Forest Ecology and Management 259 (2010) 1819–1835

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Growth and physiological responses to silviculture for producing solid-wood products from *Eucalyptus* plantations: An Australian perspective

David I. Forrester[a,b,*], Jane L. Medhurst[a,c], Matthew Wood[a,d], Christopher L. Beadle[a,e,f], Juan Carlos Valencia[a,g]

[a] Cooperative Research Centre for Forestry, Private Bag 12, Hobart, Tasmania 7001, Australia
[b] Department of Forest and Ecosystem Science, The University of Melbourne, 500 Yarra Boulevard, Richmond, VIC 3121, Australia
[c] School of Plant Science, University of Tasmania, GPO Box 252-55, Hobart, Tasmania 7001, Australia
[d] Forestry Tasmania, 79 Melville Street, Hobart, Tasmania 7000, Australia
[e] CSIRO Sustainable Ecosystems, Private Bag 12, Hobart, Tasmania 7001, Australia
[f] Tasmanian Institute of Agricultural Research, GPO Box 252-54, Hobart 7001, Australia
[g] INFOR, Fundo Teja Norte, Casilla 385, Valdivia, Chile

ARTICLE INFO

Article history:
Received 10 March 2009
Received in revised form 16 August 2009
Accepted 24 August 2009

Keywords:
Pruning
Thinning
Fertiliser
Leaf area index

ABSTRACT

We review the main silvicultural interventions used when managing *Eucalyptus* plantations for solid-wood products, including fertilising, pruning and thinning. The growth of a plantation and the quality of the wood produced is closely linked to the development of the tree crowns. These silvicultural interventions influence crown dynamics and can interact with each other, as well as the species, site and the age at which they are applied. This review focuses on the growth and physiological responses observed in *Eucalyptus* plantations, particularly from an Australian perspective. The implications for wood quality, while given some attention, are beyond the scope of this review.

1. Background

Fast-growing commercial plantations of *Eucalyptus* species play an important role worldwide to satisfy both an increasing demand for wood and the provision of environmental services (Ekström, 2005; Arroja et al., 2006). The total area of *Eucalyptus* plantations now exceeds 19M ha (Iglesias and Wilstermann, 2008) of which about 1.2M ha have sawlog potential (FAO, 2005). The majority of this global resource is distributed in about one dozen countries and owned by either a few large corporations or numerous small-holders (Cossalter and Pye-Smith, 2003; Montagu et al., 2003; FAO, 2005). The resource mainly consists of extensive mono-specific plantations. Genetically improved material is planted at 800–2000 trees ha^{-1}. Most plantations are intensively managed, remain unthinned, and in sub-tropical and tropical environments are harvested in as little as 6 years. Average annual growth rates of wood volume can reach 70 m^3 ha^{-1} $year^{-1}$ (Cossalter and Pye-Smith, 2003; Nutto et al., 2006).

Approximately 35% of this resource is in the temperate and mediterranean zones of countries such as Argentina, Australia, Chile, Portugal and Spain: *Eucalyptus globulus* and *Eucalyptus nitens* are the most common species planted and are considered to have the most potential to produce high quality sawlogs; the other 65% is in sub-tropical and tropical zones of countries such as Argentina, Australia, Brasil, China, India, South Africa, Uruguay and Vietnam: *Eucalyptus cloeziana, Eucalyptus dunnii, Eucalyptus grandis, Eucalyptus pellita, Eucalyptus pilularis, Eucalyptus saligna, Eucalyptus urophylla, Corymbia* species and their hybrids are the most commonly planted species (Medhurst et al., 2001; Cossalter and Pye-Smith, 2003; Montagu et al., 2003; INFOR, 2004; ÓNeill, 2004; Nutto and Touza-Vázquez, 2004; Washusen et al., 2004; Marcó, 2005; Volker et al., 2005; Yan and Minsheng, 2005; CSIR, 2006; ENCE, 2006; Lima et al., 2006). The majority of this resource is managed for products other than solid wood, mainly pulpwood and firewood. For example in Australia, the eucalypt plantation area is currently 0.88M ha (Gavran and Parsons, 2008). However, only about 15% of the resource is managed for appearance and structural grade timbers (Nolan et al., 2005).

Eucalypt plantations are also managed for solid wood in other countries either because pulpwood production is not technically and/or economically feasible or to replace hardwood sawlogs that can no longer be supplied from natural forests (Montagu

* 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 address: davidif@unimelb.edu.au (D.I. Forrester).

0378-1127/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.foreco.2009.08.029

et al., 2003; Ronggui et al., 2003; Donnelly and Flynn, 2004; INFOR, 2004; Nutto and Touza-Vázquez, 2004; Valencia and Cabrera, 2005; Nutto et al., 2006). Predicted market opportunities for appearance and structural eucalypt plantation-grown timber have also motivated some growers to manage their plantations for either pruned sawlogs/veneer logs suitable for high-value solid- and/or engineered-wood products (Ronggui et al., 2003; Donnelly and Flynn, 2004; INFOR, 2004; Flynn, 2005; Nolan et al., 2005; Venn, 2005; Nutto et al., 2006). Examples of successful market experiences with eucalypt plantation-grown timber are represented by Lyptus® in Brasil; Grandis® and Vida Grandis™ in Argentina; Eucanova® in Uruguay; Ibersilva-Plantation Wood® in Spain and EcoAsh™ in Australia (Flynn, 2005; ENCE, 2006; e-grandis, 2007; FEAPlantations, 2007).

Compared to industrial eucalypt plantations for pulpwood, those managed for solid wood in Australia are in an earlier state of development. This is related not only to current market maturity and size, and the need to develop industries based on such a resource, but also a requirement for new applied silvicultural and processing technologies (Flynn, 2005; Baker and Volker, 2006). These are crucial issues that define economic viability, financial risk and certainty for investment in this sector.

This review focuses on the silvicultural interventions of fertilising, pruning and thinning, and how they interact with each other, the site and the age at which they are applied. Each of these interventions can influence crown architecture and growth dynamics, which in turn strongly influence the quality and quantity of wood produced in eucalypt plantations. Crown architecture plays a large role in driving productivity because it determines how the foliage of a tree is displayed and the extent of light interception by the crown. The size and vigour of tree crowns influence the amount of carbon fixed and hence the quantity of wood produced. As a tree grows taller and the canopy rises, dead branches are left behind and wood quality is influenced by the processes of branch senescence, ejection and occlusion (Montagu et al., 2003). The rates at which the processes of crown development and rise occur depend on the site quality and can be influenced by fertiliser application. The quantity of high-quality or 'clear' wood (wood free of value-limiting defects such as knots and decay) produced can be increased through the manipulation of the canopy by pruning and thinning. Both of these interventions have the potential to significantly influence the light environment and hence performance of a plantation (Fig. 1). Variability between

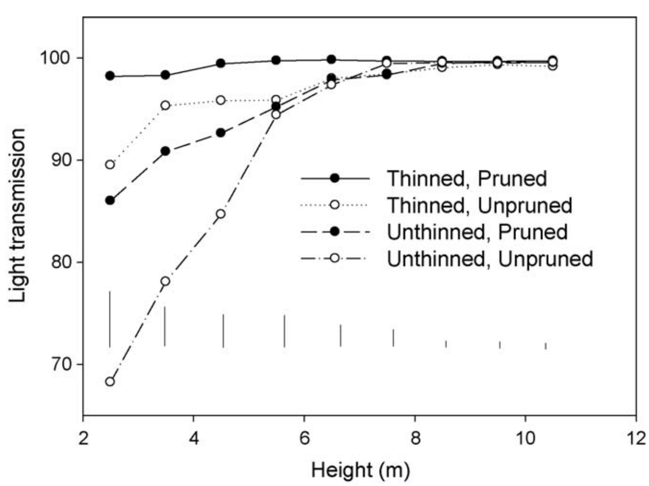

Fig. 1. Vertical light profiles in a *Eucalyptus nitens* stand near Carrajung, Victoria, Australia, thinned (from 930 to 300 trees ha^{-1}) and pruned (half of the green crown length) at age 3.3 years. Light transmission is the percentage of photosynthetically active radiation above the canopy. Error bars are standard errors of difference (Forrester, unpublished data).

species, sites, costs of inputs and the value of products means that there is no general optimal fertilising, pruning and thinning regime. However, an understanding of the mechanisms behind the growth and physiological responses to these treatments can facilitate the development of specific regimes for specific sets of conditions. The implications for wood quality, while given some attention, are beyond the scope of this review.

2. Fertiliser, nutrient uptake, and canopy development

The eucalypt species used in plantations are capable of rapid early growth but this is accompanied by high demand for nutrients and water and thus potential for their depletion. Decisions about appropriate fertilising regimes in plantations should be linked to knowledge of nutrient dynamics and how this depends on the stage of development. The demand for, and distribution and storage of, nutrients can be divided into two major phases (Grove et al., 1996). The first phase occurs prior to canopy closure when the accumulation of nutrients increases up to a maximum that is reached just prior to or around the time the canopy closes (Cromer et al., 1993b; Misra et al., 1998). Canopy closure can be linked with maximum rates of biomass production (Ryan et al., 1997). The nutrients captured are largely used to build the canopy and there is little redistribution due to leaf senescence as rates of litterfall are low. Growth may be limited by nutrient and water availability as the roots have not fully explored the soil profile. Therefore it is during this phase that trees are most responsive to fertiliser application and weed control, as well as the cultivation and residue-management practices used prior to planting (Grove et al., 1996).

The development of a plantation is closely linked to the growth and size of its tree crowns, which can be described using the leaf area index (LAI: foliage area per unit land area: Beadle, 1997); the LAI for eucalypt plantations varies between about two and nine (Beadle, 1997). Generally LAI is higher in cooler than warmer climates, where canopy photosynthesis may be optimised at lower LAI and a higher proportion of carbon allocated to the stem (Beadle, 1997). Maximum LAI and thus the initial rapid growth phase ahead of canopy closure may occur within the first year for *E. grandis* (Cromer et al., 1993a) or within about 3–6 years for *E. globulus* and *E. nitens* (Beadle et al., 1995; Forrester et al., 2010-a). Significant growth responses to fertiliser application are commonly observed during this period (McKimm and Flinn, 1979; Cromer et al., 1981, 1993a; Bennett et al., 1996; Duncan and Baker, 2004; Hubbard et al., 2004; Stape et al., 2006; Turnbull et al., 2007b). Responses are associated with increases in LAI (Cromer et al., 1993a; Bennett et al., 1997; Smethurst et al., 2003; Hubbard et al., 2004; Turnbull et al., 2007b), resource-use efficiency (Binkley et al., 2004), and a shift in carbon partitioning from below- to above-ground (Misra et al., 1998; Giardina et al., 2003). The responses to fertiliser application depend on species, site characteristics and silvicultural practices such as cultivation, weeding, thinning and pruning. Growth responses will probably be lower when other resources such as soil moisture or other nutrients are also limiting to growth. For example the growth increment of *E. grandis* and hybrids with *E. urophylla* in Brasil was higher in fertilised plots during wet seasons than dry seasons (Stape et al., 2006).

During the second phase, following canopy closure, the LAI may stabilise for a short period and then decline (Almeida et al., 2008; du Toit, 2008). Current annual increments will also typically decline (Ryan et al., 1997). Nutrient accumulation is largely due to increasing wood mass, which requires fewer nutrients than canopy development, so the rate of nutrient accumulation slows. Fine roots will have explored most of the soil and nutrient cycling processes develop (Attiwill, 1979; Grove et al., 1996). Inter-tree