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Restoration and management of callitris forest ecosystems in Eastern Australia: Simulation of attributes of growth dynamics, growth increment and biomass accumulation

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ABSTRACT

Availability of quantitative information on growth increment, biomass accumulation and growth dynamics of fragmented and degraded forest ecosystems is a common challenge in restoration work. Ecological models of forest dynamics have the potential to provide a structure through which data, observations and assumptions can be combined and explored. The utility of such models, however, is often limited by lack of validation. In this paper we used growth data for 143,200 tree measurements, in 121 plots spanning up to 70 years of forest monitoring from uneven-aged mixed species callitris forests of Australia to test the Ecosystem Dynamics Simulator (EDS). These are among the least known and most degraded forest communities in Australia and are known habitat for threatened and rare fauna species including brush-tailed rock wallaby (*Petrogale penicillata*), glossy black-cockatoo (*Calyptorhynchus lathami*), grey falcon (*Falco hypoleucos*), golden-tailed gecko (*Strophurus taenicauda*) and others. We determined growth parameters for 26 woody species and applied these to the EDS to validate projected stand structure and growth. The model projections explained 93.9% (diameter at breast height (dbh)), 88.9% (basal area), 90.5% (stem density) and 88.6% (aboveground biomass) of the observed variation. To our knowledge, this is one of the most accurate validations of forest dynamics simulation achieved to date. Diameter growth rates for most species were <0.3 cm yr^{-1} and reproduced well by the EDS, for all the species in the callitris forest communities. These growth rates indicate that exceptionally long periods will be required to restore the degraded or cleared forests to a mature state. Results can guide restoration and sustainable management of callitris forest ecosystems by providing projected measurable forest attributes to meet multiple goals, including harvesting of forest resources, carbon storage and conservation of biodiversity.

1. Introduction

The loss, fragmentation and degradation of natural forest ecosystems and associated loss of biodiversity, increased soil erosion and effects of climate change are widely recognised as human-induced global environmental challenges (Newton, 2007; FAO, 2010). In most countries, the main causes of forest ecosystem loss and fragmentation include clearing for permanent pastures and cropland, conversion of native forest ecosystems to plantations, and catastrophic wildfire (both natural and human-induced). In some countries, such as the United States of America and Australia, early European settlers cleared forest to establish farms, towns, cities and roads. Other subtle but recurrent activities such as inappropriate fire regimes, logging, browsing by livestock and thinning for fuel wood can cause progressive and serious forest degradation (Yates and Hobbs, 1997; FAO, 2010; Rodriguez-Trejo and Myers, 2010). Depending on their extent, these processes directly affect flora and fauna by reducing habitat area and connectivity, damaging habitat condition, and modifying population dynamics of species.

In recognition of these problems in the last several decades (United Nations, 1992), there has been a concerted effort to integrate biodiversity conservation in the management of native forest ecosystems (FAO, 2010). This has led to different approaches including greater emphasis on protecting biological diversity with complete exclusion of raw wood harvesting, a combination of protection of biological diversity and resource harvest, and the development of forest plantations to meet demand for raw wood supply (Sedjo and Botkin, 1997; FAO, 2010). Clearly, the critical first

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step in restoring the structure, function, productivity and native species diversity in degraded forest ecosystems is to halt degradation activities that prevent recovery (Lamb and Gilmour, 2003; Temperton et al., 2004). Here then is the conundrum: if management intervention is warranted to assist this recovery, how can one determine intermediate and measurable restoration goals for long lived ecosystems?

Restoration attempts often endeavour to recreate an ecosystem that is as close as possible to that which originally existed on a site, often referred to as the pre-clearing or pre-exploitation ecosystem (Sattler and Williams, 1999; Lamb and Gilmour, 2003; Doley et al., 2012). The implicit assumption in this restoration goal is that forest ecosystems have a fixed steady-state (Botkin and Sobel, 1975) and that that state is depicted by the pre-clearing ecosystem state. On the contrary, forest ecosystems are dynamic over time and space in relation to climate, fire and human effects, undergoing successional changes often over decades and hundreds of years (Bowler et al., 1976; Ash, 1988; Botkin, 1993; Hopkins et al., 1993; Turnbull, 1995; Lamb and Gilmour, 2003). Vegetation dynamics models have a demonstrated capacity to mimic these successional dynamics but rarely have there been suitable data to validate projections (Botkin, 1993; Shugart, 1998, 2002; Fyllas et al., 2007; Golicher and Newton, 2007; Ngugi and Botkin, 2011).

Callitris forest ecosystems were a major component of natural Australian ecosystems extending from the arid tropics in northern Australia to the Australian Alps in the south, and covering 40,278 km^2 (Australian National Resources Atlas, 2009). Over the last 200 years callitris forests have been subjected to significant anthropogenic and ecological disturbances that have dramatically altered their distribution (Harris and Lamb, 2004; Thompson and Eldridge, 2005), area extent, species composition and stand structure (Lunt et al., 2006; Whipp et al., 2012). Of the estimated 4.0 million ha pre-1750 extent (Australian National Resources Atlas, 2009) callitris forests now occupy around 2.6 million hectares scattered within predominantly agricultural landscapes (National Forest Inventory, 2008). Compared to eucalypt forests, callitris forests in Australia were preferentially cleared, because clearing was easier and they grew on more arable soils (Jurskis, 2009). Only 5% of the pre-1750 extent is protected for conservation within Protected Areas (Australian National Resources Atlas, 2009). Of the remaining 95%, active restoration of degraded values is required to sustainably balance resource utilisation and conservation of biological diversity.

Remnant callitris woodlands in Australia have been shown to provide habitat for over 350 vascular plant species and at least 32 fauna species that have been listed as threatened or rare in conservation status (Thompson and Eldridge, 2005). The variety of wildlife includes mammals (for example brush–tailed rock wallaby (*Petrogale penicillata*), eastern long-eared bat (*Nyctophilus corbeni*), squirrel glider (*Petaurus norfolcensis*), birds (for example glossy black-cockatoo (*Calyptorhynchus lathami*), painted honeyeater (*Grantiella picta*), grey falcon (*Falco hypoleucos*)), reptiles (including yakka skink (*Egernia rugosa*), golden-tailed gecko (*Strophurus taenicauda*)) and invertebrates such as *Lycosid* species among others (Nature Conservation Act, 1992; Thompson and Eldridge, 2005). The extent of loss of biodiversity in callitris forest ecosystems in Queensland is not fully documented (Kennedy, 2011) but the biodiversity potential and the added benefits of carbon storage in the mitigation of possible greenhouse induced climate change is evident. Consequently, management approaches are being sought to inform restoration of flora and fauna species diversity in these ecosystems (Kennedy, 2011).

Deficiencies in quantitative information and understanding of long-term growth dynamics of *Callitris–Eucalyptus* forest ecosystems are evident (Lunt et al., 2006; Whipp et al., 2012). Models exist for projecting the timber volume of white cypress pine (*Callitris glaucophylla*) in Queensland (Vanclay and Henry, 1988), and the growth dynamics of white cypress pine species under various thinning regimes in New South Wales (Ross et al., 2008). Although no calibrated and validated growth models exist for mixed species stands within callitris forest ecosystems, we contend that forest dynamics models provide one effective method of identifying realistic goals for restoration and defining the operational requirements for success (Golicher and Newton, 2007; Ross et al., 2008; Ngugi et al., 2011). This potential is based on the capacity of these models to simulate structural and species composition dynamics of an ecosystem in response to disturbances and management options (Shugart, 1984, 1998, 2002; Botkin, 1993; Golicher and Newton, 2007).

In the present study, we used a long-term dataset collected from permanent forest plots located in callitris forest ecosystems in Queensland and monitored for a period of over 70 years. Our aims were to calibrate and validate the Ecosystem Dynamics Simulator (EDS) to model the growth dynamics of uneven-aged mixed species stands, to analyse tree growth increments and estimate carbon storage within callitris forest communities. The model was calibrated using 81 plots and model validation was achieved by comparing projections against independent dataset observed from 40 permanent plots. We believe the results will be useful both for the callitris forests of Australia but also as an important example of how scientific information can be applied to aid conservation and vegetation management worldwide.

2. Materials and methods

2.1. Study area

The study covered the major callitris-containing State Forest reserves in southern Queensland: Barakula (285,212 ha), Western Creek (79,478 ha), Yuleba (71,304 ha) and Braemar (14,370 ha), located between latitudes 25.98° and 28.01° S and longitudes 149.28° and 151.20° E (Fig. 1). The regional climate is semi-arid to subtropical, characterised by hot humid summers and cool, dry winters. The mean annual rainfall is between 500 and 800 mm. Mean monthly temperature for these forest reserves is between 19 and 20 °C, with December and January as the hottest months, while July is the coldest. Monthly total rainfall and mean temperatures data for each reserve between 1936 and 2009, required for growth simulation, were obtained from the Australian Bureau of Meteorology (Fig. 2).

The topography in these areas is undulating to flat with a wide range of soils but mainly with distinct texture contrast. These soils have sandy to loamy A horizons extending to 30 cm depth over clay B horizons extending to 100–300 cm deep (Northcote et al., 1975). Surface soil characteristics for each plot (Table 1) were obtained from a soil sampling database for native forest permanent sample plots. Estimates of soil water holding capacities of the various soil texture types recorded on the plots were derived from regional soil descriptions made by the Queensland Department of Primary Industries (Harris, 2006). These soils are associated with different dominant tree species across the study area (Table 1).

2.2. Callitris forest ecosystems

Callitris forest ecosystem reserves on State land in Australia were originally designated to supply wood to the timber industry and harvested using single tree selection. These forests and woodland communities in Australia are characterised by 14 species of the genus *Callitris*, of which the most common is *Callitris glaucophylla* (white cypress pine). Although pure stands of *Callitris*