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The effect of silvicultural treatments on fire behaviour potential in radiata pine plantations of South Australia

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ABSTRACT

Large plantations of radiata pine (*Pinus radiata* Don) are susceptible to widespread damage from wildfires that compromise the sustainability of forest production and downstream industries. Fuel management zones, strategically located plantation areas where an intensive silvicultural prescription comprising multiple prunings and thinnings aim to constrain the onset and spread of crown fires, have been implemented for decades in Australia, although their effectiveness has yet to be quantified. We aimed to quantify the effect of these silvicultural-based fuel management prescriptions on fuel complex structure and fire behaviour potential. We characterised fuel complex structure associated with the various silviculture treatments and contrasted it with stands representative of the standard silvicultural regime. This information and local weather were used to estimate fire potential in fuel management zones and control stands.

We found the pruning and thinning fuel treatments significantly changed the plantation fuel complex, relocating ladder and canopy fuels to the surface layer, while breaking up fuel vertical continuity. Key beneficial effects such as the decrease in the vertical continuity of the fuel complex were found to be long lasting, whereas disadvantageous effects such as the increase in surface fuel load were short lived. The fuel management zone prescriptions resulted in significantly lower fireline intensity (e.g., first thinning reduced mean intensity during Very High Fire Danger days from 8613 to 760 kW m^{-1}) and likelihood of crowning (e.g., second pruning reduced the incidence of crowning during Very High Fire Danger days from 25% to nil) under a broad range of burning conditions. Analysis of the effect of silvicultural operations conducted in fuel management zones should not view each operation independently, but as a process where a succession of treatments transforms a highly "flammable" fuel complex into a low one early in the rotation.

1. Introduction

Radiata pine (*Pinus radiata* Don) is a commercially important timber species widely planted in mild, mesic, and oceanic climates with a worldwide plantation area exceeding 4 million ha (Lavery and Mead, 1998; CAB International, 2002), with significant estates in Chile, Australia, New Zealand, Spain, and South Africa (Mead, 2013). In Australia, radiata pine plantations are grown in 30–40 year rotations with the main aim of producing saw logs. A typical silvicultural system calls for a pruning operation between 5 and 10 years after planting and a subsequent second pruning reserved for more productive sites. Two to three thinning operations are prescribed between 13 and 30 years depending on site productivity, stand development and market demand. Variations in this silvicultural system occur in less intensively managed plantations where pruning may be absent and thinning treatments are fewer (Snowdon and James, 2008; Forest NSW, 2012; Mead, 2013). Herbicides are used to suppress competing vegetation and fertilizing operations may also be applied early in the rotation (Burdon, 2002; Snowdon and James, 2008).

Wildfires are a common threat to the sustainability of industrial radiata pine plantations in Australia and elsewhere (Alexander, 1998; Cameron et al., 2007; Fernandes and Rigolot, 2007). Plantations are commonly organized into large blocks, up to 15,000 ha in size, comprising a matrix of age-classes and stand structures. Large losses of plantation estates due to wildfire occur intermittently in south-east Australia (Geddes and Pfeiffer, 1981; Keeves and Douglas, 1983; Cruz and Plucinski, 2007), with a notable number of incidents in recent decades (Bartlett, 2012). Large plantation

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fires can lead to the disruption of forest yield to downstream industries, resulting in significant negative economic and social impacts to local communities.

The growth characteristics and silvicultural systems that characterize radiata pine plantations established on productive sites result in fuel complexes that can be exceptionally flammable, particularly in younger ages (Douglas, 1964; Williams, 1976; Fernandes and Rigolot, 2007). After canopy closure, the relatively high amount of biomass in the canopy layer coupled with the absence of self-pruning and accumulation of ladder fuels (e.g., dead bole branches and dead, suspended needles), high surface fuel accretion rates, and the development of a well-aerated litter layer lead to the formation of fuel complexes capable of sustaining high-intensity crown fire propagation, even under relatively mild burning conditions (de Ronde, 1980; Williams, 1978; Cheney and Richmond, 1980; Cruz and Plucinski, 2007). From canopy closure to the first silvicultural treatment, the tree crowns are intermingled and form a 3-dimensional, continuous fuel complex, with a homogeneous fuel distribution from the lower stem space to about 60% of the tree height (Williams, 1976). The key in reducing flammability in these stands is to break the vertical and horizontal fuel continuities through silvicultural interventions (Graham et al., 1999, 2004; Johnson and Peterson, 2005). An effective fuel treatment would modify canopy structure (e.g., increase canopy base height and reduce canopy bulk density), hence limiting the potential for the onset and subsequent development of high-intensity crown fires (Douglas, 1964; Agee and Skinner, 2005; Moghaddas and Craggs, 2007). Surface fuel modification, either by mechanical means (e.g., slash compaction (Burrows, 1980; Norman, 1985) or by prescribed burning, are also fuel management options for reducing the flammability of radiata pine plantations (Nicholls and Cheney, 1974; Woodman and Rawson, 1982; Burrows et al., 1989; Fernandes et al., 2008). For a review of fuel complex dynamics and fuel reduction techniques in Australian radiata pine plantations see Woodman and Rawson (1982) and Forest Fire Management Group (2007).

After the infamous events associated with the Ash Wednesday fires of 16 February 1983, where >23,000 ha of radiata pine plantation estate, out of a total burned area of 418,000 ha, burned in one afternoon in South Australia and Victoria (Keeves and Douglas, 1983; Rawson et al., 1983), fuel hazard reduction became a core component of large radiata pine plantation management. The concept of fuel management zones (FMZ; also called fuel modified zones or crown fire free zones) was established as part of this strategy. FMZs are 50–200 m wide stands strategically located along roads within a landscape scale network where the silvicultural prescription (e.g., high pruning followed by a thinning) and other fuel treatments (e.g., prescribed fire or slashing) were used to modify the fuel arrangement so as to create less flammable fuel complexes. The basis of the fuel treatments was to increase the separation between the surface and crown fuel layers and reduce the canopy continuity in order to lower the risk of crown fire development (Pfitzner et al., 1987; Keyes and O'Hara, 2002; Agee and Skinner, 2005; Bartlett, 2012). The aim of a FMZ is to develop a stand where fireline intensity and rate of spread are reduced, thereby allowing for: (i) safer and more effective fire suppression; and (ii) compartmentalization of the larger plantation estate to limit the occurrence of exceedingly large fires.

Typically, a FMZ in radiata pine plantations is based on expert opinion that takes into account the perceived local fire risk (Pfitzner et al., 1987). For example in South Australia, FMZ silviculture is defined by an initial low prune up to no less of 2.5 m when the stand has reached a mean tree height of 7.5 m and an age of 4–6 years. A second higher pruning to 6 m is conducted around the age of 7–9 years in high site quality stands. This is followed by an early first thinning that removes approximately 50% of the stock (Cruz, 2011). After this first thinning, other silvicultural operations (e.g., a second or third thinning) are aligned with the rest of the compartment.

Despite the recurring large investment in maintaining these fuel managed areas, their effectiveness in reducing fire potential over a range of fire danger conditions have not been formally quantified. Operational experience supports the view that their existence allows for a safer and more effective initial attack and enables safe undertaking of indirect suppression operations such as backburning (Luke and McArthur, 1978). However, an understanding of the way in which changes in fuel and stand structure directly and indirectly affect fire behaviour is lacking. The limits of effectiveness of FMZ treatments are also not known, including determining under what conditions FMZs are and are not effective in reducing fire behaviour potential. Additionally, the target reduction in fire behaviour potential that should be achieved with the treatment versus non-treated areas has not been defined.

Currently the ability to quantitatively assess both surface fire and crown fire potential exists through the use of fire behaviour simulation software tools (McHugh, 2006; Varner and Keyes, 2009; Andrews, 2014). Model systems are available to researchers and fire and land managers to enable the calculation of a number of fire behaviour characteristics that are relevant to gauging the effect of fuel modification on the "flammability" (or fire behaviour potential) of a particular fuel complex (Stephens, 1998; Fulé et al., 2001; Agee and Lolley, 2006; Kobziar et al., 2009; Vaillant et al., 2009; Stephens et al., 2012). Of particular relevance for radiata pine plantations is the Pine Plantation Pyrometrics (PPPY) model system designed to predict wildfire behaviour in Australian pine plantations (Cruz et al., 2008). This system comprises a suite of submodels that describe surface fire characteristics and crown fire potential (e.g., onset of crowning, type of crown fire and associated rate of spread) in relation to the fuel complex structure, fuel moisture content and wind speed. An operational implementation of PPPY is found in Amicus, a fire behaviour knowledge base system designed to enable fire behaviour predictions for fuel types found throughout Australia (Plucinski et al., 2017; research.csiro.au/amicus). Evaluation of key model components, such as the surface fire spread model, the model for crown ignition and the model for crown fire spread are reported respectively in Cruz and Fernandes (2008), Cruz et al. (2006b) and Cruz et al. (2005).

The objective of this study was to quantify the effectiveness of FMZ fuel treatments in South Australian radiata pine plantations under a range of fire weather conditions. In order to characterize the fire behaviour potential associated with fuel treatments in radiata pine plantations we quantified fuel complex structure and fuel moisture content in treated and non-treated (control) areas. We then used this information with historical weather and climate data to simulate free-burning fire behaviour characteristics using PPPY, to then contrast fireline intensity levels and the incidence of crowning activity between FMZ and non-treated areas.

2. Methods

2.1. Study area

The broader study area consists of the "Green Triangle" region of Australia which extends over south-eastern South Australia and south-western Victoria. It is home to a major forest plantation area with a well-established forest industry, with approximately 298,000 ha of industrial forestry, 56% of it comprised of radiata pine plantations (Parsons et al., 2006). The study was conducted in the western half of the Green Triangle, around Mount Gambier, South Australia (37.8°S, 140.8°E). The area is characterised by a