Forest Ecology and Management 288 (2013) 21–30

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

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

Effect of thinning, pruning and nitrogen fertiliser application on light interception and light-use efficiency in a young *Eucalyptus nitens* plantation

David I. Forrester [a,b,*], John J. Collopy [a], Christopher L. Beadle [b,c,d], Thomas G. Baker [a,b]

[a] Department of Forest and Ecosystem Science, The University of Melbourne, 500 Yarra Boulevard, Richmond, Victoria 3121, Australia
[b] Cooperative Research Centre for Forestry, Private Bag 12, Hobart 7001, Australia
[c] CSIRO Ecosystem Sciences, Private Bag 12, Hobart, Tasmania 7001, Australia
[d] Tasmanian Institute of Agricultural Research, Private Bag 54, Hobart, Tasmania 7001, Australia

ARTICLE INFO

Article history:
Available online 15 December 2011

Keywords:
Defoliation
Leaf area
PAR
MAESTRA model

ABSTRACT

Thinning, pruning and fertiliser application are used by forest managers to increase growth rates of retained trees and to improve log quality. Understanding whether growth responses are due to changes in light interception, light-use efficiency (LUE) or both, and whether they are subject to treatment interactions could assist the design of more productive and light-use efficient plantations. Two levels each of thinning, pruning and nitrogen fertiliser treatments were applied in factorial design to a *Eucalyptus nitens* plantation in south-eastern Australia at age 3.2 years, and responses measured to age 8.1 years. Treatments were: unthinned, or thinned from ca. 900 to 300 trees ha^{-1}; unpruned, or 50% of the live crown length pruned of the largest-diameter 300 potential sawlog crop trees ha^{-1}; and nil, or 300 kg ha^{-1} N fertiliser. Light-use efficiency was defined as annual above-ground biomass (AGB) or stem-wood growth per unit of absorbed photosynthetically active radiation (APAR). Growth responses were associated with changes in both light interception and LUE. There were interactions between thinning and pruning: thinning effects were weaker for APAR, and stronger for LUE for pruned than unpruned trees. During the first year after treatment, thinning increased AGB growth of the 200 largest-diameter sawlog crop trees (SCT$_{200}$) by 34% (7.1–9.5 Mg ha^{-1} year^{-1}), APAR$_{200}$ by 24% (0.77–0.95 GJ m^{-2} year^{-1}), and LUE$_{200}$ by 13% (0.93–1.05 g MJ^{-1}); fertiliser application increased AGB$_{200}$ growth by 23% (7.4–9.1 Mg ha^{-1} year^{-1}), APAR$_{200}$ by 6% (0.83–0.89 GJ m^{-2} year^{-1}), and LUE$_{200}$ by 13% (0.93–1.05 g MJ^{-1}). Thinning and fertiliser application both increased APAR$_{200}$ by increasing tree leaf areas, and increases in LUE were associated with increases in photosynthesis. Pruning reduced tree leaf area by about 75%, but AGB$_{200}$ growth and APAR$_{200}$ were only reduced by 12% (8.8–7.7 Mg ha^{-1} year^{-1}) and 37% (1.06–0.67 GJ m^{-2} year^{-1}), respectively, and LUE$_{200}$ increased by 36% (0.84–1.14 g MJ^{-1}) during the first year after treatment. Pruning increased LUE by removing the least efficient lower canopy foliage, and by increasing the efficiency of the remaining foliage. This study shows how changes in stand structure, crown architecture and tree nutrition can be used to alter APAR and LUE, and improve our understanding of responses to silvicultural interventions in eucalypt plantations managed for solid-wood products.

1. Introduction

Plant growth can be described as a function of resource supply, the proportion of resources captured and the efficiency with which they are used (Monteith, 1977; Binkley et al., 2004; Richards et al., 2010). Plant growth is also a function of carbon (C) partitioning when examining a specific component of production, such as wood or above-ground biomass (Binkley et al., 2004). Light interception is usually the main determinant of plant growth which at the stand level generally increases linearly with absorbed photosynthetically active radiation (APAR); the slope (ε) of this relationship provides a measure of light-use efficiency (LUE; e.g. Mg of above-ground biomass production MJ^{-1}) (Monteith, 1977; Landsberg and Waring, 1997). In forests, differences in APAR, LUE and C partitioning can all account for significant proportions of growth responses to increasing resource availabilities (Stape et al., 2008; Binkley, 2009; Binkley et al., 2010; Ryan et al., 2010). Forest managers can accelerate growth and improve wood quality by manipulating APAR and LUE using treatments such as thinning, pruning and fertiliser application.

Thinning can significantly reduce leaf area index (LAI) and stand APAR, but at the level of the retained individual trees, leaf area and

---

* Corresponding author. Present address: Institute of Silviculture, Freiburg University, Tennenbacherstr. 4, 79108 Freiburg, Germany. Tel.: +49 761 203 8623; fax: +49 761 203 3781.

E-mail addresses: davidif@unimelb.edu.au (D.I. Forrester), jcollopy@unimelb.edu.au (J.J. Collopy), Chris.Beadle@csiro.au (C.L. Beadle), tgbaker@unimelb.edu.au (T.G. Baker).

0378-1127/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.foreco.2011.11.024

APAR increase in response to the more open stand structure (West and Osler, 1995; Medhurst and Beadle, 2005). Increases in resource availability following thinning can also lead to faster leaf-level rates of photosynthesis (Medhurst and Beadle, 2005). This may increase the LUE of retained trees, depending on the availability of nutrient and water resources (West and Osler, 1995). Thinning often encourages crown expansion (Medhurst and Beadle, 2001) and the larger branches produced to support these crowns can reduce the quality of the log. Pruning is therefore used to directly modify crown architecture and thereby increase wood quality. By removing the lower and relatively inefficient sections of the crown, pruning can instantaneously increase LUE (Linder, 1985). Pruning can also result in increased rates of photosynthesis in the retained upper canopy (Forrester et al., 2010b), which may further increase LUE. Growth responses to fertiliser application often involve increases in LAI (Smethurst et al., 2003) and hence APAR (Sampson and Allen, 1998; Balster and Marshall, 2000). Increases in LUE have also been observed (Landsberg and Wright, 1989; Gholz et al., 1991; Martin and Jokela, 2004; Trichet et al., 2008), which may result from increases in above-ground C partitioning (Giardina et al., 2003) and increased rates of photosynthesis (Smolander and Oker-Blom, 1989; Green and Mitchell, 1992; Clearwater and Meinzer, 2001).

Thinning, pruning and fertiliser application are often done simultaneously in plantations. Since each influences stand structure, light interception and LUE via different mechanisms, there may be interactions between these treatments. Furthermore, since thinning and pruning focus on specific size classes, an individual tree approach to examine these mechanisms may be preferable, because different size classes cannot be assumed to respond in the same way to these treatments (Binkley et al., 2010). Scale is also important because the relationship between APAR and leaf area varies between the tree and stand levels (Binkley et al., 2013). At the stand level, a range of patterns have been observed. Stand APAR can follow a negative exponential relationship with LAI, where increasing LAI leads to more shading and a declining marginal gain in APAR (Hocker, 1982; Sampson and Allen, 1998). However relationships can also be linear (Vose and Swank, 1990; Will et al., 2005), or not significant such that stand APAR may stay relatively constant as LAI increases (Brown and Parker, 1994). In contrast, at the single tree level, relationships between tree leaf area and APAR are linear or even (positively) exponential (Binkley et al., 2013). The slope of this relationship can vary with stand structure, age, resource availability and species (Binkley et al., 2010, 2013; Gspaltl et al., 2013).

Little attention has been given to the effect of thinning and pruning on relationships between individual tree growth, APAR and LUE, as well as their interaction with fertiliser application. The aim of this study was to examine how these silvicultural treatments and their corresponding effects on crown architecture and stand structure might influence these relationships in a *Eucalyptus nitens* plantation that was treated at age 3.2 years. We hypothesised that (1) thinning and fertiliser application would both increase individual tree growth by increasing the APAR and LUE of individual trees; (2) pruning would reduce growth by reducing APAR but that LUE would increase, thereby limiting the reduction in growth relative to the reduction in APAR; (3) thinning would increase and fertiliser application decrease the APAR per unit leaf area.

2. Methods

2.1. Site characteristics

The experiment was located 1.5 km south-west of Carrajung, Victoria, Australia (38°23′ S, 146°41′ E) at an elevation of about 610 m and with a mean annual rainfall of about 1124 mm. Mean maximum temperature in January is 22.3 °C and mean minimum temperature in July is 3.9 °C. The soils have a gradational texture profile, with silty loam to clay loam A-horizons and light clay to medium clay B-horizons, and are classified as Humose-Acidic, Dystrophic, Red or Brown Dermosols (Isbell, 1998), Gn4.11 or Gn4.71 Primary Profile Form (Northcote, 1979). In June 2003 *E. nitens* (Deane and Maiden) was planted at a spacing of 2.5 × 4 m (1000 trees ha^{-1}). Fertiliser was applied to individual trees 2 and 12 months after planting, a total equivalent of 170 N, 110 P and 50 K kg ha^{-1}. More detail about the site is provided in Forrester et al. (accepted for publication-a).

2.2. Experimental design

The experiment was a 2 × 2 × 2 factorial design containing two levels each of fertiliser application, thinning and pruning. Plots contained nine trees × eight rows, with about 70 trees (0.07 ha), not including a surrounding buffer row. This was arranged in a randomised block design in three replicate blocks. Fertiliser treatments included unfertilised plots that received no additional fertiliser after 12 months (F0) and fertilised plots that received 300 kg N ha^{-1} at age 3.2 years (F1).

Plots were either unthinned (T0) or thinned to 300 trees ha^{-1} at age 3.2 years (T1). Retained and pruned trees were selected immediately prior to treatment, when trees were about 9 m tall, based on form (single-stemmed, straight, vertical), size (larger diameters) and spacing (uniformity). Initial stand density, basal area, volume, total above-ground biomass (AGB) and LAI at age 3.2 years were 903 trees ha^{-1}, 10.4 m^2 ha^{-1}, 38.9 m^3 ha^{-1}, 29.5 Mg ha^{-1} and 3.1, respectively (Forrester et al., accepted for publication-a). Thinning to 300 trees ha^{-1} resulted in the retention of 32% of the trees, 39% of basal area, 41% of volume, 44% of AGB and 45% of LAI. The largest-diameter 200 trees ha^{-1} of these trees in both treatments are referred to as potential sawlog crop trees (SCT_{200}).

Trees were either unpruned (P0) or pruned to retain the upper 50% of the green crown length (25% of the leaf area) at age 3.2 years (P1). Half of the plots contained P1 trees and the other half contained no P1 trees. The average pruning height was about 4.5 m. When the trees were pruned the live-crown height (h_L; m), where the lowest main-crown live branch joined the stem, was about 1 m. All trees retained in T1–P1 plots were pruned (300 trees ha^{-1}); in T0–P1 plots only the 300 selected trees ha^{-1} were pruned. At age 4.7 years, P1 trees were pruned up to 6.5 m to be consistent with commercial practice.

2.3. Measurements and modelling

Tree diameters (at 1.3 m height, d), total heights (h_T; m) and live-crown heights (h_L) were measured at ages 3.4, 4.4, 5.1, 6.3 and 8.1 years. Tree leaf area, crown radii, stem-wood mass (now referred to as wood mass) and total AGB were estimated using allometric equations (based on d, h_T and age) developed from 59 trees destructively sampled at ages 3.2, 4.0 and 6.0 years (Forrester et al., accepted for publication-a). Different equations were required for each pruning treatment while thinning and fertiliser application had no influence on these equations that were not accounted for by d, h_T and age.

The absorption of photosynthetically active radiation by individual tree crowns was estimated using the MAESTRA model (see Wang and Jarvis, 1990a,b; Medlyn, 1998). This three-dimensional model estimates absorbed photosynthetically active radiation (APAR) while calculating the penetration of radiation through the canopy using the radiative transfer model of Norman and Welles (1983) as a sub-model. Direct and diffuse radiation are treated separately, with the transmission of the latter modelled using the method of Norman (1979). The beam fractions of radiation are cal-