Forest Ecology and Management 405 (2017) 92–100

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Impact of mechanical thinning on forest carbon, fuel hazard and simulated fire behaviour in *Eucalyptus delegatensis* forest of south-eastern Australia

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ARTICLE INFO

Keywords:
Allometric equations
Forest carbon
CWD
Fuels
Wildfire
Eucalyptus delegatensis
Alpine Ash

ABSTRACT

Forest mega-fires have become a global phenomenon in recent decades including in south-eastern Australia where large areas of forest have been fire-killed with loss of human lives and property and impacting carbon sequestration and greenhouse gas emissions. The vast extent and impact of mega-fires has induced a re-evaluation of fuel reduction methods as a key management strategy in wildfire risk mitigation in many countries. This study investigated the impact of a commercial thinning in *Eucalyptus delegatensis* forest on fuel hazard, fuel loads and wildfire behaviour, eight years after completion of a bay and outrow thinning operation. At the stand level, thinning reduced overstorey tree stocking by more than 50%, increased canopy openness and stimulated the growth of retained trees. Thinning also encouraged the profuse regeneration of over 1000 saplings ha^{-1} of *E. delegatensis,* mostly in the outrows, compared with no sapling regeneration in unthinned forest. A system of additive biomass equations was developed to estimate total biomass and component biomass (stem wood, bark, branches and foliage) of individual trees. The aboveground tree carbon was 433 ± 49 Mg C ha^{-1} in unthinned forest and 322 ± 47 Mg C ha^{-1} in thinned forest. Thinning decreased surface fuel hazard ratings and fuel loads but had no significant effect on the mass of coarse woody fuels. Fire simulation under severe to extreme weather conditions, as occurred in the 2006/7 Great Divide Fires, indicated an almost 30% reduction in fireline intensity and about 20% reduction in the rate of spread and spotting distance in thinned forest compared with unthinned forest. This study indicates the potential of thinning to reduce wildfire severity and to increase the fire-survival of *E. delegatensis*.

1. Introduction

Tall open forests dominated by *Eucalyptus delegatensis* (R.T. Baker) or Alpine Ash occur in the cooler high altitude areas of south-eastern Australia in parts of New South Wales (NSW), Victoria, Australian Capital Territory (ACT) and Tasmania (Boland and Dunn, 1985). *E. delegatensis* is an obligate seeder with regeneration usually associated with periodic high intensity fires, and cold winter conditions to stratify seed prior to germination (Ashton 1981). Wildfires in the summer months of 2003, 2006/07, 2009 and 2013 burnt through about 50% of *E. delegatensis* forests in Victoria, including areas burnt two or three times within a ten year period (Fagg et al., 2013; Bassett et al., 2015). Those double and triple burns of *E. delegatensis* between 2003 and 2013 led to a series of publications suggesting that *E. delegatensis* forests are at risk of extirpation and conversion to non-forest vegetation (Bowman et al., 2013; Bowman et al., 2014). To prevent the disappearance of *E. delegatensis* from triple burnt areas of the Alpine National Park in Victoria, where no mature seed trees survived the fires, park managers re-seeded burnt areas of the park (Fagg et al., 2013; Bassett et al., 2015). Following this unprecedented step, Ferguson (2011) recommended that current seed collection and storage for *E. delegatensis* be increased, to ensure sufficient seed supply in the event of further extensive wildfires within the next 20 years, and to maintain the current distribution of *E. delegatensis* beyond 2050.

Wildfire occurrence and severity have been predicted to increase in south eastern Australia (Lucas et al., 2007) and it will require strategic and broad scale landscape management decisions to increase the resilience of *E. delegatensis* forests and reduce the risk of extirpation. Prescribed burning is widely used across Australian dry sclerophyll forests, open forests *sensu* Specht (1970), dominated by resprouting *Eucalyptus* species, to reduce hazardous fuel loads and fuel connectivity, and to reduce the severity of potential wildfires (McCaw, 2013). However, it is generally not applied in tall open forests such as those dominated by Mountain ash (*E. regnans*) or *E. delegatensis*, due to a short window of

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http://dx.doi.org/10.1016/j.foreco.2017.09.032
Received 24 April 2017; Received in revised form 8 September 2017; Accepted 12 September 2017

appropriate weather conditions suitable for burning, as these forests are situated in high rainfall zones with the mean annual rainfall range of 1000–1500 mm (Boland et al., 2006).

In these forests other forms of fuel modification such as thinning can be applied. Thinning (i.e. a conventional silvicultural practice to stimulate individual tree growth by increasing tree growing space), mastication (i.e. removal of ladder fuels) and thinning combined with prescribed burning are widely used fuel reduction treatments in North American forests, with proven results in reducing wildfire severity in treated areas (Stephens et al., 2009; Safford et al., 2012; Stephens et al., 2012). A number of these studies have shown that thinning treatments result in increased tree resilience, decreased fire severity and reduced greenhouse gas emissions. In Australian *Eucalyptus* forests thinning is a widespread land management practice and has been investigated mostly for silvicultural reasons (e.g. Turner et al., 2011) with lesser research emphasis on its application to modifying fuels and fire behaviour (e.g. McCaw et al. 1997). A recent study in dry *Eucalyptus* forests of south eastern Australia by Proctor and McCarthy (2015) indicated that, while thinning reduced fuel hazard and fire suppression difficulty during wildfire, an increase in woody debris due to thinning may lead to prolonged fire extinguishment efforts.

E. delegatensis has considerable commercial importance for the timber industry of Victoria and Tasmania (Turner et al., 2011). Because large areas of these forests are classified as native production forests, greenhouse gas emissions from them are required to be reported under Australian international commitments (Volkova et al., 2015). Despite this reporting requirement, only a few studies are available in the literature on *E. delegatensis* biomass (e.g. Dean et al., 2012 for old growth forest in Tasmania) on which to base accurate emissions estimates. Therefore, improving the knowledge base for more accurate carbon storage and fire-emissions estimates of these forests is important for Australia's international greenhouse gas emissions reporting obligations as well as for better accounting at the regional and State level.

In the late 2000 s, approximately 320 ha per year of *E. delegatensis* were thinned, yielding about 60,000–70,000 m^3 per year of largely non-sawlog and small sawlogs (Fagg, 2006). Our study in 2016 was based in a small area of these thinned forests to investigate the effect of commercial thinning in 2008–2009, on bushfire fuel hazard and carbon storage in aboveground biomass of *E. delegatensis* forests. Firstly, we assessed the impact of thinning on forest carbon, fuel hazard and fuel loads in thinned and unthinned (hereafter "control") treatments. Secondly, we ran fire simulations using these fuels data and the weather conditions from the 2006/07 Victorian Great Divide Fires, which burnt over 1 million hectares of land including > 100,000 ha of *E. delegatensis* forests (Flinn et al., 2008; Weston and Volkova, 2015). The fire simulations were used to model the severity and extent of fires with and without treatment and to assess the potential for benefits from treatment in terms of reduction in burnt area and fire intensity

2. Materials and methods

2.1. Study sites

The *E. delegatensis* study sites are located in the Big River State Forest on an elevated plateau above 1100 m above sea level, near Matlock in the state of Victoria, south eastern Australia (146.13E, −37.64S). The forests occur on deep clay-loam textured soils (ferrosols) developed on granitic bedrock and rainfall is around 1300 mm per year. The forests are even-aged regrowth from stand-replacing wildfires in 1939, that have not been subjected to fuel reduction burning or any fire disturbance since 1939 (77 years unburnt). An area of about 65 ha of this forest, north of the Warburton-Woods Point road, was thinned in 2008 and 2009 according to the Victorian Government's Native Forest Silviculture Guideline No. 13 (Fagg 2006). Trees were thinned using a bay and outrow method, with outrows of up to 7 m wide to allow for removal of larger trees and for areas of felling equipment, and wide retained bays of approximately 20 m width. This method results in about 24–27% of the stand being non-selectively removed in the outrows, while trees bays were thinned from below. Trees were usually not marked in advance, with the harvest operator selecting trees based on the target spacing and basal area. The thinning prescription called for a minimum retained basal area of 32 $m^2\ ha^{-1}$ made up of around 80–140 stem per hectare.

To estimate fuel hazard and loads, ten transects of 100 m length were established in January 2016, with five at the southern end of the thinned forest area and five in nearby unthinned forest (Fig. 1). In thinned forest areas the transects were oriented near perpendicular to the 6 m wide strips where trees had been removed (Fig. 1) and each transect was marked at 25 m intervals with metal pegs to clearly define a sample line.

2.2. Sampling design

2.2.1. Visual fuel hazard assessment and fuel sampling

The Overall Fuel Hazard Assessment Guide [OFHG] (Hines et al., 2010) was used to categorize the fine, near-surface and elevated fuels into hazard ratings "Low", "Moderate", "High", "Very High" and "Extreme". For the analysis, fuel hazard ratings were converted from categorical to ordinal values, where 'Low" = 1 and "Extreme" = 4.

To improve the accuracy of the mass estimate of fuels, their mass was determined from destructive sampling along each transect, rather than extracted from the conversion table in the OFHG (Volkova et al., 2016). Litter (i.e. fallen leaves, twigs, bark, fruits, small branches with diameter < 2.5 cm and partly-decomposed organic matter) was sampled as composites from both sides of the 100 m transect at 25 m intervals (0 m, 25 m, 50 m, 75 m and 100 m) using a circular fuel ring of 0.1 m^2. Litter samples were sorted into the following three size categories in the laboratory; duff (i.e. well decomposed organic matter sieved to < 0.2 cm fraction), fine (i.e. leaves and twigs < 0.6 cm) and twigs (d = 0.6–2.5 cm). Height and percent cover of shrub fuels, within 5 m radius of the five assessment points, were also recorded. Litter was oven dried to 60 °C for 48 h and reported on a dry weight basis.

2.2.2. Trees

Trees were measured within 3 m of each side of the 100 m transect, comprising a 0.06 ha sample plot. Diameter overbark at the breast height 1.3 m (DBH) and tree status (live or dead) was recorded for all trees with DBH > 5 cm. For trees with DBH > 20 cm, bark thickness was measured with a 2.5 mm bark syringe inserted to the point of resistance by the sapwood at 3 points around the stem at 1.3 m height. Tree height to the top of the canopy was measured using a Vertex III laser rangefinder (Haglof, Sweden) by taking the average of three measurements per tree. Saplings of *E. delegatensis* (DBH < 5 cm) were counted within each 0.06 ha plot and a subset of trees ranging from 2 cm to 5 cm DBH was destructively sampled, oven dried and weighed.

2.2.3. CWD

The mass of coarse woody debris (CWD) diameter ≥2.5 cm was estimated along the entire length of each 100 m transect by the line intersect method of Van Wagner (1968). Each piece of CWD intersecting the transect was assigned to one of two classes, sound – intact wood or just beginning to decay, or rotten – substantially decayed wood. CWD was also separated into diameter classes to create dead fuel moisture timelag categories (i.e. diameter 2.5–7.5 cm = 100 h fuel, > 7.5–22.5 cm = 1,000 h fuels and > 22.5 cm = 10,000 h fuels) following the method of Sikkink and Keane (2008). Mass estimates assumed a wood density of 600 $kg\ m^{-3}$ for sound and 300 $kg\ m^{-3}$ for rotten CWD.

2.3. Estimating forest carbon pools

Biomass estimates were separated into the following carbon pools: