

In response to the limitations of current models and the sensitivity of carbon market analyses to variations in estimates of carbon sequestration from reforestation projects we developed locally-calibrated models of primary productivity and carbon sequestration from reforestation in the agricultural regions of South Australia. These models were intended to facilitate better regional land use planning by providing more reliable spatial and temporal estimates of primary productivity of reforestation options in the region, inform carbon markets of typical sequestration rates of these options, and anticipate the likely effects of climate change on future carbon stocks. Regional planners and natural resource managers can access this information through the South Australian Government's geographic information system and a land use planning tool (Landscape Futures Analysis Tool, Summers et al., 2015).

2. Methods

2.1. Study area

This study considers the 10.2 million hectares of agricultural land in South Australia. These lands are dominated by annual cereal cropping and livestock grazing productions systems with minor components of plantation forestry and high intensity agriculture (Fig. 1). The region experiences a Mediterranean climate with cool wet winters and warm dry summers. Mean annual rainfall in the study area currently ranges between 244 and 1056 mm year^{-1}, with mean annual potential evaporation between 1194 and 2489 mm year^{-1} and mean annual temperature between 12.4 and 18.6 °C. Most climate change forecasts suggest this region is likely to experience a decrease in rainfall, and increases in temperature and evaporation in the coming decades (Suppiah et al., 2006; IPCC, 2013).

2.2. Productivity of reforestation

Reforestation sites with reliably documented planting dates were surveyed to assess plant growth and carbon sequestration of Kyoto-compliant species (i.e. ≥2 m height at maturity) over a wide range of environmental conditions in the agricultural zone of South Australia (Fig. 1). These sites were chosen to represent two main planting designs: 1. woodlots (mainly monocultures); or 2. environmental plantings (mainly mixed species). Surveys focussed on block planting designs (i.e. >4 row plantations) but included some windbreak sites (i.e. ≤4 row plantations).

Sites were sub-sampled using 6 randomly located sections of continuous plants along rows (and avoiding ends of rows). Row sections typically comprised of 10 individuals in mixed species plantings and 6 individuals in monocultures. The larger number of observations in mixed species plantings was used to determine the proportion of biomass contribution by each species within the plantation. At each row section, individual species (≥2 m high) were recorded and plant measurements included height, crown width, life form (single-stemmed tree/multi-stemmed tree/shrub), distance to neighbouring plants, stem count and circumference at two lower section heights (basal and intermediate: 0.5 m and 1.3 m; for single-stemmed trees and multi-stemmed trees; and at 0.2 m and 0.8 m for shrubs). Exceptions to this protocol applied to an agroforestry field trial site (8 species blocks; average 249 individuals per block) and detailed surveys located at 3 sites where all individuals at each site were measured.

Distance to neighbouring plants (≥2 m high) for each individual