ANTONIO CARLOS FERRAZ FILHO

MANAGEMENT OF EUCALYPTUS PLANTATIONS FOR SOLID WOOD PRODUCTION

Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Engenharia Florestal, área de concentração em Ciências Florestais, para obtenção do título de Doutor.

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LAVRAS - MG

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RESUMO

Foram estudados os efeitos de diferentes regimes silviculturais de poda e desbaste em talhões de *Eucalyptus* para fins de produção de madeira sólida. Enquanto a poda de galhos permite a melhoria na qualidade da madeira por meio da eliminação de nós, o desbaste visa reduzir o efeito da competição entre as árvores permitindo que os melhores indivíduos do talhão cresçam a elevados diâmetros. O presente trabalho é constituído de quatro artigos. O primeiro artigo é composto por uma revisão de literatura abordando o manejo do *Eucalyptus* por meio da talhadia com remanescentes. Este tipo de manejo mantém um baixo número de árvores de alto fuste no talhão após o primeiro corte, conduzindo simultaneamente as árvores cortadas por meio de regeneração por talhadia. Por ser um sistema relativamente simples e por permitir a diversificação do rol de produtos advindos de um mesmo talhão, possui aptidão para ser aplicado por pequenos e médios produtores florestais. Os artigos 2 e 3 lidam com a questão da poda em dois cenários distintos, aplicação após o fechamento do dossel em um talhão adensado e antes do fechamento do dossel em um talhão com baixo número de árvores. A resposta em crescimento do talhão foi distinta para os dois estudos. No estudo onde a poda foi aplicada após o fechamento do dossel, foi possível atingir altura de poda de até 70% da altura total da árvore (removendo cerca de 60% da porção inferior da copa viva) sem grandes prejuízos ao crescimento diamétrico e nenhum efeito no crescimento em altura. Para o estudo onde a poda foi aplicada no talhão antes do fechamento do dossel, a remoção de 40% da porção inferior da copa viva causou redução tanto no crescimento diamétrico quanto na altura das árvores. O quarto artigo abordou os efeitos de diferentes densidades iniciais de plantio e regimes de desbaste em talhões de *Eucalyptus* em oito experimentos. O crescimento em diâmetro antes do fechamento do dossel foi mais acelerado nos tratamentos com baixo número de árvores plantadas, sendo o maior crescimento obtido em densidades abaixo de 617 árvores por hectare (atingindo 6 cm por ano). A proporção de mortalidade antes da aplicação do desbaste também foi mais baixa nos tratamentos com baixo número de árvores plantadas. O regime de desbaste que apresentou maior evolução diamétrica foi o de desbaste aos 2,5 anos com 150 árvores remanescentes. Neste regime, valores de até 40,5 cm de diâmetro médio foram encontrados aos 11,5 anos de idade. Se for desejada uma maior produção volumétrica do talhão e não apenas a obtenção de toras de elevados diâmetros, regimes de desbaste menos intensivos com rotações mais longas devem ser considerados.

Palavras-chave: Manejo florestal. Desbaste. Poda. Produção de madeira sólida.

ABSTRACT

The effects of different silvicultural regimes (pruning and thinning) on *Eucalyptus* stands for the production of solid wood products were studied. While pruning enhances wood quality by eliminating knots, thinning aims to reduce between tree competition effects allowing that the best individuals grow to large diameters. The present work is composed of four articles. The first one is a review paper on *Eucalyptus* management through coppice with standards. This type of management maintains a low number of seedling trees in the stand after the first cut, grown simultaneously with the harvested trees through regeneration by coppice. Since it is a relatively simple system and by allowing diversification of wood products from a same stand, it has potential to be applied by small and medium forest owners. Articles 2 and 3 are related to pruning in two distinct scenarios, application after canopy closure in a crowded stand and before canopy closure in a low density stand. Stand growth response was distinct for both studies. When pruning was applied after canopy closure, it was possible to reach pruning heights of 70 % of total tree height (removing about 60 % of lower green crown) without major effects on diameter growth and with no effects on height growth. When pruning was applied before canopy closure, removing 40 % of lower green crown caused reduction on diameter and height growth. The fourth study related to the effects of different initial planting densities and thinning regimes in *Eucalyptus* stands from eight trials. Diameter growth prior to canopy closure was accelerated in treatments with low number of planted trees, being highest for densities below 617 trees per hectare (reaching 6 cm per year). Mortality proportion prior to thinning intervention was also lower in the treatments with low number of planted trees. The thinning regime which presented the highest diametrical evolution was of thinning at age 2.5 years with 150 trees per hectare remaining. In this regime, mean diameter values of up to 40.5 cm were found at age 11.5 years. If a higher volumetric yield is expected from the stand and not just the production of large diameter logs, less intensive thinning regimes coupled with longer rotation lengths should be considered.

Keywords: Forest Management. Thinning. Prunning. Solid wood production.

SUMÁRIO

PRIMEIRA PARTE

1 INTRODUÇÃO

Por produtos de madeira sólida, entendem-se os compensados, laminados, madeira serrada e produtos remanufaturados, como pisos, portas, moldes, móveis, entre outros. Florestas para fins de celulose e energia têm como objetivo a maximização do volume do talhão, pois os diâmetros mínimos exigidos para tais fins (geralmente 7 cm) não são restritivos, ou seja, até certos limites biológicos, quanto mais árvores no talhão maior o rendimento volumétrico. Diferentemente, as florestas com fins de produção de madeira sólida possuem diâmetros mínimos mais restritivos, tornando assim, a essência de seu manejo à regularização do estoque do talhão por meio de desbastes.

Para a produção de madeira sólida, é costumeiro o emprego de dois distintos regimes de manejo, o “utility” e o intensivo. O manejo “utility” possui o objetivo maior de maximizar a produção volumétrica do talhão, tanto de produtos de madeira sólida quanto produtos energéticos ou celulósicos, daí o nome do regime de manejo. O manejo florestal conceituado intensivo possui a característica de maximizar a produção das árvores do corte final, e não do talhão como um todo. Isto é atingido por meio da remoção de quaisquer fatores que reduzam o crescimento das árvores finais, por meio das operações silviculturais de fertilização, que removem empecilhos ao crescimento relativo a problemas do solo, e desbaste e controle de ervas daninhas que removem a estagnação do crescimento devido à competição.

Considerando as amplas opções disponíveis para a condução de plantios para produtos sólidos, bem como a incipiente experiência brasileira com o gênero *Eucalyptus* empregados neste tipo de manejo, experimentos que avaliem o comportamento de plantios de *Eucalyptus* submetidos a diferentes regimes de desbaste e poda são de extrema importância para garantir a viabilidade do empreendimento florestal.

O objetivo com as pesquisas realizadas para esta tese foi avaliar diferentes fatores que são inerentes ao manejo florestal para produção de madeira para produtos sólidos, abordando aspectos de condução de um talhão florestal por meio de podas e desbastes.

O conteúdo deste material é dividido em duas partes. Na primeira parte é apresentado o referencial teórico sobre o tema bem como as conclusões gerais obtidas no trabalho como um todo. A segunda parte e composta por quatro artigos. O primeiro artigo é uma revisão de literatura sobre o manejo do eucalipto por meio de talhadia com remanescentes. Este tipo de manejo permite a obtenção tanto de madeira de pequenas dimensões em ciclos curtos como madeira de maiores dimensões em ciclos mais longos do mesmo talhão. Os artigos 2 e 3 abordam o tema da poda em plantios de eucalipto. O quarto e último artigo apresentam resultados e tendências de produção para vários diferentes regimes de desbaste em eucalipto.

2 REFERENCIAL TEÓRICO

Segundo estimativas do International Tropical Timber Organization, ITTO (2009) e FAOSTAT (2011), o Brasil produziu cerca de 15,5 milhões de metros cúbicos de madeira serrada tropical em 2009, sendo que 93% deste total foram destinados para o consumo interno, tornando-o o maior consumidor de madeira tropical serrada do mundo.

O destino da madeira serrada proveniente de plantios no Brasil segue a mesma tendência da madeira tropical, ou seja, sua grande maioria é para fins de abastecimento interno. Segundo o FAOSTAT (2011), em 2009 foi produzido um total de 9,5 milhões de metros cúbicos de madeira serrada de coníferas, sendo que 11% deste montante foram exportados.

Segundo a Associação Brasileira de Produtores de Florestas Plantadas, ABRAF (2011), apesar do forte crescimento da produção de madeira de *Eucalyptus*, o volume de serrados desse gênero ainda é pequeno quando comparado à produção de serrados de coníferas. Entretanto, em médio prazo, estima-se que essa tendência seja revertida. Historicamente, as florestas de *Eucalyptus* no Brasil foram conduzidas para fins energéticos e de celulose, com característica de espaçamentos fechados, poucas intervenções silviculturais após o estabelecimento da floresta e idades de rotação precoces.

Em contrapartida, florestas com o objetivo de produção de madeira sólida se distinguem das florestas energéticas, principalmente devido à sua condução em espaçamentos mais amplos. Quando uma árvore é conduzida com espaçamento vital sem restrição, ocorrem características indesejáveis como o aumento da produção de madeira juvenil e a presença de galhos grossos. Assim, tratamentos silviculturais adicionais são necessários na condução destas florestas, como a realização de desramas ou podas para eliminação de galhos e desbastes para a regulação do espaçamento de plantio. Estes tratos silviculturais aumentam o custo, porém a receita superior oriunda de produtos de madeira sólida torna estes regimes rentáveis.

2.1 Desbastes em povoamentos florestais

Os desbastes são cortes parciais no povoamento, realizados a partir do fechamento do dossel ou em povoamentos imaturos no caso de manejo intensivo, com o objetivo de estimular o crescimento das árvores remanescentes e aumentar a produção de madeira de melhor qualidade. As árvores com melhor qualidade são as de maior dimensão, pois além de fornecerem um alto rendimento na serraria, possuem preços de venda elevados. A realização de desbastes tem o propósito de concentrar o potencial de produção de madeira do povoamento, em um número limitado de árvores selecionadas, que ao atingirem grandes dimensões produzirão um máximo de renda.

Os desbastes podem ser efetuados de diversas maneiras, em função da espécie, da estrutura do povoamento, da qualidade do plantio e do uso a ser dado à madeira. Essa diversificação na maneira de efetuar os desbastes gera o regime de desbastes. O regime de desbastes é constituído pelo tipo, pela intensidade de desbaste e pelo número e época, conforme mostra a Figura 1.

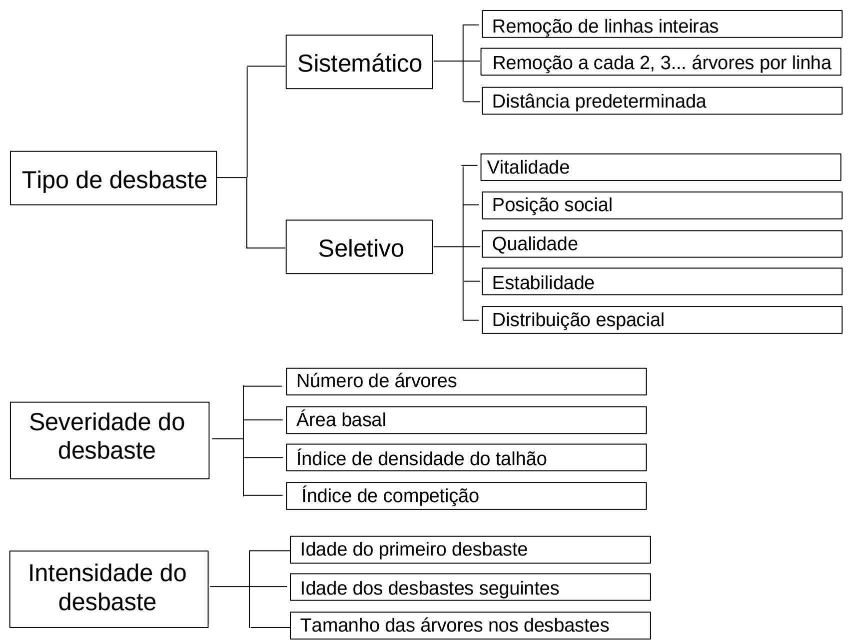

Figura 1 Tipo, severidade e intensidade de desbaste como critério para prescrições silviculturais e parâmetros para sua quantificação.
Fonte: Adaptado de Pretzsch (2009).

2.1.1 Tipo de desbaste

A escolha do tipo de desbaste está condicionada ao tipo de povoamento, ao estado em que este se encontra ao objetivo da produção florestal e também à análise econômica de sua execução. O tipo de desbaste indica quais árvores serão removidas e quais deverão permanecer no povoamento, pode ser agrupado em duas classes, os sistemáticos ou geométricos e os seletivos. A denominação desbaste misto é utilizada quando ambos os tipos de desbastes são realizados simultaneamente.

O desbaste sistemático é realizado com o objetivo de facilitar operacionalmente outros tratamentos silviculturais, uma vez que a retirada de uma linha de plantio facilita a entrada de máquinas. Por este motivo, este tipo de desbaste é normalmente realizado na primeira intervenção de desbaste. Geralmente o tipo de colheita é o que determina quais e quantas linhas remover.

O desbaste seletivo indica que a escolha das árvores a serem removidas é determinada por algum critério. Desbastes onde as menores árvores são removidas são conhecidos como desbastes por baixo ou método alemão de desbaste. Desbastes onde as maiores árvores são removidas são conhecidos como desbaste por alto ou método francês de desbaste. Outros critérios podem ser utilizados, tais como a remoção de árvores doentes ou de má qualidade, ou a manutenção adequada da distribuição espacial das árvores, por exemplo.

Segundo Assmann (1970) e Pretzsch (2009), em 1884 o pesquisador Kraft criou um sistema de classificação de árvores de um talhão com bases naturais e sociais. Esta classificação utiliza a situação das copas das árvores, distinguindo as seguintes classes:

1 predominantes: copas excepcionalmente bem formadas;
2 dominantes: formam a maior parte do talhão, copas bem formadas e recebendo luz por todos os lados;

3 co-dominantes: copas normais, porém de estrutura mais frágil em relação à classe anterior; esta classe forma o limite inferior das árvores dominantes;

4 dominadas: copa restringida lateralmente, tendo suas copas comprimidas entre os espaços das copas das árvores dominantes e co-dominantes,

   a. recebendo pouca luz de cima e nenhuma dos lados;
   b. copa não recebe luz direta

5 suprimidas: são aquelas que não tem condições de sobrevivência e as mortas.

A classificação das árvores de um talhão segundo a metodologia de Kraft ajuda a qualificar o tipo de desbaste a ser empregado. Como exemplo, Pretzsch (2009) cita que Kraft classificou três tipos de desbaste de acordo com sua intensidade, são eles: padrão 1, desbaste leve removendo apenas a classe 5; padrão 2, desbaste moderado removendo as classes 5 e 4b; padrão 3, desbaste pesado removendo as classes 5, 4b e 4a.

Normalmente, mais de um parâmetro é utilizado para determinar quais árvores serão removidas em um desbaste seletivo. Como exemplo, Altsuler (2003) cita os parâmetros de retirada de árvores para desbastes seletivos realizado em plantios de *Eucalyptus* e *Pinus* no norte do Uruguai. Segundo o autor, os parâmetros, em ordem de prioridade, são: 1 - Árvores doentes ou com danos severos por insetos; 2 - Árvores com fuste bifurcado ou com curvatura maior que 10 cm do eixo da árvore; 3 - Garantir a distribuição uniforme dos indivíduos; 4 - Tamanho, retirando as menores. Estes parâmetros foram citados por Altsuler (2003) para a realização do desbaste pré-comercial. Este tipo de prescrição de árvores a serem retiradas no desbaste não deve ser rígido, mas sim se adaptar para cada caso específico.

2.1.2 Severidade e intensidade do desbaste

A severidade do desbaste determina o peso do desbaste, podendo ser expressa pelo número de árvores ou quantidade de área basal removida. Em muitos casos a intensidade do desbaste é determinada de maneira empírica, com base em experiências do passado.

De acordo com Ginrich (1967), o termo densidade de talhão é uma medida quantitativa de um talhão em termos de área basal por hectare, número de árvores por hectare ou volume por hectare. Já o termo estocagem se refere ao adequamento da densidade de um determinado talhão para atender a algum objetivo de manejo. Assim, um talhão com $40m^2/ha$ de área basal pode ser classificado como sub ou super estocado, dependendo em qual densidade é considerada desejável (GINRICH, 1967).

A determinação da severidade do desbaste e consequentemente a estocagem desejada incluem o uso de índices de densidade do talhão e índices de competição, tais como: Reineke (1933), Krajicek et al. (1961), Ginrich (1967), Kumar, Long e Kumar (1995), Long; Shaw (2005), entre outros.

A intensidade do desbaste refere-se à idade de quando os desbastes devem ser aplicados bem como ao tamanho das árvores no momento da intervenção. Geralmente a idade do desbaste é alocada de maneira a evitar que o talhão sofra uma redução de crescimento devido à competição. Normalmente, o ponto onde ocorre o máximo incremento médio anual (IMA) de alguma característica dendrométrica é definido como o momento ótimo de desbaste.

De acordo com Assmann (1970), a ordem de culminação do IMA é a seguinte: altura < diâmetro < área basal < volume. Assim, quando considerando qual característica do povoamento a ter seu incremento médio anual maximizado para relacionar a um esquema de corte final, a escolha do volume ou área basal pode ser empregada. Já quando considerando um desbaste, a escolha do diâmetro como característica para maximizar pode ser vantajosa por resultar em um plantio que terá menor competição entre indivíduos, maximizando o crescimento dos seus melhores exemplares.

Modelos de crescimento e produção florestal normalmente são utilizados para a determinação do comportamento do IMA ao longo da idade do talhão, tais como: Pienaar (1979), Pienaar, Shiver e Grider (1985), Scolforo e Machado (1999), Ferraz Filho (2009), entre outros.

2.2 Poda

Enquanto conduzir uma floresta em amplos espaçamentos possibilita a obtenção de madeira de elevadas dimensões, em um reduzido espaço de tempo, ocorre a indesejável característica da produção de galhos grossos que reduzem a qualidade da madeira. Vários autores relataram o aumento de incidência e diâmetro de galhos para árvores crescendo com maior espaço vital, tais como: Moberg (1999), Baldwin Jr. et al. (2000) e Henskens et al. (2001). Para amenizar este problema, operações de poda são realizadas para eliminar os galhos indesejados das porções inferiores do fuste.

Para garantir a cicatrização adequada dos galhos, a poda deve ser realizada em galhos vivos (Smith et al., 2006). Apenas após a cicatrização do galho ocorrerá à produção de madeira livre de nós, o principal objetivo da aplicação de poda. Como as espécies do gênero *Eucalyptus* possuem poda natural muito pronunciada, as operações de poda devem ser realizadas cedo na vida do povoamento, antes do início da mortalidade dos galhos da porção inferior do fuste. A Tabela 1 ilustra uma prescrição de poda para o manejo de *Eucalyptus grandis* na Argentina.

Como pode ser visto na Tabela 1, as operações de poda feitas em *Eucalyptus grandis* devem ter início por volta do primeiro ano de plantio, quando as árvores possuem cerca de 9 cm de diâmetro médio (considerando o ritmo de crescimento destas florestas na Argentina).

Tabela 1 Prescrição de poda para *Eucalyptus grandis* na Argentina

	DAP (cm)	Idade (anos)	Altura de poda (m)	Desbaste N/ha	Remanescentes N/ha
Primeira poda	8 – 9	1 – 2	2 – 2,5	–	1000
Segunda poda	–	2 – 3	5,5	400 – 500	500 – 600
Terceira poda	–	5 – 6	7 – 9	250 – 300	250 – 300

Fonte: Aparício e Caniza (2009).

Quanto à quantidade de copa que pode ser removida, Pinkard e Beadle (2000) relatam que até 50% da copa viva pode ser removida sem causar grandes prejuízos no crescimento diamétrico, onde a espécie estudada foi o *E. nitens*. Segundo esses autores, a remoção de galhos deve ser feita de maneira que o índice de área foliar (IAF) remanescente após a poda seja igual ao IAF ótimo da determinada espécie, onde o IAF máximo corresponde a 95% da absorção da radiação solar incidente. Segundo os autores, um valor de IAF 4 corresponde ao ótimo para o *E. nitens*.

2.3 A intensidade do desbaste na determinação do regime de manejo

Dentro do sistema silvicultural alto fuste, os regimes “pulpwood” ou “energywood”, “utility” e “clearwood” são os mais comuns. O regime “pulpwood” ou “energywood” prioriza a produção de madeira de menores dimensões para uso principalmente em indústrias de papel, celulose a para fins energéticos. Sua característica é a de não prever intervenções periódicas e o corte raso por volta dos 7 e 15 anos para *Eucalyptus* e *Pinus*, respectivamente. O regime “utility” preconiza desbastes periódicos durante o ciclo produtivo (2-3). Sua aplicação gera toras de diversas bitolas, possibilitando o atendimento dos mercados de madeira fina à madeira de maiores dimensões. Este regime de manejo também é chamado de “manejo com otimização de volume por unidade de área”. Caracteriza-se pelo espaçamento inicial semelhante ao regime para produção de madeira de menores diâmetros (pastas celulósicas e energia). Normalmente são sujeitos a 2 ou 3 eventos de desbaste e os critérios de decisão do desbaste embasam-se no máximo IMA em volume ou ainda em algum critério econômico como a maximização do valor presente liquido (VPL) para uma serie de infinitas rotações. Cada intervenção é efetuada no momento em que a competição ocasiona a queda do IMA em volume, indicando a competição entre as árvores, implicando na supressão das menores e morte de parte delas (SCOLFORO; MAESTRI, 1998).

O manejo “clearwood” proporciona uma ampla variação de alternativas de mercados e opções para o proprietário florestal. O nome “clearwood” define que o produto alvo do manejo é a produção de madeira livre de nós. Geralmente este regime é aliado a um manejo intensivo. Segundo Fox (2000), o manejo intensivo pode ser considerado como a manipulação das condições do solo e talhão que restringem o crescimento da árvore. A Figura 2 mostra que dos fatores que influenciam a produtividade florestal, o manejo da densidade do talhão e consequentemente o controle da competição pode ser atingido por meio de desbastes precoces e intensivos, característica do manejo intensivo. Como o manejo intensivo envolve periódicas intervenções no talhão, seja por motivos de correção do solo ou operações de desbastes não comerciais, os seus custos são altos. Para compensar o maior investimento, o manejo intensivo também é aliado a podas, para gerar madeira de melhor qualidade e consequentemente maior valor de venda.

A Tabela 2 mostra as principais diferenças entre os regimes de desbaste para os regimes “utility” (para plantios localizados no sul da Bahia) e intensivo (para plantios localizados na província de Corrientes, Argentina). A intensidade de desbaste é o que caracteriza o tipo de regime de manejo aplicado. Enquanto regimes de manejo intensivo aplicam desbastes cedo e pesados, regimes de manejo “utility” aplicam desbastes mais tardes, frequentes e mais leves. A quantidade total de madeira produzida no regime "utility" é superior àquela produzida no regime de manejo intensivo ou regime de manejo cujo foco é a árvore, considerando uma mesma idade de rotação.

Figura 2 Fatores que influenciam a produtividade florestal.
Fonte: Adaptado de Fox (2000).

Tabela 2 Principais diferenças entre as prescrições de desbaste para os regimes "utility" e intensivo na condução de plantios de *Eucalyptus* spp.

	"Utility"		Intensivo	
Regime de desbaste	Idade	Árvores remanescentes/ha	Idade	Árvores remanescentes/ha
Plantio	0	1111	0	625
Pré-comercial	-	-	1,5	500
Primeiro comercial	5 - 6	700	4,5	350
Segundo comercial	8 - 9	400	7-8	200-250
Corte raso	> 15	0	13-14	0

Fonte: Maestri, Nutto e Satório (2005); Azúa (2003).

3 CONSIDERAÇÕES GERAIS

Ao longo dos quatro artigos desta tese é abordado como o manejo do eucalipto para produção de produtos sólidos é condicionado ao objetivo de produção do talhão, bem como as características inerentes às condições em que se encontra o talhão.

O regime de manejo de talhadia com remanescentes apresentado no primeiro artigo possui a vantagem de diversificar a produção florestal provinda de um mesmo talhão. Este manejo possui potencial para ser aplicado por pequenos e médios produtores que cultivam o gênero *Eucalyptus*. Foi concluído que espécies do gênero *Eucalyptus* apresentam ganhos em termos de qualidade da madeira quando cresce livre de competição, o que é uma das características do manejo por talhadia com remanescentes. Foi abordado também como é possível em uma rotação de 28 anos produzirem quatro ciclos de madeira de pequenas dimensões com a obtenção de toras de grande porte no corte final.

Os artigos 2 e 3 permitiram a conclusão que a condução da poda em *Eucalyptus* sofre alteração significativa conforme as características do talhão. Podas aplicadas em talhões adensados (1111 árvores por hectare) após a ocorrência do fechamento do dossel permitiram atingir elevadas alturas (removendo até 60% da copa viva inferior) sem causar grandes prejuízos ao desenvolvimento do talhão. Por outro lado, podas aplicadas em talhões instalados com baixa densidade ou feitas antes do fechamento do dossel devem ser conduzidas de forma menos intensas a fim de evitar redução do crescimento do talhão. Estes resultados permitem inferir que se for optado por iniciar operações de podas antes do fechamento do dossel, quantidades pequenas da copa devem ser removidas (até 20% da copa viva inferior) a fim de evitar prejudicar o crescimento do talhão. Após o talhão atingir o fechamento do dossel, quantidades maiores de copa poderão ser removidas.

Considerando o efeito do desbaste na produção florestal, foi concluído que o regime de desbaste deve ser alinhado com os objetivos de manejo da floresta. Quando maior interesse é dado à produção de toras de grandes dimensões, desbastes pré-comerciais deixando baixo número de árvores remanescentes são indicados. Regimes de desbastes mais tardios deixando números intermediários de árvores remanescentes (450 a 600 árvores/ha) devem ser privilegiados quando há interesse tanto em produção de madeira para produtos sólidos como madeira para fins energéticos ou de celulose.

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SEGUNDA PARTE – ARTIGOS

ARTIGO 1 - Coppice with standards silvicultural system applied to *Eucalyptus* plantations - a review

Abstract

Context This review paper provides an overview of the management of *Eucalyptus* species under the coppice with standards (CWS) silvicultural system. CWS management results in product diversification, permitting production of small and large scale timber from the same stand. Some reasons that make *Eucalyptus* species suitable candidates for CWS management are: large worldwide plantation areas, sprouting capacity, and multipurpose species.

Aims Discussion on (1) short rotation *Eucalyptus* coppice management for energy and pulping and (2) *Eucalyptus* seedling management for solid wood products is provided.

Method A review of the literature relating experiences with *Eucalyptus* managed under the CWS system is given. Works dealing with *Eucalyptus* coppice management, stand density regulation, pruning, stand and wood quality are also assessed.

Results The growth environment of the standard trees (heavy competition up to the first harvest, free growth afterwards) coupled with long rotations (e.g. 28 years or longer) result in high quality logs for solid wood products. Early pruning should be applied to enhance wood quality.

Conclusion We propose a system for the silvicultural management of *Eucalyptus* under the CWS system, elaborating on the consequences of initial planting density, site productivity, and standard tree densities as well as timing of basic silvicultural applications.

Keywords Stand density regulation; Coppice management; Pruning; Silvicultural system; Stand production diversification

1 Introduction

Coppice with standards (CWS) is a silvicultural system traditionally applied in European forest management since the Middle Ages. This system consists in managing a low density of seedling trees as an overstory for one or more cycles of coppice as an understory. This way, CWS system enables the production of small diameter wood for energy or pulping purposes as well as large dimension timber for solid wood products.

The destination of a forest stand to produce multi-products represents a potentially competitive differential for forest landowners, aggregating flexibility in the commercialization of the products and consequently reducing risks of financial loss (Soares et al. 2003). In this context, the development of silvicultural management regimes that are able to enhance multi-product production is desirable. CWS silvicultural system is ideal to promote diversification of forest wood products. The use of *Eucalyptus* for energy and pulping purposes is consolidated, and according to Montagu et al. (2003), all of the commercially grown *Eucalyptus* species are capable of producing solid wood products, given appropriate management (mainly pruning and thinning operations).

Eucalyptus plantations are spread worldwide and are destined for the production of several goods, such as: charcoal, pulp and paper, construction timber, fire wood, honey, essential oil, ornamental, and solid wood products. Currently there are about 20 million hectares of *Eucalyptus* plantations worldwide, of which about 50% are located in India, Brazil and China (Iglesias-Trabado and Wilstermann 2008). The reasons that this genus is so widely cultivated can be attributed to: fast growing species (values of up to 83

m^3/ha/year at age six years have been reported by Stape et al. 2010), many species coppice readily, it is a multi-purpose species, allows a high level of genetic improvement, and presents consolidated markets.

The majority of the world's *Eucalyptus* forests are managed for pulping and energy, characterized by high planting densities, few silvicultural interventions after establishment, and short rotation lengths. For instance, out of 113 million m^3 of *Eucalyptus* harvested from Brazilian plantations in 2010, 45% were destined for cellulose and paper production, 45% for industrial firewood and charcoal, and 9% for solid wood products (ABRAF 2012).

Eucalyptus species are appropriate candidates for management by the CWS system, since many species present good sprouting capacity and are suitable for solid wood products. Reynders (1984) deemed the CWS system as the most appropriate management system for *Eucalyptus* plantations established to fulfill the needs of rural communities in developing countries. Thus, management of *Eucalyptus* under CWS is very promising for small and medium scale private forest landowners.

Many factors must be observed in order to successfully manage a stand through the CWS system. These include: successful regeneration through coppice shoots; ability to respond with rapid growth once the stand canopy is opened; stand resistance to the abrupt canopy opening; and wood quality response to the growing conditions. This review paper aims to address how *Eucalyptus* species respond to these major factors when managed under to CWS system. The experiences of *Eucalyptus* managed under the CWS system are presented, as well as inferences drawn upon pruning, thinning, and sprouting studies, which are more abundant.

2 Characterization of silvicultural and CWS systems

In its broader sense, a silvicultural system is a set of rules applied to a forest stand in order to ensure its renewal (Bellefontaine et al. 2000). Matthews (1991) defined silvicultural systems as being the processes by which the crops constituting a forest are tended, removed, and replaced by new crops, resulting in the production of stands of distinctive structure. Silviculture can be regarded as the set of tools available to forest managers in order to meet the aims and goals of the enterprise as a whole.

Silvicultural systems are traditionally classified as clear-cutting, shelterwood, and selection systems (Kerr 1999). This classification regards to the type of harvest applied in the stand, from cutting the entire stand in the clear-cutting system to a few selected trees in the selection system.

Savill (2004) suggested the classification of silvicultural systems into three major axes: the method of regeneration applied, even-agedness of the stand, and by the size of the silvicultural unit. Considering the method of regeneration, a system can be regarded as high forest (regeneration from planting, direct seeding, or natural regeneration) or low forest (regeneration from coppice or root suckers). Age variation in a stand classify selection forests as the most diverse and clear-cutting and coppice systems as the least diverse, with shelterwood systems in between. As for the size of the silvicultural unit, the classification distinguishes systems that concentrate harvest operations in larger areas, such as the clear-cutting and coppice systems, from progressively smaller cutting areas in the strip, group, and selection systems.

Given the flexibility and many variations of silvicultural systems, correct classification is not always easy. This is true for the CWS system, which combines several aspects of different silvicultural systems.

Troup (1928) defined the CWS system as consisting of two distinct elements: (1) a lower even-aged story treated as simple coppice, and (2) an upper story of standards forming an uneven-aged crop and treated as high forest on the principle of the selection system. Troup (1928) also defined a variation of the CWS termed coppice of two rotations. The coppice of two rotations is a simpler system than the traditional CWS, since the standards are not managed by the selection system and as such form an even-aged crop. The management of a stand by the coppice of two rotations system will result in a two layered forest, composed by the coppice shoots in the understory and the standards in the overstory.

3 History and application of the CWS system

The CWS system has been applied in Europe since the Middle Ages, dating from the 7th century in Germany and from the 12th century in England. In the year of 1544 a series of statutes for the preservation of woods was applied in England, consisting, among others, in management schemes to be followed by wood owners. Concerning coppice woods, it was required that a minimum of 30 standard trees be retained per hectare (Troup 1928). About 11 thousand hectares of *Quercus* spp. are still managed as CWS system in England (Forestry Commission 2003).

According to Machar (2009), the CWS system in France was developed for the management of the royal forests, between the years of 1664 and 1683. A three-fold objective was aimed for the management of the king’s forests: (1) production of standard oak trees used for building and the navy, (2) production of firewood and charcoal, (3) pig grazing on acorns from the mature oaks of the top stand layer.

The CWS system was once very significant in Europe, in such countries as France, England and in Central Europe. Up to 1920 one third of all French forests were managed by the CWS system (Stewart 1980). In beginning of the 20th century 3% of the current territory of the Czech Republic (60000 ha) was managed by the CWS system (Machar 2009). Coppice systems eventually lost importance in European countries, mainly due to the rise of mineral coal use for energy. This reduced the value of firewood and small scale timber, culminating in the conversion of many simple coppice and CWS stands to high forest.

The CWS system is also applied in other parts of the world. In India the species *Tectona grandis* and *Shorea robusta* are grown as standards, while in Korea timber species are grown as standards over coppiced leguminous species for firewood coppice (Stewart 1980). The CWS system preserves 10 to 20 trees as standards in Indian forests (Bebarata 2006). In Nepal some *Shorea robusta* stands are managed by the CWS system, with standards covering 25% to 50% of the canopy cover and the coppice understory cut every seven years (Department of Forest Research and Survey 2009).

During colonial times in southern Africa, some native species (*Baikiaea plurijuga*, *Pterocarpus angolensis*, and *Marquesia macrourasob*) were managed under the CWS system by British and Belgium forest managers. The system was also used for the management of African miombo formations, with the removal of the coppice material every 40 years and harvest of the standards every 60 to 100 years (Bellefontaine et al. 2000).

The CWS system is used in the tropics, but there is little information about the areas involved (Matthews 1991). There are few experiences of CWS system with *Eucalyptus* species. Some trials have been established under this system in Africa with *E. grandis*, *E. saligna*, and *E. maidenii* (Poynton 1981; Reynders 1984); in Brazil trials have been installed with *E. grandis* and *E. saligna* (Inoue and Stöhr 1991; Spina-França 1989).

4 Coppice in *Eucalyptus*

Species of the genus *Eucalyptus* possesses great coppice regrowth following felling or defoliation. This ability is attributed to the presence of epicormic buds as well as lignotubers situated in the live bark and cambium near the root and stem junction point (Little and Gardner 2003, Reis and Reis 1997).

Eucalyptus coppice management is a common practice worldwide, widely used to manage plantations that produce wood for the pulp and biomass industries. The number of coppice cycles before beginning a new rotation (e.g. replanting the stand) is mainly dependent upon sustained wood production of the coppice cycles. For instance, Brazilian *Eucalyptus* coppice management historically consisted of a three cycle rotation, one high forest clear cut followed by two coppice clear cuts (Souza et al. 2001). Recent studies have shown that a two cycle rotation is more profitable considering the higher productivity of current *Eucalyptus* genetic material and lower establishment costs (Rezende et al. 2005). The current silvicultural technology used in the coppice management of Brazilian *Eucalyptus* forests (minimum cultivation methods, high fertilizer rates) guarantees wood production of the second rotation very similar to the first rotation (Gonçalves et al. 2008).

Regeneration of a coppiced stand requires less intensive silvicultural interventions than replanting. Economical viability studies conducted in the savanna region of Brazil have shown that *Eucalyptus* coppice management is an economically viable option, even if productivity is 70% of the original high forest stand (Guedes et al. 2011). Higher productivity sites are more sensitive to the reduction of coppice productivity. Considering the mutually exclusive option of replanting or coppice regeneration, a coppice volume production equal to 70% of the previous high forest cycle can generate the same economic benefits as replanting in a low productivity site. Considering a high productivity site, coppice productivity must reach at least 88% of the of the previous high forest cycle to generate equal economic benefits (Ferraz Filho and Scolforo 2011).

Not all *Eucalyptus* species can be managed as coppice stands, either because of low sprouting capacity or low vitality of the coppice grown stems not being able to obtain commercial dimensions (Geldres et al. 2004). *Eucalyptus* species belonging to the subgenus *Symphyomyrtus* (such as *E. camaldulensis*, *E. grandis* and *E. globulus*) generally present high sprouting capacity. On the other hand, *Eucalyptus* species belonging to the subgenus *Monocalyptus* (such as *E. fastigata*, *E. pilularis* and *E. fraxinoides*) tend to present a more variable sprouting capacity (Higa and Sturion 1997, Sims et al. 1999).

Besides species, there are many different factors that influence the successful management of a coppice regenerated stand (table 1). Operational factors can be controlled by correct stand management, such as fertilization and weed control. There are factors that are inherent to the site and species and are more difficult to control, such as the sprouting capacity of the present genetic material and climate of the site.

Operational factors that can readily be controlled by silvicultural interventions include: stump height after tree felling, number of sprouts per stump, and harvest residue cleaning around the stumps. With higher stumps a greater number of epicormic buds and lignotubers remain, increasing the probability of sprouting (Stape et al. 1993). *Eucalyptus* coppice is normally cut at a maximum height of 12 cm, the stool being given a sloping surface to prevent water from settling (Matthews 1991).

The abundant regeneration of sprouts per stump can either be managed by thinning down to one, two, or three sprouts per stump and be harvested at later ages or be left unthinned and harvested for biomass at early ages. A stump thinning operation reduces growth competition between sprouts, which can result in more vigorous growth for the remaining sprouts. Souza et al. (2012) found that out of eight different *Eucalyptus* clones in a Brazilian site (cut at age 13 months and tested for stump thinning down to two stems per stump 9 months after cutting), three responded with greater diameter growth, while the rest presented greater but not statistically different values when compared to unthinned stumps. Geldres et al. (2004) recommends that for coppice management of *E. globulus* and *E. viminalis* in Chilean sites a stump thinning down to three sprouts be conducted 18 months after harvest if the intended purpose use is pulp or firewood. For sawn wood the thinning should be down to one or two sprouts per stump.

Table 1 Example of influential factors determining successful *Eucalyptus* coppice management grouped per conditioning factors and sprouting phase, adapted from Stape (1997)

Conditioning factor	Sprouting phase	Influential factors
Genetic	Emission	Species/Provenance/Clone
		Hydraulic stress
		Nutritional stress
Operational	Establishment	Stump height
		Ant and termite control
		Stump shading
		Harvest damage
		Sprout density per stump
Environmental	Growth	Thermal regime
		Water Resources
		Soil and Physiographic condition
		Fertilization/irrigation
		Weed control

Stump mortality may occur if the harvest residue impede direct sunlight incidence or if the stumps are damaged during wood harvest and forwarding operations. Camargo et al. (1997) reported 8% higher stump mortality comparing harvest residue shaded and unshaded *E. grandis*. Machado et al.

(1990) found stump mortality of about 15% for *E. alba* stumps damaged during a wood forwarding operation. Both aforementioned authors reported sprout height growth reduction for shaded and damaged stumps.

5 Stand density regulation and growth response

When managed under the CWS system, the growth space of the standard trees experience two distinct phases, crowed stand at the high forest stage and very large opening after the first cut is carried out. Due to competition from neighbors, diameter growth restriction of the standard trees occurs during the first growth phase. This is more pronounced if close spacing is used, as is usually the case to guarantee a successful regeneration of the coppiced stand.

The way the standard trees respond in growth after acquiring additional growing space depends on the amount of crown mass available. When grown in close spacing, *Eucalyptus* trees tend to produce small crowns. This occurs because many *Eucalyptus* species are crown shy. Crown shyness reflects the sensitivity of naked buds of *Eucalyptus* to any sort of abrasion. These buds, which occur in the axil of every leaf and are capable of very rapid growth where environmental conditions are favorable, are delicate and the branch is sensitive to abrasion where crowns touch each other due to wind sway (Florence 2004).

In a CWS system, the first cut of the stand will occur when the trees attain commercial dimensions (five to seven years for fast growing sites), resulting in relatively small crowns of standard trees. Considering the different growth processes that account for biomass accumulation of a tree, foliage growth can be ranked as being of greater importance than stem growth (Dobbertin 2005). Thus, before tree resource can be concentrated in stem diameter growth, the trees must first develop a crown mass that can sustain high growth rates.

After crown expansion takes place, *Eucalyptus* trees can take advantage of the greater site resource availability and, given enough time, growth to large diameters. Late thinning trials that have gone down to low densities of remaining trees can be used to estimate the growth potential of standard trees. For example, the *Eucalyptus citriodora* thinning trial presented by Aguiar et al. (1995) tested the effect of different thinning intensities on tree growth in the Southeastern region of Brazil (fig.1). The initial spacing of the trial was 3 x 2 m and the thinning intervention was undertaken at age seven years, where a selective thinning from below was applied. Even when a late thinning is applied, the diameter growth capacity of *Eucalyptus* trees when freed from competition and grown in low density stands is high. Low thinning intensities (unthinned treatment and thinning up to 833 remaining stems/ha) resulted in a 22% diameter gains. Higher thinning intensities (leaving up to 333 stems/ha) resulted in higher diameter gain, reaching 30%. The highest diameter gain was observed in the most intensive thinning treatment (167 stems/ha), reaching 50% seven years after the thinning intervention. In the CWS system, even lower densities of remaining trees/ha would be left after the first cut, which may accelerate diameter gain.

The initial competition suffered by the trees before liberation means that they will not be able to take advantage of the high diameter growth rates that *Eucalyptus* exhibit during young ages. Nutto et al. (2006) estimated that growth rates of up to 6 cm per year are possible for *E. grandis* during the first 3.5 years of age for stands planted at low densities. However, the authors mention that at sites of upper quality growth rates of up to 4 cm are possible at latter ages if low stand density is maintained.

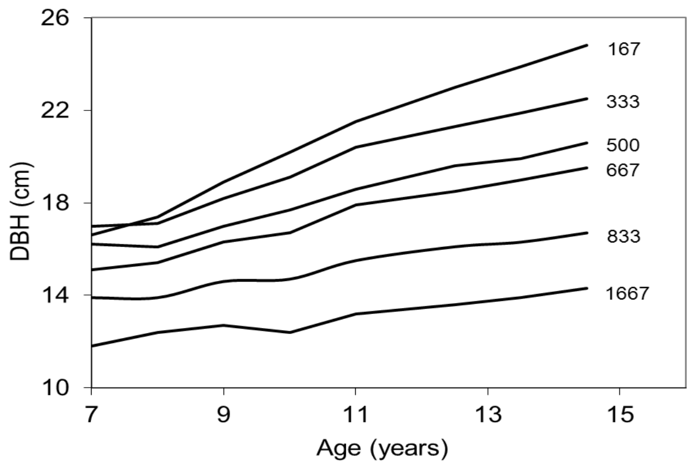

Fig. 1 Influence of different thinning intensities in diameter growth for *Eucalyptus citriodora*. A selective thinning from below was applied at age seven years down from 1667 trees/ha. The numbers next to the lines correspond to trees/ha after thinning. Data based in Aguiar et al. (1995)

If very low densities of standard trees are left after the first cut (e.g. densities lower than 50 tress/ha), and enough time is given for the trees to grow (e.g. rotations of 21 years or longer), very large diameter trees can be obtained from the CWS system. Nutto et al. (2006) estimated that in a site of higher quality (mean diameter increment of 3.6 cm/year), trees with average diameter of 54.5 cm are possible considering a 15 year rotation for *E. grandis*, with thinning regimes starting at age 5 years and final densities of 115 trees/ha. The same target diameter of 54.6 cm is possible for *E. globulus* planted in the Iberian Peninsula in a 31 year rotation, with thinnings starting at age 6 and a final density of 100 trees/ha (Nutto and Touza Vázquez 2004).

6 Stem form and wind resistance

During the first growth phase of the standard trees the lateral restriction from neighbors will accelerate live crown height rise. A more cylindrical stem results from this initial competition for light, since proportionally more assimilates are allocated in or near the live crown height than in other stem sections (Larson 1963). For instance, Maestri (2003) reported stem taper values of 1.6, 1.1 and 0.7 cm/m between stem heights of 1.3 and 4.15 m for ten year old *Eucalyptus* sp. trees grown in densities of 250, 450 and 1111 trees/ha, respectively. The author attributed this variation in stem taper as caused by the lower green crown height of lower density stands.

The competition for light in stands grown at high densities prioritizes height growth over diameter growth. This means that after the first cut, residual tress will have high slenderness values, as characterized by the height/diameter ratio. Slenderness ratios lower than 80 m/m are usually associated with wind resistant trees, while values over 100 m/m classify unstable trees (Slodicak and Novak 2006; Wonn and O'Hara 2001).

Eucalyptus trees, unless open grown, tend to present high slenderness values. For example, Warren et al. (2009) reported mean slenderness ratios for three *Eucalyptus* species at age six years as ranging from 90 to 114 m/m for planting densities of 714 and 3333 trees/ha, respectively. The authors also identified that planting densities over 1250 trees/ha resulted in mean slenderness values equal to or greater than 100 m/m.

Thinning operations results in increased exposure of retained trees to wind, increasing risk of windthrow (Fagg 2006). Thus, the abrupt opening of stand after the first harvest, coupled with the high slenderness values of the standard trees, makes wind damage to the residual stand a possibility in sites prone to strong winds. The dispersed nature of the standard trees also contributes to a higher wind damage possibility (de Montigny 2004).

The small crowns of the standard trees after stand opening is a factor that can reduce wind damage possibility, due to reduced wind penetration and sail area of small crowns (Rowan et al. 2003; Wood et al. 2008). Accelerated diameter growth of the standard trees after the first harvest will reduce the tree's slenderness ratio, increasing wind resistance over time. For Australian *Eucalyptus* forests, a recovery time of 2 to 5 years is considered adequate for stands to regain wind resistance after thinning (Wood et al. 2008).

7 Wood quality implications

Wood quality of standard trees may benefit from management in a CWS system in three different ways: higher basic density values, lower levels of growth stresses, and elevated production of mature wood.

Eucalyptus trees tend to present higher wood density values when grown in low densities (DeBell et al. 2001; Espinoza et al. 2009; Malan and Hoon 1992), but this response is not always consistent (Goulart et al. 2003; Trevisan et al. 2007). Trees with higher basic densities are associated with quality wood for solid wood products, with basic density affecting wood properties such as stiffness, hardness, modulus of elasticity, and modulus of rupture (Dickson et al. 2003). Thus, if standard trees are able to respond to increased growing space with higher wood density values, higher quality logs can be produced.

Due to the low density of residual trees after the first harvest of the stand, the remaining standard trees will have space to develop large symmetrical crowns. *Eucalyptus* trees that grow with symmetrical crowns are less likely to develop elevated growth stresses (Biechele et al. 2009; Touza Vázquez, 2001). Growth stresses released during tree felling and crosscutting logs can lead to log end splitting (Valencia et al. 2011).

Touza Vázquez (2001) has shown that selective thinnings that prioritizes adequate spacing of the residual trees can reduce longitudinal growth strains (a proxy for growth stress) up to 60% when compared to row thinnings. This author identified three patterns of longitudinal growth strain formation for *E. globulus* trees (fig. 2).

The tree represented in fig. 2a is growing in an environment of low competition. Thus, crown development is symmetrical and stem bending caused by the wind is reduced due to greater dimensional stability. Growth stresses develop in low intensity causing little or no splitting when the tree is cut.

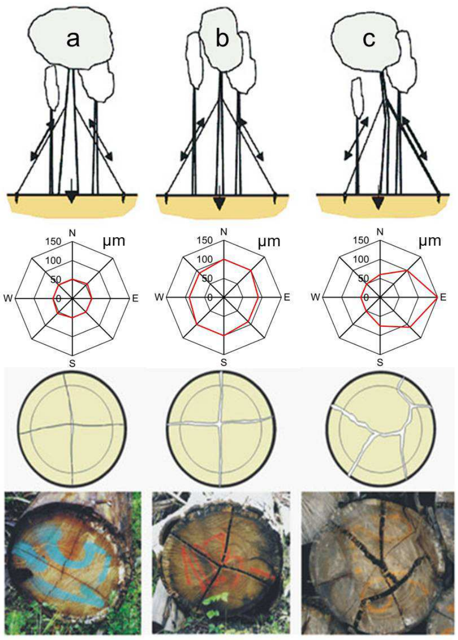

Fig. 2 Relation between *Eucalyptus* growth, distribution of longitudinal growth strains (µm) and log end splitting, where: a) tree growing without crown lateral restriction, b) tree growing with symmetrical crown lateral restriction, c) tree growing with unsymmetrical crown lateral restriction. Adapted from Touza Vázquez (2001), reprinted with permission from CIS-Madera

In the case of fig. 2b the tree is growing in an environment of strong competition, but evenly on all sides. In this case, the tree presents a small crown and stem diameter, rendering it unstable and severely affected by wind sway. The longitudinal growth strains are evenly distributed, but occur at high levels in order to stabilize the tree. When cut, the stress between the center and periphery of the log is released immediately, causing deep cracks.

The tree represented in fig. 2c is affected by environmental conditions forcing the development of an asymmetric crown. The tree reacts with formation of tension wood on the opposite side. This uneven distribution of the crown results in high intensity of growth stresses that can cause deep asymmetrical end splits when the tree is cut.

Thus, a standard tree will first grow with a small crown, and since the initial diameter increment is impeded, the growth strains associated with the small crown will be concentrated in a smaller inner section of the stem. Once the standard trees are liberated, the development of large crowns will decrease growth stress rates and produce more stable wood.

The impediment of initial diameter increment coupled with a high green crown height will ensure a log with large portions of more stable mature wood, limiting juvenile wood formation to a small inner core. Juvenile wood possesses less desirable wood properties than mature wood. It is formed during the earlier growth stages of the tree (around 3 years) in the central core of the stem and also produced in the stem within the living crown or in proximity to physiological processes emanating from the living crown (Larson et al. 2001).

Kojima et al. (2009) identified that the transition between juvenile and mature wood formation for South American *E. grandis* plantations depends on, among other factors, the proximity of the stand to the equator. Xylem maturation for stands planted close to the equator starts when the trees attain a certain diameter (around 40 cm). On the other hand, stands planted further from the equator (below latitude 18°S) start xylem maturation once a certain age is reached (9 to 14 years), regardless of tree growth rate.

It can be inferred that high quality logs can be produced from *Eucalyptus* trees managed under the CWS. The initial diameter restriction imposed on the standard trees before the first harvest means that juvenile wood will mostly be confined to a small inner core. After the first harvest, the standard trees will be reaching the age to begin producing a transition zone between juvenile and mature wood. Consequential development of large symmetrical crowns results in lower growth stress development and production of high quality logs for solid wood products (Biechele et al. 2009).

8 Pruning

Eucalyptus species possesses self-pruning behavior; this process can be relied on to produce high-quality logs in native forests, where rotations are long and densities high (Kearney et al. 2007). *Eucalyptus* plantations for solid wood products are managed at shorter rotations. Under short rotations self pruning does not guarantee clear wood production, since dead branches are not always shed from the tree (Pinkard and Beadle 1998). These unshed dead branches are dragged through the stem as radial increment occurs, creating kino veins (Eyles and Mohammed 2003).

To ensure production of high value clear wood form the standard trees, early pruning interventions must be applied. Table 2 shows a common pruning regime for intensively managed South American *Eucalyptus* stands.

The pruning regime presented in table 2 is applied to stands established at low densities (620 trees/ha), where the first pruning operation is combined with a thinning to waste down to 450 to 500 remaining trees/ha. The first pruning intervention is done early to ensure that mostly live branches with small diameters are pruned. Pruning dead branches may create loose knots and increase susceptibility to decay entry, inefficient branch stub ejection may create problems of kino traces through the log (Smith et al. 2006). Pruning small branches also reduces the chance of decay spreading into the stem from pruned branches (Wardlaw and Neilsen 1999). The aforementioned authors suggest a maximum allowable branch diameter of 30 mm for *E. nitens* pruning.

Table 2 Example of a commercial pruning regime for intensively managed *Eucalyptus* plantations in South America, after Azúa (2003) and Maestri (2003)

Pruning	Age (years)	Pruned height (m)	Pruned trees/ha
First	1.5	3 – 4	450 – 500
Second	2.5	6 - 7.5	300 – 350
Third	3 - 4	9 - 10.3	250

Green pruning (pruning of live branches) accelerates pruning wound occlusion, maximizing clear wood production. Programming the pruning regime to begin with canopy closure is ideal for quality wood production as well as wood growth, since after canopy closure lower branches become shaded and contribute little carbon to the tree (Montagu et al. 2003).

The pruning of trees under a CWS management can differ from the regime presented in table 2 in two aspects: moment of intervention and lower number of pruned trees/ha. Initial spacing affects the moment of canopy closure, where stands planted at higher densities go through this process earlier than low density stands (Ryan et al. 2004). Depending on the initial density used, the moment of first pruning might have to be anticipated to ensure pruning of live branches.

Since trees harvested in the first cut will be used primarily for energy and pulping, pruning should be restricted to standard trees only. This implies that selection of the standard trees must occur in the moment of the first pruning intervention. Selection criteria typically include dominance (a proxy for vigour), stem form, and evidence of bole defect (Smith and Brennan 2006), as well as a homogeneous distribution in the stand. Since a reduction in growth after pruning may result in a loss of dominance in the pruned trees in relation to unpruned trees (Montagu et al. 2003), care must be taken as to not remove excessive amounts of green crown in the pruning operations.

9 Non-timber resource values

Recent changes in forest management perspectives have led to a shift from the sole purpose of timber production to the development of multifunctional forests and the structural diversification of stands, incorporating recreational needs and nature conservation into traditional forest management (Lassauce et al. 2012; Wohlgemuth et al. 2002).

Coppice with standards may be more appealing to maintain non-timber resource values, when compared to high forest or simple coppice systems. Coppice woods with standard trees are generally richer in wildlife than those without (Fuller and Warren 1993). Standard trees create an additional stratum of vegetation which is important for many insects and birds. Standard trees can also be a source of dead wood production for the stand. Woody debris in a stand is important to maintain saproxylic insect diversity (Lassauce et al. 2012).

Understory plant regeneration may also be more diverse under CWS stands. For example, Decocq et al. (2004) found a higher and more functionally diverse understory plant species pool in a temperate deciduous forest managed under a CWS system, compared to a close to nature selective cutting system.

All these result findings are restricted to the more traditional CWS plantations of European countries. Similar research is warranted for *Eucalyptus* plantation forests managed under this system.

10 Worldwide experiences with *Eucalyptus* under CWS system

Eucalyptus plantations have been managed to some extent under the CWS system in South African countries. *E. grandis* stands were managed by the CWS system in Zimbabwe and Malawi for the supply of transmission and building poles, posts, and fuelwood. In these plantations, 50 to 200 standards were retained after the first harvest at age 5 to 7 years, with the final harvest of the whole stand by age 12 (Poynton 1983).

Recent research concerning the management of *E. globulus* for the production of quality solid wood products in northwestern Spain under short rotations has taken note of the possibility of application of the CWS system (Nutto and Touza Vázquez 2004). This regime is composed of an initial planting density of 1111 trees/ha, followed by two thinnings (ages 6 and 11 years) down to 530 and 130 trees/ha, respectively. The whole stand is cut by age 26 years (or later), guaranteeing large diameter standard trees for solid wood products as well as 100 m^3 of additional wood from the coppice growth for pulping.

A high density of standard trees can impose elevated competition on the coppice crop. Finding the ideal trade-off between standard tree density and coppice growth is important for the success of the management of *Eucalyptus* under CWS system.

Reynders (1984) studied the species *E. saligna* and *E. maidenii* managed under simple coppice, CWS, and high forest systems in Eastern Africa (Rwanda and Burundi). The experiment was installed in stands with initial density of 4444 trees/ha at 5 years of age, being implemented with seven treatments: clearcutting, keeping 6 different intensities of standard trees in the stand (100, 150, 200, 250 and 350 to 400 trees/ha), and thinned to about 2000 trees/ha (fig. 3a and b). Total volumetric production of the different treatments was very similar. Only clearcutting and thinning to approximately 2000 trees/ha treatments were statistically different. This lack of significant difference allows the manager a great freedom of action. This author recommended the application of the CWS system by cutting the coppice growth and some standard trees every 5 years, to reach a final density of 50 standard trees/ha. As for the remaining density of the standard trees, a low intensity CWS system (between 100 and 250 trees/ha) allows the coppice wood to reach appropriate commercial size between cut periods (every 5 years) and allows high increment for the standard trees. For the system practiced at high intensity (up to 400 trees/ha) greater importance is given to the standard trees, making the coppice production of secondary importance.

Fig. 3 shows productivity for different *Eucalyptus* species managed under the CWS system in Africa (fig. 3a and b) and Brazil (fig. 3c and d). The numbers inside the columns represent the average volume per tree for the standards and average volume per stump for (a) and (b), average diameter per standard tree and per sprout for (c) and average diameter per standard tree and per stump for (d). The differences in productivity between the Brazilian and African sites are mainly due to initial spacing density, of circa 1800 trees/ha for the former and 4444 trees/ha for the later.

Reports of two trials of *Eucalyptus* managed as CWS system in southeastern Brazil are available, Spina-França (1989) with *E. camaldulensis* (evaluated 5 years after the first cut of an 8 year old stand, fig. 3c), and Inoue and Stöhr (1991) with *E. grandis* (evaluated 4 years after the first cut of a 7 year old stand, fig. 3d). Both studies conducted the coppice with two to three sprouts per stump.

Particularly for *E. saligna*, five years after the first cut Spina-França (1989) noted that standard trees did not influence survival, average height, and dominant height of the sprouts; standard trees did influence the development of quadratic mean diameter of the sprouts; there was no competition between the standard trees. For reasons unexplained by the author, the standard trees in the

CWS with the lowest density (25 trees/ha) did not present the highest diameter gain. This might have been due to a micro-site problem, since this treatment presented the highest stump mortality of all, 38% versus an average of 19% for the other treatments. The author did not recommend that *E. saligna* be managed under the CWS system, stating that amount of wood loss caused by not cutting the standard trees and the competition to the coppice understory as the main reasons.

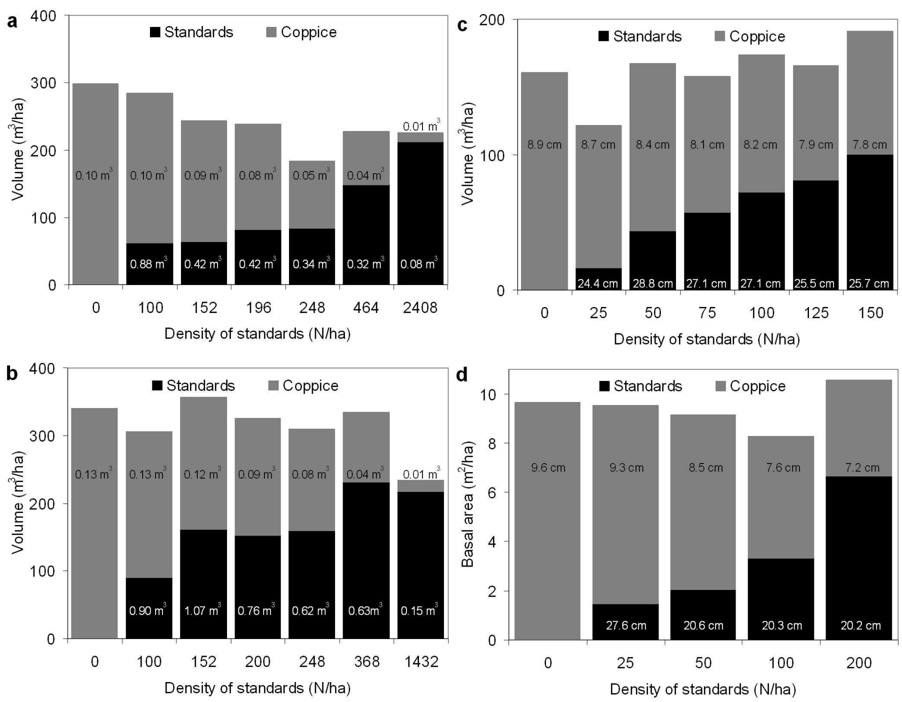

Fig. 3 Standing wood volume per hectare at age 10 for *Eucalyptus maidenii* (a), *E. saligna* (b), at age 13 for *E. saligna* (c) and standing basal area at age 11 for *E. grandis* (d) managed under the CWS system, contrasting production from standard and coppice trees. Data based on Inoue and Stöhr (1991); Reynders (1984); Spina-França (1989)

Considering *E. grandis*, Inoue and Stöhr (1991) reported that when wood prices are not differentiated by log size, simple coppice was more profitable than the CWS system for standard densities ranging from 25 to 200 trees/ha. However, when logs from the standard trees attain prices 1.4 times greater than the coppice wood, CWS system with a density of 25 trees/ha was the most profitable regime. For selling prices 3 times greater, CWS system with a density of 200 trees/ha became the most profitable regime. It is interesting to note how the standard trees conducted in the lowest density (25 trees/ha) responded in diameter growth, with values 34% higher than the next lowest density. This shows the growth capacity of *E. grandis* when freed from competition.

11 Potential application of *Eucalyptus* under the CWS system

The sprouting capacity and large dimensions attained by many *Eucalyptus* species make them excellent candidates to be managed by a two layer CWS system. The few experiences published with the genus managed under this system have not kept long term measurements, the oldest found in this study going up to 13 years. It can not be ruled out that the CWS management scheme is more profitable than clear cutting followed by coppice management when the standards are allowed to grow for three or more cycles (a rotation of 21 years considering a 7 year cycle), provided that higher prices are paid for large diameter wood. Long term research plots are needed to quantify wood production under this scenario.

A key component of the CWS system is the diversification of products obtained from the stand. To benefit from this diversification, the forest must be situated within economical transportation distance to small scale wood markets. Since large scale wood can be sold at premium prices, it may be able to sustain longer transportation distances. Even larger diversification of products obtained from the forest can be achieved in the CWS system if an essential oil producing

Eucalyptus species is used. This way, leaf production can also be sold at the moment of wood harvest. Common oil yielding *Eucalyptus* species include: *E. citriodora* (currently *Corymbia citriodora*), *E. globulus*, *E. polybractea*, and *E. camaldulensis* (Batish et al. 2008).

E. critriodora is an ideal candidate for management by the CWS system. The species presents high wood basic density, with values ranging from 790 to 910 kg/m^3 (Almeida et al. 2010; Néri et al. 2000). This high wood density designates that the species is suitable for charcoal as well as solid wood production. *E. critriodora* can reach large diameters if grown in low densities, even when late thinnings are applied (fig. 1).

Thus, the growth, wood properties, and essential oil production of *E. critriodora* can result in successful management of the species under the CWS system, especially if conducted in high charcoal consuming areas. While studies claim that *E. critriodora* possesses good sprouting potential (Andrade 1961; Ferrari et al. 2004), some authors have reported problems with sprouting capacity (Higa and Sturion 1991; Webb et al. 1984). Silveira et al. (2000) indicated that the sprout growth of the species is linked to the nutrient status of the plants. In this sense, fertilizer application around the time of harvest, as well as amelioration of the many factors that can negatively influence coppice regeneration (table 1), are important to ensure the successful management of *Eucalyptus* under the CWS system.

An example of a suitable area for the management of *Eucalyptus* under the CWS system is Minas Gerais State, Brazil. Due to a large charcoal based steel industry, Minas Gerais State is the largest consumer of *Eucalyptus* charcoal in Brazil, consuming 81% from a total national consumption of 3.5 million tones in the year 2010. This State was also responsible for the production of 40% out of a total of approximately 10 thousand tones of the nation's *Eucalyptus* leaf production used for essential oil extraction in 2010 (IBGE 2011). As for solid wood products market, the State houses the third largest furniture industry of the country (Pires et al. 2008), with many companies using *Eucalyptus* wood as raw material (Teixeira et al. 2009). The combination of diverse markets and the current 1.4 million hectares of *Eucalyptus* plantations in Minas Gerais (ABRAF 2012) make it a potential site for small and medium forest owners to diversify forest production using the CWS system.

11.1 Recommended management regime for *Eucalyptus* in CWS system

An outline for the silvicultural management of *Eucalyptus* under the CWS system is presented (table 3). It is important to note that this scheme will vary according to specific site and species peculiarities.

Table 3 Outline of the main silvicultural operations to be applied in *Eucalyptus* stands managed under the CWS system considering two different initial planting densities

1st rotation	Unit	High density (2 x 2 m)	Low density (4 x 3 m)
Pruning	Years	1 - 2	1.5 - 2.5
1st cut	Years	5.5 - 7.5	6.5 - 8.5
Remaining standards	Trees/ha	25 – 100, depending on objective	
Coppice management			
Stump thinning	Months	6 – 9 after cut	
Number of sprouts	Sprouts/stump	1 – 3, depending on objective	
Coppice cut	Years	7, 6 or 5 years after harvest for 1, 2 and 3 sprouts/stump, respectively	

The first silvicultural operation that must be conducted on the standard trees is live crown pruning. The appropriate time to conduct this operation is upon canopy closure, which varies with species, site and planting density. The growth rate of the trees will also determine the appropriate time for the first harvest, with higher productivity sites, and higher initial densities, requiring earlier intervention. The number of standard trees to remain in the stand will depend upon the desired target diameter of these trees and importance given to the coppice production. If high coppice yield coupled with large diameter standard trees is desired, very low standard densities can be practiced (e.g. 25 trees/ha).

Fertilizer application prior to or right after the first cut may be helpful to guarantee a successful regeneration and growth of the coppice understory. A sprout thinning operation can be conducted to avoid excessive competition between sprouts, which can start around 6 months after the first cut. The number of sprouts per stump will determine the size of final coppice production as well as the age of sub sequential coppice harvests. For instance, leaving three sprouts per stump will result in small scale wood for energy and early harvest to avoid growth stagnation of the coppice wood.

The number of coppice cycles before the harvest of the standard trees will be determined by the target diameter of the standard trees as well as their density. For example, a low initial planting density followed by three coppice harvests leaving one sprout per stump will allow the standard trees to grow during a 28 year rotation. This long rotation of the standard trees will ensure large diameter logs with abundant production of stable mature wood. The advanced age and possible damage to the remaining stumps may require replanting the entire stand after the standard trees are harvested

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ARTIGO 2 - Effects of green pruning on clonal *Eucalyptus grandis* x *Eucalyptus urophylla* growth

Abstract

The present paper focuses on the effects of pruning on the growth of *E. grandis* x *E. urophylla* in Espírito Santo (Brazil). The objective of this work is to determine the level of green crown pruning that does not effect tree growth, this way increasing the amount of clear wood production in a single lift. It was found that it is possible to reach up to a mean height of 7.3 m (70 % of total tree height pruned corresponding to a 62 % of live crown removal) in a single pruning lift without affecting the size of a residual thinned stand to 700 trees per hectare. Management implications of different pruning and thinning regimes are discussed.

1 Introduction

Eucalyptus plantation areas in Brazil are among the largest in the world, covering about 4 million ha, which represents 20% of the total area planted worldwide (Iglesias-Trabado and Wilstermann, 2008). The majority of these plantations are oriented to energetic and pulping purposes, characterized by high planting densities, few silvicultural interventions after establishment and short rotation lengths. The production of sawn wood derived from planted eucalypt is, however, increasing (Brazilian Association of Forest Plantation Producers, ABRAF, 2011).

When growing forests for solid wood production purposes, the quality of the wood is a key factor determining the price of the final product. Wood quality can be achieved through the production of clear wood, e.g. wood without the occurrence of knots. *Eucalyptus* species posses self-pruning behavior, and this process can be relied on to produce high-quality logs in native forests, where rotations are long and densities high (KEARNEY et al., 2007). On the other hand, self pruning does not ensure clear wood production in plantation forests, since many times dead branches are not effectively shed from the stem due to lower stocking and short rotations lengths.

Artificial pruning can be applied to ensure the production of quality products in plantation forests, being considered the main management technique available to restrict the knotty core and therefore reliably maximize the production of clear wood within the log (SMITH et al., 2006). To ensure that the full benefits of pruning are attained, it is recommended that pruning intervention occurs when the branches are still alive, as early as 12-24 months for eucalypts species (MONTAGU; KEARNEY; SMITH, 2003). Smith et al. (2006) showed that the occlusion rates of pruned dead branches were similar to those of unpruned dead branches. Green crown pruning ensures that the branches are small, facilitating pruning wound occlusion (POLLI et al., 2006) .

According to Alcorn et al. (2008), understanding the intensity of live crown removal that reduces growth is critical to the development of appropriate pruning regimes that minimize long-term growth reductions. Pruning operations that are too drastic can delay tree growth. Pruning is an expensive silvicultural operation, so it is advisable to reach the highest pruning height as possible with out effecting tree growth.

According to Forrester et al. (2010), many species are capable to withstand as much as 40% of the green crown length removal without reducing stem growth. Eucalypt species are generally more resistant to pruning, resisting up to 50% of lower live crown removal with little effect on tree growth (PINKARD; BEADLE 1998a), if conducted at or after canopy closure.

While many studies have reported the effects of pruning *Eucalyptus* after canopy closure in Brazilian sites (e.g., FINGER et al., 2001, PULROLNIK et al., 2005, FONTAN et al., 2011), the treatments applied were not severe enough to cause growth loss from excessive crown removal. This leaves an information gap concerning exactly how much crown area can be removed in a single lift when applied to Brazil's fast growing sites.

The objective of this work is to determine the level of clonal *E. grandis* x *E. urophylla* green crown pruning that does not effect tree growth, this way increasing the amount of clear wood production in a single lift. The main hypothesis of this work is that higher pruning interventions will result in trees with smaller mean diameters and basal area values, with no effects in height development.

2 Material and methods

2.1 Origin of data

Two experimental sites were established in Aracruz (Espírito Santo, Brazil). The stand of the first experiment (trial 1) was planted in November 2000 with 3 x 3 m spacing. In the autumn of 2002 (1 year 4 months after planting), a single lift pruning was conducted on all trees reaching five alternative heights: 0, 40%, 55%, 70% and 85% of the total tree height. The second experiment (trial 2) was planted in May 2002 and subjected to the same treatments, but the single lift pruning on all trees was conducted during spring (also 1 year 4 months after planting). Pruning was done using a pruning saw attached to an extension, where branch removal was flush with the stem. The site index (mean height of the 100 thickest trees per hectare at age 7 years) for trials 1 and 2 were of 27.0 and 28.5 meters, respectively (estimated using an equation from FERRAZ FILHO et al., 2011).

Trials 1 and 2 are located 13 kilometers from each other (grid references 19° 55' S 40° 08' W and 19° 48' S 40° 12' W), at altitudes of 34 and 59 m asl, respectively. The climate of the region is classified as tropical humid with a dry winter season (Aw according to the Koppen classification), with average temperature of 23°C and average annual precipitation of 1,400 mm (MARTINS et al., 2011). The prior use of both trial areas were eucalypt plantations. The soils of both trials are classified as Yellow Argisol with medium to clayey texture. This soil is moderately deep and well drained, with the presence of a textural B horizon. Stand soil preparation prior to planting was similar for both sites, including a subsoil ripping operation 80 cm deep and soil correction and fertilization. Prior and post plantation fertilization was conducted in accordance to current Brazilian commercial standards (e.g. GONÇALVES et al., 2008) 3 and 12 months after planting. When necessary, weed competition was controlled using glyphosate based products

The experiments where set up in a randomized block design, consisting of three repetitions. Each sample plot is comprised of eight trees, with a double buffer row in the exterior and single buffer row in the interior of the experiment. All the trees had their circumference and total height measured at the time of the trial establishment. Afterwards, measurements where taken every three months until the stands completed approximately 3 years. Additional measurements were made at age 3.4 and 4.4, when the experiment ended.

At time of the pruning, the stands presented mean diameters (dbh) of 9.5 cm and 7.9 cm, and a mean height of 11.0 m and 9.5 m for trials 1 and 2, respectively. The height of the living crown was measured for all trees prior to pruning (only in trial 1). Average live crown height before pruning, not considering isolated green branches, was 2.3 m for trial 1 (table 1).

Table 1 Average pruning height (ph) values for trials 1 and 2 and amount of removed live crown (rc) for trial 1, the values in parenthesis are the standard deviations.

	Trial 1		Trial 2
Treatment	ph (m)	Rc (%)	ph (m)
0%	0.0 (0.00)	0.0	0.0 (0.00)
40%	4.5 (0.21)	22.6	3.8 (0.15)
55%	6.1 (0.23)	43.3	5.2 (0.18)
70%	7.9 (0.22)	62.1	6.7 (0.17)
85%	8.9 (0.74)	81.1	8.2 (0.25)

2.2 Statistical analysis

Analysis of variance (ANOVA) using a split plot in time scheme (as presented in CASELLA, 2008) was used to asses the effect of pruning on tree and stand growth. The variables analyzed were: diameter at breast height (dbh, measured at 1.3m from the ground), dbh mean monthly increment, total height (h), h mean monthly increment; stand basal area and slenderness index (expressed as H/DBH). The statistical software SISVAR (FERREIRA, 2008) was used to perform the ANOVA. Variables with *P*-values smaller than 5% were considered as statistically significant.

Considering that the studied stands will undergo a thinning operation after the end of the pruning trial, the effect of pruning on dbh of different size class trees was also analyzed. This was accomplished using a linear mixed model approach. The model (1) formulation consisted in relating the dbh of different size classes (mean diameter of the 140, 280, 420, 560, 700 and 830 thickest trees per hectare, as well as the overall mean diameter) to the logarithm of age and pruning treatment as a factor. To account for the different starting points of both trials, a random intercept in function of the trial was inserted in the model. All the mixed models were parameterized in the statistical software R, using the nlme package (PINHEIRO et al., 2012).

$$dbh_{lk} = \beta_0 + \beta_1 * \ln(age_{lk}) + \beta_2 * T_k + u_l + e_{lk} \quad (1)$$

Where dbh is the mean diameter at breast height; age corresponds to the measurement date; and T is a factor variable to account for treatment variability. Subscripts l and k refer to trial and plot, respectively. ul and elk are independent and identically distributed random between-trial and within-trial factors with a mean of 0 and constant variances of σ^2_{tr}, and σ^2_{pl}, respectively.

3 Results

The interaction between pruning and measurement age significantly affected the mean dbh, dbh increment and slenderness for trial 1. Excluding slenderness, the same variables were affected by the interaction between pruning and age for trial 2, with the addition of basal area. Disregarding the variables with significant interaction between pruning and age, basal area was significantly influenced by pruning treatment for trial 1, as were height increment and slenderness in trial 2. As expected, all variables were significantly influenced by measurement age (table 2).

The coefficients of variation for the treatment factor of the ANOVAs were of 12.4% and 9.4% for trials 1 and 2, respectively. These values ranged from 6.4% (height) to 23.2% (dbh increment) in trial 1 and 4.2% (slenderness) to 15.1% (basal area) for trial 2.

Table 2 Summary of the analysis of variance using a split plot in time formulation to determine the effect of pruning treatment in different aspects of tree and stand *Eucalyptus grandis* growth.

	Pruning			Measurement Age			Pruning x Age		
Variable	df	F statistic	*P*-value	df	F statistic	*P*-value	df	F statistic	*P*-value
Trial 1									
dbh (cm)	4	5.28	0.022	8	1549.82	<0.001	32	2.04	0.005
dbh incr. (cm/month)	4	0.80	0.557	7	605.81	<0.001	28	21.18	<0.001
Height (m)	4	3.44	0.064	8	1670.29	<0.001	32	0.75	0.819
Height incr. (m/month)	4	1.73	0.237	7	71.62	<0.001	28	0.73	0.819
Basal area (m^2/ha)	4	4.93	0.027	8	1182.08	<0.001	32	1.41	0.111
Slenderness (m/cm)	4	1.02	0.451	8	147.02	<0.001	32	1.64	0.040
Trial 2									
dbh (cm)	4	5.62	0.019	8	3622.65	<0.001	32	3.35	<0.001
dbh incr. (cm/month)	4	7.14	0.010	7	926.67	<0.001	28	21.62	<0.001
Height (m)	4	3.23	0.074	8	2267.32	<0.001	32	0.75	0.817
Height incr. (m/month)	4	6.09	0.015	7	297.67	<0.001	28	1.06	0.411
Basal area (m^2/ha)	4	5.06	0.025	8	1858.68	<0.001	32	2.54	<0.001
Slenderness (m/cm)	4	4.68	0.031	8	237.01	<0.001	32	0.92	0.590

Considering mean tree values, more intensive pruning operations resulted in smaller trees with larger slenderness values, confirming the main hypothesis of this work. An exception occurred for the pruning treatment of 40% of tree height, which presented smaller diameter values than the 55% and 70% treatments for trial 1 and 55% for trial 2 (table 3, figure 1). The higher slenderness values for more intensive pruning were a result of smaller diameter and statistically equal height values. Height values showed a trend to be smaller for more severe pruning but the differences were not statistically significant.

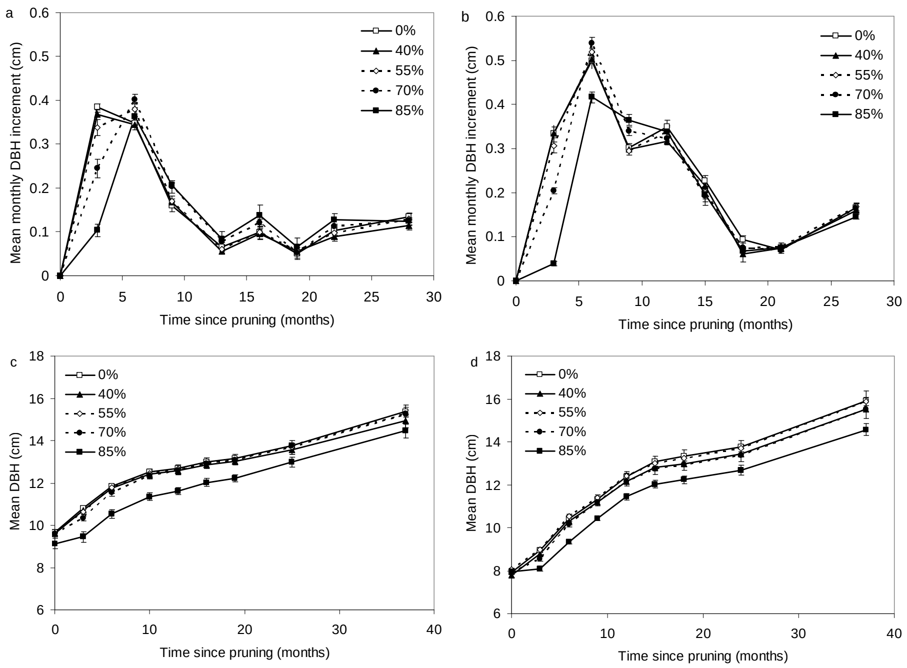

Figure 1 Mean diameter at breast height (DBH, 1.3 m) increments and mean DBH between successive measurements following pruning of 0%, 40%, 55%, 70% and 85% of total tree height in *Eucalyptus* trees at trial 1 (a, c) and 2 (b, d). Error bars represent the standard error of means.

The analyzed stand variable basal area followed the same behavior as the dbh, with more intensive pruning presenting lower values and an inversion of the 40 % treatment with treatments 55% and 70% for trial one and 55% for trial 2.

Table 3 Mean tree and stand values differentiated using Tukey's least significant difference post-hoc analysis. Values correspond to age 4.4 years, numbers in columns followed by the same letter are not statistically different.

Pruning treatment	dbh (cm)	height (m)	s (m/cm)	G (m^2/ha)
Trial 1				
0%	15.4 a	20.6 a	1.34 a	20.7 a
40%	14.9 b	20.6 a	1.38 b	19.6 a
55%	15.2 a	20.3 a	1.33 a	20.4 a
70%	15.3 a	20.5 a	1.34 a	20.4 a
85%	14.5 c	20.0 a	1.38 b	18.4 b
Trial 2				
0%	15.9 a	23.0 a	1.44 a	22.4 a
40%	15.5 b	22.9 a	1.48 a	21.2 b
55%	15.9 a	22.9 a	1.44 a	22.2 a
70%	15.5 b	23.1 a	1.49 a	21.2 b
85%	14.6 c	22.1 a	1.51 b	18.7 c

The parameter estimates for the linear mixed models of different dbh size classes in relation to the logarithmic of age and pruning treatment are shown in table 4. The pruning treatments were treated as dummy variables within the models, thus a significant parameter indicates that the treatment is different than the unpruned trees.

Table 4 Parameter estimates for the linear mixed model of different dbh size classes in relation to the logarithmic of age and pruning treatment. Asterisks indicate significance at a 99% confidence interval.

Parameter	dbh	dbh140	dbh280	dbh420	dbh560	dbh700	dbh830
Intercept	7.675*	7.948*	7.853*	7.828*	7.796*	7.766*	7.750*
log(Age)	5.318*	6.010*	5.917*	5.826*	5.742*	5.652*	5.544*
40%	-0.203	-0.007	-0.022	-0.050	-0.056	-0.093	-0.124
55%	-0.037	0.049	0.054	0.039	0.034	0.032	0.027
70%	-0.224*	-0.027	-0.047	-0.143	-0.188	-0.209	-0.229*
85%	-0.969*	-0.825*	-0.803*	-0.830*	-0.882*	-0.903*	-0.927*
Error between trials	0.386	0.453	0.416	0.397	0.386	0.391	0.393
Error within trials	0.561	0.681	0.625	0.607	0.599	0.589	0.575

4 Discussion

The present paper analyses the pruning effects on growth of *Eucalyptus grandis* x *Eucalyptus urophylla* after canopy closure with high initial density (1111 trees per hectare). At the establishment of the experiment the lower crown of the trees was undergoing mortality. Growth losses caused by pruning conducted before canopy closure or on trees planted at wider spacing are likely to be more pronounced than the response shown in this study. Under close spacing, eucalyptus trees tend to present an accentuated natural crown rise (RYAN et al., 2004). This phenomenon results in the lower part of the crown not contributing much to tree growth (MONTAGU; KEARNEY; SMITH, 2003). Since pruning was conducted in all trees of the stand, discussion and management implications are restricted to this type of pruning regime. Dominant loss of pruned trees in relation to unpruned trees might occur for high level selective pruning operations (ALCORN et al., 2008; PINKARD; BEADLE, 1998a).

Diameter growth response to pruning is linked to site productivity. For instance, Forrester et al. (2012a) reported that pruning *E. nitens* in unfertilized treatment caused less influence in stand development when compared to unpruned trees in a nitrogen enriched treatment. Three years after pruning, trial 2 presented a higher dbh growth rate for unpruned trees than trial 1. This higher productivity site presented a larger dbh growth reduction between unpruned trees and the highest pruning treatment (8.2%), compared to the lower productivity site (5.9%). For the lowest productivity site (trial 1), the 70% pruning treatment presented mean diameters statistically equal to the unpruned treatment, while a significant difference occurred in the higher productivity site (trial 2).

Pruning treatments had little effect on dbh increment. After 9 months of the pruning intervention, the most drastic pruning treatment (85%) was able to reach the same increments as the unpruned treatments (figure 1). The recovery time for the 70% treatment was even shorter, reaching unpruned increment growth 6 months after the pruning intervention. While the 70% pruning treatment was able to present mean dbh values similar to unpruned trees three years after pruning, the mean dbh of the 85% treatment was permanently affected. Longer diameter growth recovery periods post pruning for *Eucalyptus pilularis* and *E. cloeziana* were reported by Alcorn et al. (2008), 8 and 12 months for 50 and 70% green crown length removal, respectively.

Diameter growth response was more sensitive to pruning effects than height in both trials. This can be explained considering priority of carbon allocation for biomass accumulation in trees, where foliage growth (and thus height growth) can be ranked as being of greater importance than stem growth (Dobbertin 2005).

While higher pruning treatments presented higher slenderness values, all treatments had elevated slenderness values. Once thinning occurs in the stands, augmented diameter growth will reduce the slenderness values. Low slenderness values (e.g. lower than 1) are associated with wind resistant trees growing under low growth strains (BIECHELE; NUTTO; BECKER, 2009; WOOD et al., 2008). Both these characteristics are desirable for stands managed for solid wood products. This way, in high wind prone areas, it might be adequate to restrict pruning operations so as to not reduce diameter development and consequently slenderness values.

This study showed that while a desired maximum pruning height that promotes clear wood production without negatively affecting tree growth exists, there might also be an undesired minimum pruning height that negatively affects tree growth in the long term. Approximately 3 years after the pruning intervention, the 40% of total tree pruned height treatment presented lower mean diameter values when compared to the higher pruned heights of 55% and 70% for trial 1 and 55% for trial 2. This behavior could occur due to the reason that in a light pruning operation (e.g. 22% of removed green crown), trees are exposed to the negative effects of leaf area removal without benefiting from the positive effects on canopy characteristics.

Pruning causes changes in canopy architecture, biomass partitioning and up-regulation of photosynthesis in remaining leaves (FORRESTER; BAKER, 2012). The negative effects of green crown removal in canopy dynamics include: a) decrease in leaf area resulting in reduced capacity of the tree to assimilate carbon and absorb photosynthetically active radiation (FORRESTER et al., 2013; PINKARD; BEADLE, 1998b); and b) loss of nutrients from the removed branches that would be remobilized in the crown (TAGLIAVINI; MILLARD; QUARTIERI, 1998). The positive effects of green crown removal in canopy dynamics include: a) increase in remaining foliage efficiency as determined by biomass increment per unit leaf area (BANDARA et al., 1999; FORRESTER et al., 2012b); b) increase in the photosynthetic rate of remaining foliage with the increase of CO_2 assimilation (FORRESTER et al., 2012b; PINKARD et al., 1998); c) reduced stand respiration (FORRESTER et al., 2012b); and d) increased water used efficiency, light use efficiency and specific leaf area (FORRESTER et al., 2012b; 2013).

This way, the interaction between the different positive and negative effects of pruning may have reduced growth capacity of the 22% green crown removal pruning regime, resulting in greater growth response of more intensive pruning regimes in the long term.

4.1 Management implications

Two different approaches for the management of eucalypt for solid wood products are possible: intensive and multiproduct management. Intensive forest management can be defined as the manipulation of soil and stand conditions to ameliorate factors that limit tree growth (FOX, 2000). In the case of intensive forest management, this means controlling stand density in order to use the high diameter increment potential of *Eucalyptus grandis* in the first 3 years, which can be as high as 4 to 7 cm per year (NUTTO; SPATHELF; SELING, 2006). In practical terms this is accomplished by initial planting at low densities (about 550 trees per hectare) or by an early thinning to waste operation (thin to about 550 trees per hectare prior to or just after canopy closure).

Whereas intensive management focuses in the growth of a limited number of candidate trees, multiproduct forest is concerned in the growth of the stand as a whole. A typical joint management system for the production of cellulose or biomass material from thinning harvests and solid products from final cuts was described by Maestri (2003). In this system, an initial planting density of 1111 trees per hectare is thinned to 450 trees per hectare at age 5 to 6 years, and a second thinning operation is carried out at age 8 to 9 years to 250 trees per hectare, with a clear cut after age 15 years.

The results of this study imply that 70% and 85% pruning treatments resulted in lower mean dbh values when compared to the unpruned treatment. Since these stands will be thinned down to 450 trees per hectare, this growth loss will be compensated by the higher amount of clear wood produced by higher pruning. While the 85% treatment reduced mean dbh values even for the 140 thickest trees per hectare, the 70% treatment only presented lower growth than unpruned for the 830 thickest trees per hectare. This implies that the residual stands of unpruned or pruned to 70% total tree height will be equal for thinning operations that leave at least 700 trees per hectare.

The results found in this study have important implications for the management of eucalyptus for solid wood products considering a multiproduct management scheme. If first thinning wood production is not a priority, pruning can reach up to 70% of total tree height (62% of lower live crown removal) without affecting growth of a residual thinned stand. When greater importance is given to the production of the first thinning operation, less intensive pruning operations must be carried out (55% of total tree height or 43% of live crown removal) to ensure productivity equal to an unpruned stand. The possibility of this high pruning early in the life of the stand assures that mostly live branches are cut, facilitating the occlusion of the pruning wounds and consequently increasing wood quality.

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This article was written with Blas Mola-Yudego and José Roberto Soares Scolforo as co-authors.

ARTIGO 3 - Pruning effects on *Eucalyptus grandis* x *urophylla* planted at low density

ABSTRACT

The interest in *Eucalyptus* species as provider of raw materials for solid wood products is growing worldwide. Trees planted under wide spacing usually do not need early thinning operations, and since they develop large and long lasting branches, early pruning interventions become very important to ensure acceptable wood quality. The objective of this work is to evaluate the effects of different severities of pruning on *Eucalyptus grandis* x *Eucalyptus urophylla* growth. The pruning trial was installed in a one year old stand located in João Pinheiro, Minas Gerais, Brazil. The stand was managed under a silvopastoral regime, planted in 9x3 m spacing. Pruning treatments consisted in lower green crown removal at different tree heights: 0% (unpruned), 20%, 40%, and 60% of pruned total tree height. All trees in the sample plots had diameter at breast height (1.3 m) and total height measured prior to pruning and one year after pruning. The effect of pruning on tree growth was assessed considering two different resolutions, stand level and tree level effects. Considering the stand level analysis, pruning caused reduction on mean diameter and height values for treatments 40% and 60% pruned heights. Pruning up to 20% of total tree height resulted in mean stand attributes statistically equal to the unpruned treatment. The tree level analysis showed that for the two intermediate treatments, pruning reduced growth of the smallest trees of the stand, while the largest trees were able to present growth similar to the unpruned trees.

INDEX TERMS

Solid Wood Products, Silvicultural Intervention, Forest Management

RESUMO

O interesse em espécies de *Eucalyptus* como fornecedoras de matéria prima para produtos de madeira sólida é crescente no âmbito mundial. Árvores plantadas em espaçamentos amplos geralmente não necessitam de operações de desbaste precoce, e como desenvolvem galhos grandes, intervenções de poda se tornam importantes para garantir qualidade da madeira. O objetivo deste trabalho é avaliar os efeitos de diferentes severidades de poda no crescimento de *Eucalyptus grandis* x *Eucalyptus urophylla*. O experimento foi instalado em um talhão com um ano de idade, em João Pinheiro, Minas Gerais, Brasil. O talhão foi manejado em esquema silvipastoril, com espaçamento de 9x3 m. Os tratamentos consistiram na remoção da porção inferior da copa viva a diferentes alturas: 0% (não podada), 20%, 40%, e 60% da altura total da árvore podada. Todas as árvores das parcelas tiveram diâmetro a altura do peito (1,3 m) e altura total medidas antes e um ano após aplicação de poda. O efeito da poda no crescimento florestal foi avaliado considerando dois níveis: do talhão e da árvore. Considerando a análise no talhão, a poda causou redução nos valores médios de diâmetro e altura para os tratamentos 40% e 60% da altura podada. Poda até 20% da altura total da árvore resultou em atributos médios do talhão estatisticamente iguais ao tratamento sem poda. A análise por árvore mostrou que nos dois tratamentos intermediários houve redução no crescimento das menores árvores, enquanto as maiores árvores foram capazes de apresentar crescimento similar às árvores não podadas.

TERMOS PARA INDEXAÇÃO

Produtos de Madeira Sólida, Intervenção Silvicultural, Manejo Florestal

INTRODUCTION

Considering the silvicultural tools available to forest managers to grow trees for solid wood products, thinning and pruning are among the most important. While thinning allows target trees to grow to large diameters by means of stand competition reduction, pruning is associated with wood quality enhancement through clear wood production.

To minimize the cost of pruning, only stems to be grown for the final crop are generally pruned (NEILSEN; PINKARD, 2003). Under these circumstances, a thinning operation is usually combined with the pruning operation to avoid that pruned trees lose vigor in relation to unpruned neighbors. Early thinning operations are usually unnecessary when trees are planted at low densities, making pruning the main silvicultural operation to enhance wood quality.

The wood formed after recovery from pruning will be free of defects and therefore will achieve greater strength properties and yield lumber that earns a high grade (O'HARA, 2007). Pruning yields best results when applied to live green branches. For instance, Smith, Dingle and Kearney (2006) found that while branch occlusion rates did not differ between pruned and unpruned dead branches, it was significantly lower for pruned live branches in comparison to unpruned live braches. This implies that pruning interventions must anticipate branch mortality, which occurs early for fast growing shade intolerant species, such as many *Eucalyptus* species.

The timing and severity (e.g. pruned height) of the pruning operation will determine the size of the defect core of the tree. This defect core contains the inner unpruned portion of a pruned log, making logs with small defect cores more valuable than logs with large defect cores. The ideal timing and severity of pruning should be planned in a way as to minimize the defect log by pruning as early and as high as possible without negatively affecting clear wood production.

The objective of this work is to evaluate the effects of different pruning heights on diameter and height growth of a *Eucalyptus grandis* x *Eucalyptus urophylla* stand planted at low initial density. The main hypothesis of this work is that higher pruning interventions will result in trees with smaller mean diameters, with no effects in height development.

MATERIAL AND METHODS

The present study was carried out in a *Eucalyptus grandis* x *E. urophylla* (clone I144) stand, in the municipality of João Pinheiro, Minas Gerais, Brazil, located at coordinates 17° 44’ 26” S and 46° 10’ 27” O. The climate of the region is characterized as tropical, with the following attributes: mean annual precipitation of 1,250 mm concentrated from October to March; mean annual temperature of 23.9° C; mean altitude of 540 m.a.s.l.; the soil in the stand was classified as an oxisol with sandy loam texture.

Silvicultural operations conducted before planting consisted in a sub soil ripping operation at 50 to 60 cm deeps with simultaneous addition of reactive phosphate rock at 30 cm deep at a concentration of 600 g/plant. Post planting fertilizer applications consisted of: ten days after planting applying 120 g/plant of NPK (6-30-6); eight months after planting applying 180 g/plant of NPK (10-0-30 + 1% B + 0.5% Zn + 0.5% Cu); one year after planting applying the same dosage as the prior fertilization.

The stand is intended to be used in a silvopastoral regime, and as such the initial planting density was of 9x3 m. The trial was installed when the stand reached one year of age. Pruning treatments consisted in lower green crown removal at different total tree heights: 0% (unpruned), 20%, 40%, and 60%. The mean pruned heights were of 0, 1.2, 2.4, and 3.5 meters for treatments 0%, 20%, 40%, and 60%, respectively. At the time of pruning intervention, lower tree crowns did not present natural pruning or branch mortality, and as such the tested pruning heights also represent total live crown height removal. A randomized complete block design was used, consisting of four treatments and five repetitions. The sample plots consisted of five rows and fourteen trees per row, with a measurement area of 30 trees (ten trees per central rows). All trees of each plot had diameter and height measured prior to treatment installation and one year after pruning. At the moment of the pruning intervention, the stand presented mean diameter value of 5.5 cm and mean height value of 5.9 m.

Statistical analysis

Influence of pruning in eucalyptus clones was assessed considering two different scales, stand and tree level. To evaluate pruning effects at the stand level, diameter and height mean plot values were assessed using analysis of variance (ANOVA). Upon significant difference detected in the ANOVA test, the Scott Knott post hoc test (SCOTT; KNOTT, 1974) was applied to the separate different pruning treatments. This test was chosen since it is considered to be more robust in controlling type I errors (BORGES; FERREIRA, 2003)

Linear regression models were used to evaluate pruning effects at tree level. One year diameter and height increment were related to tree size prior to pruning with treatment inserted as a factor variable (model 1). To account for the lack of independence of trees belonging to the same blocks, linear mixed models were used. A random variable was inserted in the model to account for block variance.

$$ix_{lk} = \beta_0 + \beta_1 * x_{lk} + \beta_2 * T_k + \beta_3 * (x_{lk} * T_k) + u_l + e_{lk} \qquad (1)$$

where ix is tree diameter or height increment one year after pruning; x is tree diameter or height at the moment of the pruning intervention; and T is a factor variable to account for treatment variability. Subscripts l and k refer to block and tree, respectively. ul and elk are independent and identically distributed random between-block and between-tree factors with a mean of 0 and constant variances of σ^2_{bl}, and σ^2_{tr}, respectively.

All statistical inferences were performed using the program R (R CORE TEAM, 2012) and the following packages: Jelihovschi, Faria and Oliveira (2012) and Pinheiro et al. (2012).

RESULTS AND DISCUSSION

The ANOVA results showed that not only did pruning affect mean stand diameter values ($F(3, 12) = 3.91$, $p = 0.04$, CV = 5.31%), but also mean height values ($F(3, 12) = 3.87$, $p = 0.04$, CV = 5.34%). According to the Shapiro-Wilk, both ANOVA models presented residuals with mean zero and normally distributed ($W = 0.95$, $p = 0.40$ and $W = 0.97$, $p = 0.68$ for diameter and height, respectively). Homogeneity of variances between treatments was identified by the Bartlett test (chi-square = 2.47, $p = 0.48$ and chi-square = 1.00, $p = 0.80$ for diameter and height, respectively). Table 1 presents mean stand diameter and height values one year after pruning along with the Scott Knott mean grouping results.

Table 1 Influence of different pruning heights one year after intervention on mean stand diameter (d) and height (h) values, values followed by the same letter are statistically equal according to the Scott Knott test at a 0.05 level of significance. Numbers in parenthesis represent the standard error.

T (%)	d (cm)		h (m)	
0	12.1 (0.4)	a	12.4 (0.4)	a
20	11.7 (0.4)	a	12.1 (0.6)	a
40	11.2 (0.3)	b	11.5 (0.2)	b
60	10.9 (0.3)	b	11.2 (0.5)	b

The results presented in Table 1 confirmed the hypothesis that higher pruning causes growth reduction on diameter growth. However, the hypothesis that pruning does not influence height devolvement was rejected.

Regression analysis confirmed that tree growth loss due to pruning followed the same behavior as mean stand level growth reduction. Table 2 presents the results of the parameterization of the diameter and height increment models. Figure 1 shows the behavior of the equations considering different diameter and height starting points. Visual analysis of residual dispersion of both models did not indicate any undesired trend that could negatively influence model performance.

Table 2 Parameterization of the diameter and height increment models at the tree level.

	Diameter increment			Height increment		
Parameter	Value	Std. Error	*p*-value	Value	Std. Error	*p*-value
β0	9.4269	0.523	0.000	10.8216	0.668	0.000
β1	-0.5245	0.072	0.000	-0.7317	0.078	0.000
T20	-2.3459	0.547	0.000	-3.0305	0.610	0.000
T40	-2.1910	0.487	0.000	-1.7550	0.552	0.002
T60	-0.5082	0.581	0.382	-1.5752	0.664	0.018
T20*x	0.3458	0.096	0.000	0.4636	0.102	0.000
T40*x	0.2799	0.088	0.002	0.1653	0.094	0.079
T60*x	-0.1246	0.104	0.230	0.0555	0.111	0.617
σ^2_{bl}		0.556			1.175	
σ^2_{tr}		0.696			0.532	

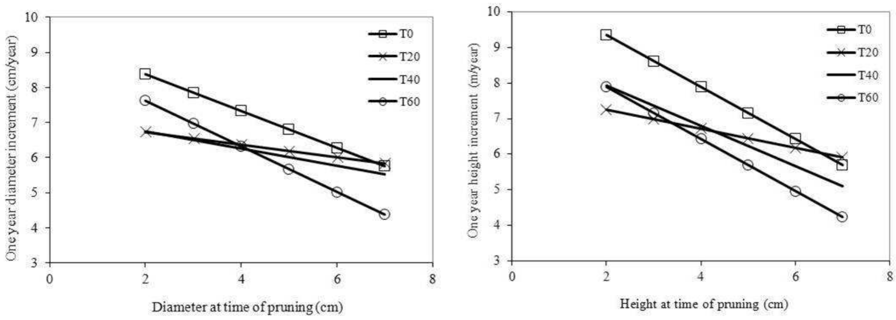

Figure 1 Behavior of one year diameter (a) and height (b) increment considering different tree sizes at the moment of the pruning intervention.

The present paper studied the effects of pruning prior to canopy closure on growth of clonal *Eucalyptus grandis* x *E. urophylla* trees planted at a low initial density (370 trees per hectare). Canopy closure can be defined as the moment when the crowns of adjacent trees touch each other. The results of this experiment are still at a young age, as such it is important to note that the impact of green crown pruning in tree and stand growth may vary as the stand approaches maturity and as successive pruning operations are applied.

The amount of lower green crown that can be removed from *Eucalyptus* trees in pruning operations without resulting in growth loss have been reported by many different authors (e.g. BRENDENKAMP; MALAN; CONRADIE, 1983; PINKARD; BEADLE, 2000; MONTE et al., 2009). A general consensus is that 40 to 50% of the lower green crown can be removed without affecting tree growth (PINKARD; BEADLE, 1998; ALCORN et al., 2008; FORRESTER et al., 2010). However, these results have mainly focused in pruning at the moment or just after canopy closure, when the lower tree crown had begun undergoing mortality due to excessive shading. The moment of canopy closure is dependant on the planting density and growing conditions (BEADLE, 1997; MONTAGU; KEAMEY; SMITH, 2003). For *Eucalyptus* species, canopy closure usually occurs between the ages of 1 and 4 years (MEDHURST et al., 1999; RYAN et al., 2004). At the moment of canopy closure, the tree's lower crown does not contribute much in terms of carbon allocation and tree growth (MONTAGU; KEAMEY; SMITH, 2003), allowing high levels of green crown removal (up to 50%) without affecting tree growth.

When pruning occurs much after canopy closure, or in crowed stands, even higher pruning heights can be achieved without affecting tree growth. For instance, Finger et al. (2001) reported that pruning up to 80% of total tree height did not significantly reduce *Eucalyptus saligna* height and diameter growth in a high density stand (4x1.5 m). Regarding late pruning, Muñoz et al. (2008) related that pruning *Eucalyptus nitens* trees up to 7 m heights at the age of 6 years did not affect growth or aboveground biomass production.

The results found in this study indicated a stronger response of growth loss following pruning than usual, with mean stand attributes suffering reduction with the removal of 40% of lower green crown onwards. This probably occurred due to the canopy characteristics of the stand at the time of pruning application. The lower tree crowns were not undergoing mortality at the time of pruning. This was due to the early moment of pruning intervention and the wide spacing applied at installation. Thus, the lower crown of the trees was still contributing to tree growth, and its removal affected tree development.

These results are in conformity with other pruning trials in *Eucalyptus* species when conducted prior to canopy closure and planted at low density. For instance, Pinkard (2002) found that 20% leaf area removal of pre-canopy closure *Eucalyptus nitens* trees caused stem growth reduction. Fontan et al. (2011) reported diameter growth reduction for a *Eucalyptus camaldulensis* x *Eucalyptus grandis* clone established in 9.5x4.0 m spacing when pruning all trees of the stand, removing 33% of live crown height plus removal of some thick branches above this height in three lifts. To avoid growth reduction in these stands, the aforementioned authors recommended pruning interventions removing 33% of live crown height plus removal of some thick branches above this height in four lifts (beginning at age 9 months with 6 month intervals) only for trees selected for final harvest (60% of the stand).

As for the tree level analysis, smaller trees presented the largest diameter and height increments, regardless of the pruning treatments. The tree level analysis also indicated that, for the two intermediate pruning treatments, growth reduction was mainly concentrated on the smaller trees of the stand, with larger trees presenting growth similar to unpruned trees (Figure 1). This helps to explain why the 20% pruning treatment presented mean stand attributes statistically equal to the unpruned treatment, since the growth of the larger trees were able to compensate the growth loss of the smaller trees.

CONCLUSION

The tested pruning heights reduced eucalypt height and diameter development when more than 20% of the lower live green crown was removed. From a management perspective, this suggests that it should be possible to implement a light pruning prior to canopy closure (e.g. removing up to 20% of lower green crown), and more severe pruning post-canopy closure (e.g. removing up to 50% of lower green crown), without affecting stem growth.

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ARTIGO 4 - Evaluating different initial spacing and thinning intensity for *Eucalyptus* plantations in Brazil

Abstract

The management of *Eucalyptus* plantations for solid wood products requires that stands be thinned in order to reduce competition for a selected number of final crop trees, allowing these trees to attain dimensions suitable for commercial purposes. This study focuses on the effects of different thinning regimes on clonal *Eucalyptus* plantations growth. For this, 8 different trials located in Bahia and Espírito Santo States were used. Aside from thinning, initial planting density, and post thinning fertilization application was also evaluated. Four of these trials were planted in 1999 and the other four between 2003 and 2004. Before canopy closure, and therefore before excessive competition between trees took place, it was found that stands planted under low densities (under 700 trees per hectare) presented a lower mortality proportion as well as higher diameter growth when compared to stand planted under high densities (1111 trees per hectare). After canopy closure and the application of the thinning treatments, it was found that thinning regimes beginning early in the life of the stand and leaving a low number of residual trees presented the highest diameter and height growth. Unthinned treatments and thinning regimes late in the life of the stand, leaving a large number of residual trees presented the highest values of basal area production. The choice of the best thinning regime for *Eucalyptus* clonal material will vary according to the objective of growing the plantation.

Keywords: Solid wood products, growing space, forest management.

1 Introductionll

Of Brazil's 7 million hectares of planted forests, 70% are constituted of eucalyptus forests. The majority of these eucalypt forests are destined for energetic and pulping purposes, characterized by high planting densities, few silvicultural interventions after establishment and short rotation lengths. Of the total Brazilian eucalyptus industrial round wood production in 2011 (118 million m^3), about 10% was destined for solid wood products (plywood, sawn wood, and treated wood) with the remainder destined for cellulose (45%) charcoal (14%) and fire wood (30%) purposes (ASSOCIAÇÃO BRASILEIRA DE PRODUTORES DE FLORESTAS PLANTADAS, ABRAF, 2012).

The use of eucalyptus for the production of solid wood products is an attested possibility, with many successful commercial examples available. Specifically in Brazil, the product Lyptus® is a high quality eucalyptus kiln dried wood, which is used in the manufacture of furniture and floor desks (TEIXEIRA et al., 2009).

According to the International Tropical Timber Organization, ITTO (2009), in 2009 Brazil produced circa 15.5 million cubic meters of tropical sawn wood, of which 93% was for domestic use. These figures make Brazil the world's largest consumer of tropical sawn wood. The production of quality wood from planted eucalyptus forests for solid products purposes can help to alleviate the pressure of wood demand from native Brazilian forests.

There is no doubt that thinning leads to an increase in the growth rates of retained crop trees; however, there is little information that enables the prediction of the magnitude of these responses which are likely to vary with many factors including site and species (FORRESTER et al., 2010).

This research focuses on the analysis of the behavior of *Eucalyptus grandis* hybrids cultivated in the Brazilian Coastal Region of Bahia and Espírito Santo states submitted to different initial spacing and thinning regimes. This information is crucial for decision support in forestry decision-making, allowing the generation of optimal management schedules for eucalypt solid wood production.

2 Material and methods

Stand establishment

The data consisted of 311 plots in eight different thinning experiments. Table 1 presents the characteristics of the different experiments. Four of the experiments were conducted in stands planted at year 1999 using clone 3918; and four experiments were conducted in stands planted at year 2003 and 2004 using different clones. Trial 117 was located in Espírito Santo State (grid reference 19° 42' S 40° 12' W), the rest of the trials were located in Bahia State (all trials located in a 40 km radius from the central grid reference 17° 58' S 39° 42' W).

Table 1 Characteristics of the eight eucalyptus different thinning trials used in this study; SI is the site index corresponding to the mean dominant height at age 12 years.

Trial	Clone	Year	Number of treatments	Final densities tested (N/ha)	Initial spacing (m)	SI (m)
117	A	1999	12	150 - 1111	3x3	34.6
118	A	1999	12	150 - 1111	3x3	43.2
119	A	1999	10	150 - 667	6x2,5	39.2
120	A	1999	12	150 - 1111	3x3	36.3
127	B	2003	5	250 - 555	6x3	37.4
130	B	2004	8	250 - 1111	3x3 and 6x2,7	33.9
131	C	2004	5	250 - 1111	3x3 and 6x2,7	37.2
132	D	2004	8	250 - 1111	3x3 and 6x2,7	37.9

All the stands used in this study are planted in areas that were previously eucalyptus forests. Silvicultural operations conducted before planting consisted in weed control using a glyphosate product and a sub soil ripping operation at 40 to 60 cm deeps.

The fertilization done at planting was roughly the same for all experiments, including the application of: 2 t/ha of dolomitic limestone, 14 kg/ha of nitrogen, 29 kg/ha of phosphorus, 11 kg/ha of potassium, 56 kg/ha of phosphorous applied with the sub soiling operation.

All the stands received post-planting fertilization, with differences between the four older and four younger experiments. The older experiments received two post-planting fertilizer applications of: 100 kg/ha of potassium at age 1 year 6 months; 20 kg/ha of nitrogen and 50 kg/ha of potassium at age 2 years 9 months. The younger experiments received four post-planting fertilizer applications consisting of: 36 kg/ha of nitrogen, 50 kg/ha of potassium and 2 kg/ha of boron at age 3 months; 25 kg/ha of nitrogen and 62 kg/ha of potassium at age 1 year; 40 kg/ha of nitrogen, 4 kg/ha of phosphorous and 33 kg/ha of potassium at ages 3 and 5 years.

Weed competition was kept under control using glyphosate application and manual control. Manual control was carried out for about three times in each experiment. Chemical control was conducted in 7 applications for the younger experiments and 5 applications for the older experiments. In the younger experiments three glyphosate applications were made before 1 year and one application at ages 1, 2, and 5. In the older experiments two glyphosate applications were made before 1 year and one application at ages 3, 6, and 8. When necessary, sprouting stumps of thinned trees were killed using glyphosate, usually one year after the stand’s thinning operation.

The trees of all treatments received two pruning operations at ages 1 year 8 months and 2 years 2 months. The pruning heights were 5 and 7.8 m at the first and second pruning, respectively.

Treatments

The thinning treatments were unthinned, one or two thinnings at different ages and number of trees remaining. Initial planting densities ranged from 555 to 1111 trees per hectare. Table 2 describes the thinning treatments carried out in the analyzed experiments.

All of the treatments showed in Table 2 consisted of four repetitions. The area of each plot depended on the number of remaining trees, with heavy thinning areas receiving larger plots. The areas of the plots varied from 438 m^2 for the unthinned plots to 1034 m^2 for the treatments with 150 trees/ha as a final density.

The initial planting densities of all the experiments are given in Table 1. Treatments 1 through 3 of experiments 130, 131, and 132 were planted at 3.0 x 3.0 m (1111 trees/ha), and the remaining treatments of the aforementioned experiments at spacing of 6.0 x 2.7 m (617 trees/ha).

Experiments 117 through 120 were divided into two blocks with two repetitions each, where a post thinning fertilization treatment was installed. After the realization of the first thinning treatment, the following fertilizer application was implemented: 35 kg/ha of nitrogen, 61 kg/ha of phosphorous, 105 kg/ha of potassium and 1.5 t/ha of dolomitic limestone. After the second thinning treatment the fertilization was: 37 kg/ha of nitrogen and 111 kg/ha of potassium.

Yearly measurements of diameter at breast height and height were made on all trees.

Table 2 Thinning treatments applied to the *Eucalyptus* stands and mean basal area before and after the last thinning operation. The basal area of unthinned control plots is from the first available measurement (the age of the earliest thinning of the experiment).

	Age	Density	Basal area (m^2/ha)		
Treatments	(years)	(trees/ha)	Pre-thinning	Post-thinning	% removed
Trials 117, 118, and 120					
1	0	1111	12.5	12.5	0.0
2	3.5 and 6.5	600 and 300	18.8	10.7	43.1
3	3.5	300	18.4	6.7	63.8
4	3.5	150	18.0	3.6	80.3
5	3.5 and 6.4	600 and 150	18.4	5.7	69.1
6	5	450	20.6	10.7	48.1
7	5 and 7	450 and 250	16.2	9.8	39.7
8	2.5 and 5.5	600 and 300	17.7	10.8	39.1
9	2.5 and 5.5	600 and 150	18.2	5.5	69.8
10	2.5	300	11.7	4.5	61.5
11	2.5	150	12.2	2.4	80.7
12	0	1111	12.5	12.5	0.0
Trial 127					
1	0	555	13.3	13.3	0.0
2	3 and 5	450 and 250	16.1	9.1	43.4
3	3	250	12.5	6.8	45.6
4	5 and 7	450 and 250	19.3	11.6	39.8
5	5	250	18.1	9.6	47.0

continues…

Continuation of Table 2

Thinning Treatment	Age of thinning (years)	Post-thinning density (trees/ha)	Basal area (m^2/ha) Pre-thinning	Post-thinning	% reduction
Trial 119					
1	0	667	10.6	10.6	0.0
2	3.5	300	15.7	8.0	48.8
3	3.5 and 6.2	400 and 250	17.0	11.7	31.1
4	3.5	150	16.7	4.5	72.7
5	5 and 7	250 and 150	12.4	9.8	20.3
6	5	250	19.5	8.7	55.3
7	2.5 and 5.5	400 and 250	18.2	12.2	33.1
8	2.5 and 5.5	400 and 150	17.1	6.8	60.3
9	2.5	300	10.5	5.4	48.8
10	2.5	150	10.7	2.8	74.1
Trials 130, 131, and 132					
1	0	1111	10.4	10.4	0.0
2	5	450	22.8	10.1	55.7
3	5	250	21.8	6.1	72.2
4	0	617	8.3	8.3	0.0
5	2 and 5	450 and 250	14.6	8.6	41.4
6	2	250	8.1	3.7	54.7
7	5	450	16.9	13.5	20.4
8	5	250	16.9	7.9	53.2

Data Methods

Establishment Mortality

Using the number of trees planted per plot and the number of trees present at the time of the first measurement, mortality proportion was calculated for each plot. These values were used to check if alternative planting densities affect the mortality levels. Only plots with no thinning interventions and below 5 years of age where used for this analysis. All treatments were pooled for this analysis. The data was stratified considering two groups, low initial planting density (under 700 trees per hectare) and high initial planting density (1111 trees per hectare).

Growth at the time of establishment

To determine the effect of the initial spacing and clone in plantation forests a distinction was made between measurements taken before and after canopy closure. This distinction was made since early diameter growth is accelerated at very young ages. Thus, to establish the effect of treatments at tree size up to the time of thinning application only plot measurements younger that 3.5 years were chosen, picking the oldest possible measurement for each plot prior to any thinning intervention. All treatments were pooled for this analysis.

Model (1) was formulated to test for variation on mean tree diameter growth in relation to spacing and genetic material as follow:

$$\mathrm{id}_{lk} = \beta_0 + \beta_1 * \mathrm{GM} + \beta_2 * \mathrm{PD} + u_l + \mathrm{e}_{lk} \qquad (1)$$

where *id* is tree diameter growth at during or right after canopy closure (cm per year); *GM* is a factor variable for the genetic material; *PD* is a factor variable of the initial planting density (trees/ha). Subscripts *l* and *k* refer to plot and tree, respectively. *ul* and *elk* are independent and identically distributed random between-plot and between-tree factors with a mean of 0 and constant variances of σ^2_{pl}, and σ^2_{tr}, respectively. This statistical model was parameterized using the program R (R CORE TEAM, 2012) and the nlme package (PINHEIRO et al., 2012).

Post establishment growth

Analysis of variance (ANOVA) using a split plot in time scheme (as presented in CASELLA, 2008) was used to asses the effect of thinning on tree and stand growth. The variables analyzed were: diameter at breast height (DBH, measured at 1.3m from the ground), diameter at breast height of the 100 thickest trees per hectare (DBH100), diameter at breast height of the 200 thickest trees per hectare (DBH200), total height (H), dominant height (H100, mean height of the 100 thickest trees per hectare), stand basal area (G), stand basal area of the 100 thickest trees per hectare (G100) , stand basal area of the 200 thickest trees per hectare (G200). The statistical software SISVAR (FERREIRA, 2008) was used to perform the ANOVA. For the experiments with the fertilizer trial, a significant distinction between blocks in the ANOVA was regarded as fertilizer effects.

3 Results and Discussion

Mortality

Figure 1 presents the mortality proportions that occurred in the plots prior to any thinning operation. The data clearly shows that higher density initial spacing establishment presents higher mortality than lower densities.

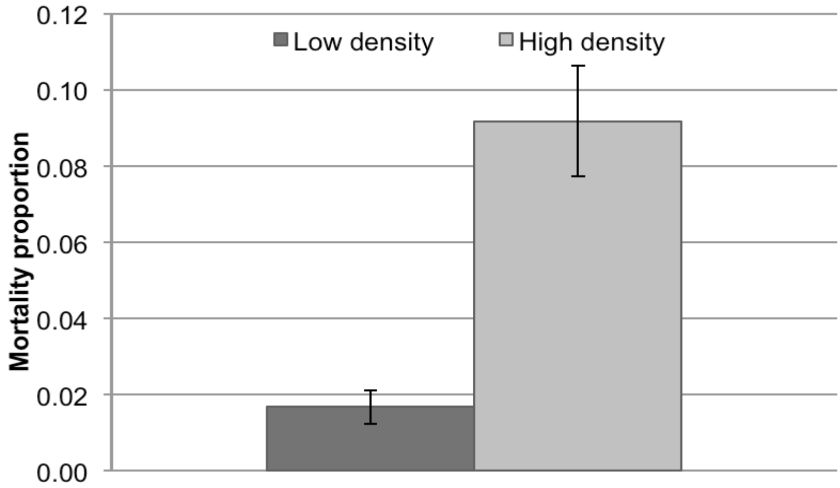

Figure 1 Mortality proportions considering high (1111 trees/ha) and low (under 700 trees/ha) initial planting densities.

Higher mortality proportions found under higher density stands is consistent with other studies, such as Schneider et al. (2005) and Leite, Nogueira and Moreira (2006). This can be attributed to the lower competition suffered by trees under low densities.

Growth at the time of establishment

The results of Table 3 account for the difference in initial diameter increment for the different clones and spacing tested, prior to canopy closure or thinning operations.

The difference between the most and least productive clones was approximately 7 %. As for the different planting densities, the plots with 555 and 617 trees/ha presented the highest and statistically equal diameter development. Higher densities cause significant diameter growth reduction, with the smallest diameter growth occurring in the plots established with 1111 tree/ha

(4.7 cm per year). Plots established with densities under 617 trees per hectare presented mean diameter increment values of 6.0 cm per year prior to canopy closure. This high initial diameter growth under low planting density is consistent with the high diameter increment potential of many *Eucalyptus* species of 4 to 7 cm per year in the first 3 years (NUTTO; SPATHELF; SELLING, 2006).

Table 3 Estimates of the parameters and variance components of the initial establishment model (annual diameter increment as a function of genetic material and planting density). The mean intercept value represents a stand of 555 trees per hectare of the clone B.

Parameters	Value	Standard Error	p-value
Intercept	5.954	0.113	0.000
GM D	0.183	0.127	0.151
GM A	0.352	0.121	0.004
GM C	0.390	0.127	0.002
PD 617	-0.152	0.150	0.311
PD 667	-0.897	0.188	0.000
PD 1111	-1.286	0.159	0.000
σ^2_{pl}	0.500	-	-
σ^2_{tr}	0.636	-	-

Post establishment growth

Tables 3 and 4 present the results of the analysis of variance for all trials and variables analyzed. Thinning, age or the interaction between thinning and age were statistically significant for all the variables analyzed.

Table 3 Summary of the analysis of variance using a split plot in time formulation to determine the effect of thinning treatment on different aspects of tree and stand growth for trials 117, 118, 119, and 120.

	Block			Thinning			Age			Thinning x Age		
Variable	df	F statistic	*P*-value	Df	F statistic	*P*-value	df	F statistic	*P*-value	df	F statistic	*P*-value
Trial 117												
DBH (cm)	1	99.797	<0.001	11	3163.713	<0.001	11	24176.395	<0.001	94	69.589	<0.001
Height (m)	1	28.231	<0.001	11	303.799	<0.001	11	6492.730	<0.001	94	1.619	0.001
G (m^2/ha)	1	102.779	<0.001	11	1721.049	<0.001	11	1921.324	<0.001	94	94.506	<0.001
DBH100 (cm)	1	27.961	<0.001	11	1549.597	<0.001	11	14351.096	<0.001	94	32.859	<0.001
G100 (m^2/ha)	1	42.080	<0.001	11	1517.472	<0.001	11	18293.943	<0.001	94	57.466	<0.001
DBH200 (cm)	1	33.518	<0.001	11	1608.169	<0.001	11	17378.951	<0.001	94	37.146	<0.001
G200 (m^2/ha)	1	29.243	<0.001	11	466.158	<0.001	11	9061.524	<0.001	94	14.307	<0.001
H100 (m)	1	4.826	0.050	11	117.044	<0.001	11	4846.172	<0.001	94	6.888	<0.001
Trial 118												
DBH (cm)	1	69.454	<0.001	11	1427.439	<0.001	11	18688.553	<0.001	94	32.435	<0.001
Height (m)	1	0.372	0.554	11	277.642	<0.001	11	6705.706	<0.001	94	0.000	1.000
G (m^2/ha)	1	80.895	<0.001	11	1287.606	<0.001	11	2445.334	<0.001	94	66.141	<0.001

continues…

Continuation of Table 3

	Block			Thinning			Age			Thinning x Age		
Variable	df	F statistic	*P*-value	Df	F statistic	*P*-value	df	F statistic	*P*-value	df	F statistic	*P*-value
DBH100 (cm)	1	2.708	0.128	11	660.207	<0.001	11	9730.176	<0.001	94	15.134	<0.001
G100 (m^2/ha)	1	3.931	0.073	11	655.678	<0.001	11	14278.795	<0.001	94	26.289	<0.001
DBH200 (cm)	1	59.347	<0.001	11	884.354	<0.001	11	14516.742	<0.001	94	21.701	<0.001
G200 (m^2/ha)	1	34.726	<0.001	11	157.088	<0.001	11	6667.872	<0.001	94	3.94	<0.001
H100 (m)	1	1.573	0.236	11	229.083	<0.001	11	4537.997	<0.001	94	0.000	1.000
Trial 119												
DBH (cm)	1	57.517	<0.001	9	183.778	<0.001	11	1436.315	<0.001	75	3.436	<0.001
Height (m)	1	29.151	<0.001	9	30.521	<0.001	11	593.399	<0.001	75	0.000	1.000
G (m^2/ha)	1	29.416	<0.001	9	330.084	<0.001	11	167.269	<0.001	75	18.37	<0.001
DBH100 (cm)	1	57.620	<0.001	9	98.535	<0.001	11	942.161	<0.001	75	3.498	<0.001
G100 (m^2/ha)	1	40.143	<0.001	9	106.321	<0.001	11	665.278	<0.001	75	5.609	<0.001
DBH200 (cm)	1	78.636	<0.001	9	94.433	<0.001	11	1084.748	<0.001	75	3.453	<0.001
G200 (m^2/ha)	1	48.540	<0.001	9	43.477	<0.001	11	876.534	<0.001	75	0.831	0.830
H100 (m)	1	58.094	<0.001	9	21.753	<0.001	11	686.037	<0.001	75	1.488	0.012

continues…

Continuation of Table 3

	Block			Thinning			Age			Thinning x Age		
Variable	df	F statistic	*P*-value	Df	F statistic	*P*-value	df	F statistic	*P*-value	df	F statistic	*P*-value
Trial 120												
DBH (cm)	1	2.549	0.139	11	1179.894	<0.001	11	2884.366	<0.001	94	25.582	<0.001
Height (m)	1	6.909	0.024	11	208.352	<0.001	11	4433.665	<0.001	94	0.000	1.000
G (m^2/ha)	1	22.556	<0.001	11	858.345	<0.001	11	351.990	<0.001	94	44.803	<0.001
DBH100 (cm)	1	47.068	<0.001	11	1536.892	<0.001	11	10256.817	<0.001	94	44.716	<0.001
G100 (m^2/ha)	1	78.772	<0.001	11	1359.601	<0.001	11	19618.103	<0.001	94	59.46	<0.001
DBH200 (cm)	1	36.879	<0.001	11	1898.255	<0.001	11	11411.448	<0.001	94	59.811	<0.001
G200 (m^2/ha)	1	23.173	<0.001	11	200.365	<0.001	11	5783.886	<0.001	94	6.162	<0.001
H100 (m)	1	6.284	0.029	11	297.354	<0.001	11	11446.951	<0.001	94	2.844	<0.001

Table 4 Summary of the analysis of variance using a split plot in time formulation to determine the effect of thinning treatment on different aspects of tree and stand growth for trials 127, 130, 131, and 132.

	Thinning			Age			Thinning x Age		
Variable	df	F statistic	*P*-value	df	F statistic	*P*-value	df	F statistic	*P*-value
Trial 127									
DBH (cm)	4	112.41	<0.001	4	1230.749	<0.001	16	13.167	<0.001
Height (m)	4	5.605	<0.001	4	1645.585	<0.001	16	2.351	0.008
G (m^2/ha)	4	34.075	<0.001	4	150.105	<0.001	16	2.779	0.002
DBH100 (cm)	4	61.689	<0.001	4	4741.566	<0.001	16	6.373	<0.001
G100 (m^2/ha)	4	65.014	<0.001	4	3675.775	<0.001	16	7.713	<0.001
DBH200 (cm)	4	63.425	<0.001	4	7223.504	<0.001	16	7.254	<0.001
G200 (m^2/ha)	4	66.418	<0.001	4	5005.285	<0.001	16	8.564	<0.001
H100 (m)	4	14.607	<0.001	4	2789.669	<0.001	16	3.211	<0.001
Trial 130									
DBH (cm)	7	127.006	<0.001	4	4693.43	<0.001	28	15.395	<0.001
Height (m)	7	116.719	<0.001	4	3524.076	<0.001	28	8.496	<0.001
G (m^2/ha)	7	794.914	<0.001	4	5164.628	<0.001	28	72.768	<0.001

continues…

Continuation of Table 4

	Thinning			Age			Thinning x Age		
Variable	df	F statistic	*P*-value	df	F statistic	*P*-value	df	F statistic	*P*-value
DBH100 (cm)	7	121.304	<0.001	4	14177.836	<0.001	28	16.068	<0.001
G100 (m^2/ha)	7	110.248	<0.001	4	4749.912	<0.001	28	17.002	<0.001
DBH200 (cm)	7	107.559	<0.001	4	14999.507	<0.001	28	15.267	<0.001
G200 (m^2/ha)	7	113.552	<0.001	4	4675.479	<0.001	28	16.668	<0.001
H100 (m)	7	162.975	<0.001	4	10954.894	<0.001	28	8.471	<0.001
Trial 131									
DBH (cm)	7	511.603	<0.001	4	722.168	<0.001	28	80.147	<0.001
Height (m)	7	188.331	<0.001	4	1953.735	<0.001	28	139.612	<0.001
G (m^2/ha)	7	1700.771	<0.001	4	731.974	<0.001	28	1003.224	<0.001
DBH100 (cm)	7	275.209	<0.001	4	1090.012	<0.001	28	38.639	<0.001
G100 (m^2/ha)	7	30.054	<0.001	4	112.298	<0.001	28	7.137	<0.001
DBH200 (cm)	7	258.678	<0.001	4	944.243	<0.001	28	34.313	<0.001
G200 (m^2/ha)	7	99.41	<0.001	4	314.631	<0.001	28	22.882	<0.001
H100 (m)	7	109.647	<0.001	4	2437.682	<0.001	28	63.287	<0.001

continues…

Continuation of Table 4

	Thinning			Age			Thinning x Age		
Variable	df	F statistic	*P*-value	df	F statistic	*P*-value	df	F statistic	*P*-value
Trial 132									
DBH (cm)	7	570.58	<0.001	4	1318.688	<0.001	28	139.576	<0.001
Height (m)	7	120.236	<0.001	4	2956.47	<0.001	28	148.238	<0.001
G (m^2/ha)	7	1178.771	<0.001	4	906.168	<0.001	28	790.166	<0.001
DBH100 (cm)	7	349.278	<0.001	4	1443.71	<0.001	28	65.48	<0.001
G100 (m^2/ha)	7	40.794	<0.001	4	157.018	<0.001	28	11.033	<0.001
DBH200 (cm)	7	278.328	<0.001	4	1334.43	<0.001	28	56.957	<0.001
G200 (m^2/ha)	7	114.319	<0.001	4	473.814	<0.001	28	32.158	<0.001
H100 (m)	7	58.921	<0.001	4	3489.064	<0.001	28	14.672	<0.001

The coefficients of variation associated with the treatment variable in the ANOVA's presented in Tables 3 and 4 were low, presenting a mean value of 3,4% and ranging from 0.7% (DBH200, trial 131) to 18.3 (G, trial 127). All the variables tested were influenced by the interaction of thinning and age or by thinning and age alone when the interaction was not significant. A post-hoc analysis using Fisher's least significant difference (LSD) was carried out. The results for the last measurement date (age 11.5 years for trials 117 through 120, 7 years for trial 127, and 6 years for trials 130 through 132) are presented in Tables 5 and 6.

Table 5 Results for the LSD post-hoc analysis for different tree and stand variables for the *Eucalyptus* thinning trials 127, 130, 131, and 132 at age 6 years (7 for trial 127), explanation of the treatments are given in Table 2. Numbers followed by the same letter on the columns are statistically equal.

Variable	Treatment	Trial 127		Trial 130		Trial 131		Trial 132	
DBH	1	22.6	a	17.2	a	17.5	a	17.0	a
	2	25.2	c	19.1	b	16.9	a	19.4	b
	3	27.0	d	19.8	cd	18.9	b	20.3	c
	4	23.4	b	19.4	bc	20.2	c	21.6	d
	5	26.4	d	22.0	ef	22.6	d	24.5	g
	6	-	-	22.6	f	25.2	f	25.4	h
	7	-	-	20.2	d	20.7	c	22.3	e
	8	-	-	21.6	e	19.8	bc	23.0	f

continues…

Continuation of Table 5

Variable	Treatment	Trial 127		Trial 130		Trial 131		Trial 132	
DBH100	1	25.0	a	20.0	a	20.5	a	21.2	a
	2	26.7	b	21.0	b	20.9	b	21.8	b
	3	28.3	c	20.8	b	20.6	a	22.2	c
	4	25.2	a	21.0	b	22.7	c	23.9	d
	5	27.7	c	23.1	e	24.3	e	26.1	f
	6	-	-	24.1	f	26.6	f	27.2	g
	7	-	-	21.6	c	22.6	c	24.0	d
	8	-	-	22.6	d	23.2	d	24.7	e
DBH200	1	24.4	a	19.7	a	20.0	b	20.6	a
	2	26.0	b	20.4	b	20.2	c	21.1	b
	3	27.6	d	20.3	b	19.8	a	21.0	b
	4	24.8	a	20.7	b	22.0	d	23.3	c
	5	26.9	c	22.5	e	23.3	f	25.0	e
	6	-	-	23.5	f	25.8	g	26.0	f
	7	-	-	21.2	c	22.1	d	23.5	c
	8	-	-	22.0	d	22.5	e	23.8	d
Ht	1	29.1	a	25.1	bc	26.5	bcd	25.5	a
	2	29.3	a	25.3	bc	23.4	a	26.2	ab
	3	29.3	a	25.3	bc	25.3	b	26.8	b
	4	30.9	b	25.4	c	27.8	de	28.4	cd
	5	29.7	a	24.7	b	27.3	cde	29.5	e
	6	-	-	22.9	a	28.4	e	29.2	de
	7	-	-	25.3	bc	28.4	e	29.1	de
	8	-	-	25.6	c	25.7	bc	28.0	c

continues…

Continuation of Table 5

Variable	Treatment	Trial 127		Trial 130		Trial 131		Trial 132	
H100	1	30.3	a	26.0	c	28.4	cd	28.0	b
	2	30.3	a	25.9	c	27.5	b	27.3	a
	3	29.9	a	25.6	c	26.4	a	27.7	ab
	4	31.7	b	26.0	c	28.8	df	29.4	d
	5	29.9	a	24.9	b	28.1	c	30.1	e
	6	-	-	23.7	a	28.8	df	29.6	de
	7	-	-	25.9	c	29.1	f	29.8	de
	8	-	-	25.8	c	29.1	f	28.8	c
G	1	21.7	b	26.5	g	25.4	h	24.7	g
	2	12.5	a	12.8	d	11.5	d	13.0	d
	3	12.1	a	8.1	a	7.4	a	8.4	a
	4	19.3	b	17.2	f	19.2	g	18.5	f
	5	13.2	a	9.8	bc	10.3	c	12.0	c
	6	-	-	10.4	c	12.7	e	13.1	d
	7	-	-	14.7	e	15.2	f	17.5	e
	8	-	-	9.4	b	8.8	b	10.8	b
G100	1	5.2	a	3.5	a	3.7	ab	3.9	a
	2	6.0	b	3.7	b	3.7	b	4.0	a
	3	6.7	d	3.6	ab	3.6	a	4.1	b
	4	5.3	a	3.7	b	4.3	c	4.8	c
	5	6.4	c	4.5	e	5.0	e	5.7	e
	6	-	-	4.9	f	5.9	f	6.2	f
	7	-	-	3.9	c	4.3	c	4.8	c
	8	-	-	4.3	d	4.5	d	5.1	d

continues…

Continuation of Table 5

Variable	Treatment	Trial 127	Trial 130	Trial 131	Trial 132
G200	1	9.3 a	6.1 a	6.3 a	6.7 a
	2	10.6 b	6.5 bc	6.5 a	7.0 b
	3	12.0 d	6.5 b	6.2 a	7.0 b
	4	9.6 a	6.8 c	7.6 b	8.6 c
	5	11.4 c	8.0 f	8.6 c	9.9 e
	6	- -	8.7 g	10.5 d	10.7 f
	7	- -	7.1 d	7.7 b	8.7 c
	8	- -	7.6 e	7.5 b	8.9 d

Table 6 Results for the LSD post-hoc analysis for different tree and stand variables for the *Eucalyptus* thinning trials 117, 118, 119, and 120 at age 11.5 years, explanation of the treatments are given in Table 2. Numbers followed by the same letter on the columns are statistically equal.

Variable	Treatment	Trial 117	Trial 118	Trial 119	Trial 120
DBH	1	18.3 a	22.0 a	24.8 a	18.8 a
	2	26.4 c	32.1 de	30.2 b	27.5 c
	3	27.7 d	32.2 ef	33.1 de	27.8 c
	4	33.2 f	39.1 i	37.4 fg	34.3 f
	5	30.9 e	35.6 h	32.1 cd	32.6 e
	6	23.8 b	28.2 c	32.8 de	24.7 b
	7	28.1 d	33.0 fg	34.1 e	28.0 c
	8	27.7 d	31.2 d	36.3 f	27.0 c
	9	32.7 f	38.9 i	30.8 bc	33.8 f
	10	28.1 d	33.2 g	38.4 g	29.3 d
	11	34.8 g	40.5 j	- -	33.5 ef

continues…

Continuation of Table 6

Variable	Treatment	Trial 117	Trial 118	Trial 119	Trial 120
DBH	12	17.9 a	24.9 b	- -	19.0 a
DBH100	1	23.6 a	29.1 a	30.2 a	24.6 a
	2	28.5 c	34.4 d	32.7 b	29.4 c
	3	30.1 d	34.9 d	34.6 cd	30.1 d
	4	34.0 f	39.9 f	39.1 f	35.5 h
	5	31.7 e	36.6 e	33.4 bc	33.6 f
	6	26.6 b	32.5 c	34.2 bc	27.4 b
	7	29.8 d	34.7 d	36.1 de	29.6 cd
	8	30.0 d	34.2 d	37.1 e	29.3 c
	9	33.7 f	40.1 f	33.5 bc	34.5 g
	10	30.3 d	36.2 e	39.7 f	31.6 e
	11	35.7 g	41.8 g	- -	36.6 i
	12	23.3 a	31.5 b	- -	24.0 a
DBH200	1	22.9 a	28.0 a	29.1 a	23.8 a
	2	27.6 c	33.4 cd	31.7 b	28.4 c
	3	29.1 de	33.9 d	33.7 cd	29.1 d
	4	33.2 g	39.1 g	37.4 fg	34.3 g
	5	30.9 f	35.6 f	32.1 b	32.6 f
	6	25.7 b	31.2 b	33.3 bcd	26.5 b
	7	28.6 d	33.6 d	34.9 de	28.6 cd
	8	28.9 de	32.8 c	36.3 ef	28.4 c
	9	32.7 g	38.9 g	32.5 bc	33.8 g
	10	29.2 e	34.8 e	38.4 g	30.4 e
	11	34.8 h	40.5 h	- -	35.8 h
	12	22.4 a	30.7 b	- -	23.3 a

continues…

Continuation of Table 6

Variable	Treatment	Trial 117		Trial 118		Trial 119		Trial 120	
Ht	1	29.8	a	36.5	a	35.1	a	29.6	a
	2	33.8	cde	41.6	de	38.0	cd	34.4	e
	3	33.6	cd	42.7	f	37.9	de	34.3	fg
	4	34.2	def	42.8	g	39.2	e	36.5	h
	5	34.4	fg	42.0	f	36.0	cde	35.9	ef
	6	31.1	b	40.8	h	38.7	f	32.4	e
	7	33.2	c	41.8	i	39.5	cd	34.5	g
	8	34.8	fgh	41.5	c	39.2	c	34.5	c
	9	34.3	efg	42.3	b	36.2	a	35.7	c
	10	34.8	gh	43.7	e	39.9	b	35.4	d
	11	35.2	h	43.9	d	-	-	34.0	d
	12	29.5	a	37.5	a	-	-	29.6	b
H100	1	33.9	cd	41.3	b	38.1	bc	34.1	c
	2	34.3	de	42.0	d	38.9	cd	34.9	d
	3	34.2	cde	43.1	e	38.3	bc	35.0	d
	4	34.2	cde	42.9	g	40.0	de	37.0	g
	5	34.6	e	42.1	f	36.3	a	36.0	e
	6	32.0	a	42.7	i	39.0	cde	33.4	b
	7	33.7	c	42.0	h	39.9	de	35.3	d
	8	35.2	f	42.0	bc	39.3	cde	35.3	d
	9	34.4	de	42.4	a	37.1	ab	35.8	e
	10	35.3	f	44.3	d	40.4	e	36.1	ef
	11	35.2	f	44.1	c	-	-	36.5	fg
	12	32.8	b	42.5	c	-	-	32.5	a

continues…

Continuation of Table 6

Variable	Treatment	Trial 117		Trial 118		Trial 119		Trial 120	
G	1	28.9	h	39.1	j	32.3	d	26.6	h
	2	17.7	d	25.2	e	22.1	bc	17.6	d
	3	19.3	e	26.9	g	22.1	bc	19.3	ef
	4	13.6	b	18.4	b	16.6	a	14.7	bc
	5	11.8	a	15.6	a	16.5	a	13.2	a
	6	20.4	f	28.6	h	20.9	b	21.0	g
	7	15.1	c	21.7	d	23.5	c	15.7	c
	8	18.9	e	25.4	ef	15.5	a	18.6	de
	9	13.3	b	18.0	b	23.7	c	13.0	a
	10	19.3	e	26.5	fg	17.0	a	20.1	fg
	11	14.9	c	20.5	c	-	-	13.8	ab
	12	27.7	g	36.2	i	-	-	29.0	i
G100	1	4.9	a	7.6	a	7.7	a	5.3	b
	2	6.8	c	10.1	c	9.1	b	7.2	d
	3	7.6	de	10.2	c	10.2	c	7.6	e
	4	9.8	g	13.5	e	12.6	e	10.8	i
	5	8.5	f	11.3	d	9.5	bc	9.7	g
	6	5.9	b	8.9	b	9.6	bc	6.3	c
	7	7.4	d	10.1	c	11.0	d	7.4	de
	8	7.6	de	10.0	c	11.6	d	7.3	d
	9	9.7	g	13.6	e	9.6	bc	10.1	h
	10	7.7	E	11.0	D	13.5	f	8.4	f
	11	10.8	h	14.9	f	-	-	11.2	j
	12	4.7	a	8.7	b	-	-	5.0	a

continues…

Continuation of Table 6

Variable	Treatment	Trial 117	Trial 118	Trial 119	Trial 120
G200	1	8.9 a	12.6 a	13.6 a	9.2 a
	2	12.2 c	18.0 cd	16.3 e	13.4 cde
	3	13.8 ef	18.4 d	18.1 f	13.6 de
	4	13.6 def	18.4 d	16.6 cd	14.7 f
	5	11.8 c	15.6 b	16.5 de	13.2 cde
	6	10.9 b	15.8 b	17.8 g	11.3 b
	7	13.3 de	18.4 d	19.6 g	13.1 cde
	8	13.4 de	17.2 c	15.5 b	12.8 c
	9	13.3 d	18.0 cd	16.9 de	13.0 Cd
	10	13.9 f	19.7 e	17.0 c	15.5 g
	11	14.9 g	20.5 e	- -	13.8 E
	12	8.5 a	15.3 b	- -	9.2 A

Fertilization results

In the cases where post thinning fertilization presented a significant difference for mean stand attributes (significance in the block factor, Table 3), the differences in the overall means were small. The trials did not present consistent responses to fertilization, where trials 117, 118, and 120 presented larger means in fertilized blocks and trial 119 smaller means. For the trials that presented elevated growth by extra fertilization, the range of response was of 0.4% to 0.9% in tree level variables (diameter and height) and of 1.2% to 2.4% in stand level variables (basal area). In the case of trial 119, a larger effect was found, with tree level attributes differences ranging from 2.2% to 3.1% and stand level attributes 3.1% to 5.2%.

In trial 117, all tested variables (except dominant height) were affected by fertilization. Trial 118, on the other hand, did not have extra fertilization applications influencing the dominant stratum of the stand (DBH, height, and basal area of the 100 thickest trees), but did influence the overall means of the other attributes. In this case, fertilizer applications seemed to benefit trees other than the dominant ones. Trial 120 presented fertilizer effects for all variables except mean DBH, indicating that fertilizer effect was concentrated on the dominant stratum of trees. The unusual response presented in trial 119 might have been due to fertilization enabling trees of the lower stratum to grow to larger sizes than the unfertilized plots. Hence, a more vigorous growth of these trees may have enabled them to give a greater degree of competition to trees of the dominant stratum of the stand, in detriment to whole stand growth. A similar hypothesis was used to explain larger stand growth for trees planted under rectangular spacing when compared to square spacing of the same size (DEBELL and HARRINGTON, 2002).

Diameter at breast height growth

For the three older trials planted under high initial density (117, 118, and 120), thinning regimes leaving 150 trees/ha resulted in the largest mean DBH production values. Also, early thinning permitted high diameter growth rates. Thus, largest diameter values were found in the thinning regime starting at age 2.5 years and leaving 150 trees/hectare (treatment 11). The largest 100 and 200 trees per hectare followed the same behavior as mean DBH results. Results for trials 117, 118, and 120 also showed that mean DBH values for treatments 4 and 9 at age 11.5 years were statistically equal. This gives a greater amount of freedom when choosing between one or two thinning operations, as long as the second thinning is conducted before final crop tress are subject to excessive competition. Since treatment 5 was statistically different from treatment 9, it can be inferred that, if second thinning is conducted before age 5.5 years, final crop trees will not be exposed to excessive competition.

The results found for trial 119 showed that trees planted under wide initial spacing (667 trees/hectare) followed the same behavior as trees planted under close spacing (1111 trees/hectare). Here, early thinning operations (2.5 years) coupled with low residual density (150 trees/hectare) resulted in the highest DBH values. When more importance is given to intermediary production from thinning operations, the statistically equal productions of treatments 8 and 4 allow for a greater degree of freedom for the manager to achieve large diameter values leaving 150 trees/hectare applying one thinning operation (3.5 years) or two thinning operations (first thinning at age 2.5 leaving 400 tress/hectare and second thinning at age 5.5).

When a higher number of final crop trees is desired (250 instead of 150 trees/hectare), the results of Table 6 showed that the largest diameter gain was achieved through two thinning operations beginning at early ages (treatment 7, first thinning at 2.5 years). Again, the statistically equal results of treatments 3 and 6 allow for similar diameter production either through 2 thinnings or one thinning down to 250 trees/hectare at age 5 years. Late thinning operations leaving 150 trees/hectare at age 7 years and early thinning operations leaving 300 trees per hectare resulted in lower diameter production than the rest of the treatments (excepting unthinned control plot). Diameter production of the dominant trees followed the same general behavior as mean DBH results.

Regarding the younger trials, the results for trial 127 showed that under low initial planting density (555 trees/hectare), early or late thinning applications (3 or 5 years) leaving 250 trees/hectare resulted in the largest and statistically equal diameter production. When two thinning operations is concerned, beginning thinning operations earlier in the life of the stand (age 3) resulted in larger diameter gain than beginning thinning operations at age 5. The unthinned check plots presented the lowest diameter value productions. The results for largest 100 and 200 trees/hectare followed the same behavior as mean DBH, except that the late thinning operation in two interventions presented diameter values statistically equal to the unthinned check plots.

Trials 130, 131, and 132 responded more or less the same in regard to mean diameter growth as well as for the largest 100 and 200 trees as affected by the thinning treatment. The treatments with the high initial density (treatments 1 to 3) had lower diameter values when compared to the low density treatments (treatments 4 to 8). Early thinning treatments (thinning at age 2, treatments 5 and 6), regardless of the number of remaining trees, presented the highest diameter values at age six years. The younger trials have not have enough time to take advantage of the increased growing space followed by thinning, since treatments with thinning occurring at age 5 years only had 1 year growth before this evaluation. The tendencies in diameter production may vary as the stands reach maturity.

For the younger trials, a 37% higher mean diameter value was found between the most intensive thinning treatment and the unthinned high density treatment, while a smaller difference was found for the mean diameter of the largest trees per hectare of 23%. For the older trials, a 78% higher mean diameter value was found between the most intensive thinning treatment and the unthinned treatment, while this value was reduced to 46% for the dominant trees. This shows that as thinned stands get older, the dominant trees of the stand are able to increasingly differentiate themselves from the mean values trees.

Height growth

Considering height growth, the same tendencies of diameter growth were found, namely higher height values for the low density and early thinned treatments. This was true for both the mean height and the dominant height. While a significant difference for mean height can be expected for *Eucalyptus* thinning trials (MUÑOZ et al., 2008, SCHEEREN; SCHNEIDER; FINGER, 2004), the significant difference found in dominant height is unusual. Several works have reported no significant difference in dominant height for *Eucalyptus* thinning trials, such as: Aguiar et al. (1995), Finger and Schneider (1999), and Zhang, BAKER and NEILSEN (2003).

Basal area production

Total basal area production for trials 117, 118, and 120 were higher amongst the unthinned check plots. For all these trials, the next highest basal area values were found for thinning at age 5, down to 450 trees per hectare (treatment 6). While this treatment allowed for high total basal area production, the values for basal area of the 100 and 200 thickest trees per hectare were the lowest among the thinned treatments. The treatments consisting of 300 trees per hectare after thinning were ranked as the next highest in total basal area production. In terms of the dominant stratum of the stand, these treatments comprised the largest basal area production after the treatments leaving 150 trees per hectare.

When considering the trial under low initial planting density (119), aside from the unthinned check plot, treatments initiating thinning at age 2.5 years with 250 or 300 trees per hectare remaining (treatments 7 and 9) presented the largest total basal area production. These were followed by the treatments with thinning beginning at age 3.5 years also leaving 250 or 300 trees per hectare. When analyzing the basal area production of the dominant stratum, the highest production came from the treatments leaving 150 trees per hectare and with early thinning interventions (treatments 4 and 10). Under the low initial planting density of 667, two thinning operations at age 2.5 and 5.5 with residual densities of 400 and 250 trees per hectare (treatment 7) produced a large amount of total basal area (third ranked) while also producing a large amount of basal area for the dominant trees (fourth ranked).

For trials 130, 131, and 132, the unthinned treatment with initial density of 1111 trees per hectare resulted in the largest total basal area production, followed by the unthinned treatment with initial density of 617 trees per hectare. The next highest basal area production belonged to the treatments installed with 617 trees per hectare and with early thinning operations (age 2), leaving 450 and 250 trees per hectare (treatments 6 and 7). In these trials, late thinning treatments resulted in the lowest basal area production (treatments 3 and 8). Considering the dominant basal area production, the highest producing treatment was with initial density of 617 trees per hectare, early thinning application at age 2 years and residual tree number of 250. Despite the fact that treatment 5 (2 thinnings leaving 450 and 250 trees at initial density of 617 trees per hectare) had a low total basal area production value, it was the second ranked in dominant basal area production.

The lowest initial planting density, trial 127, presented basal area production behavior similar to the other trials, with latter age thinning leaving a high number of residual trees reaching high total basal area values and low dominant basal area values when compared to early thinning leaving a low number of residual trees.

Management implications

Figures 1 and 2 show the development of mean DBH and basal area as well as dominant DBH and basal area for three distinct management regimes considering two initial spacing options, low and high density.

Figures 1 and 2 also demonstrate that the differences in thinning intensities provide a trade off between large diametrical production and basal area production. In the most intensive thinning regime (T11 in Figure 1 and T10 in Figure 2), large diameter trees (mean diameter of 35 cm and 38 cm for 1111 trees per hectare and 667 trees per hectare, respectively) are obtained in a short period of time (11.5 years). On the other hand, total basal area production is lower than in other regimes, concentrating growth on a few selected crop trees of the stand. This type of regime characterizes an intensive management scheme, which aims to remove any growth strains (in this case competition from other trees) on selected trees to produce high value logs (FOX, 2000; MAESTRI, 2003).

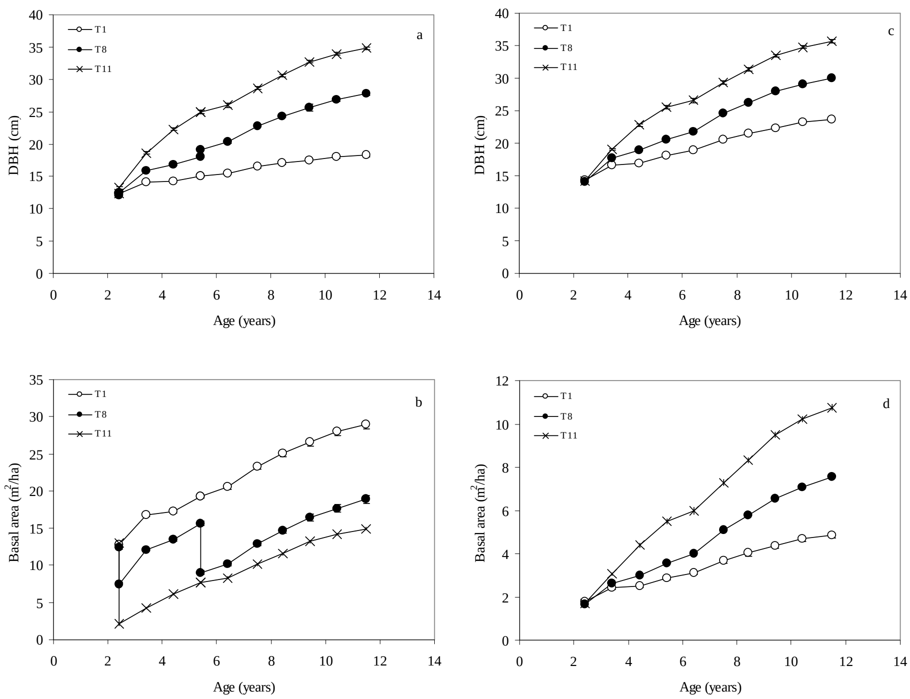

Figure 1 Development of mean DBH (a), mean basal area (b), DBH of the 100 thickest trees per hectare (c), and basal area of the 100 thickest trees per hectare (d) considering a high initial planting density (1111 trees/hectare). Data is from trial 117, explanation on the treatments is available in Table 2. Error bars represent the standard error of means.

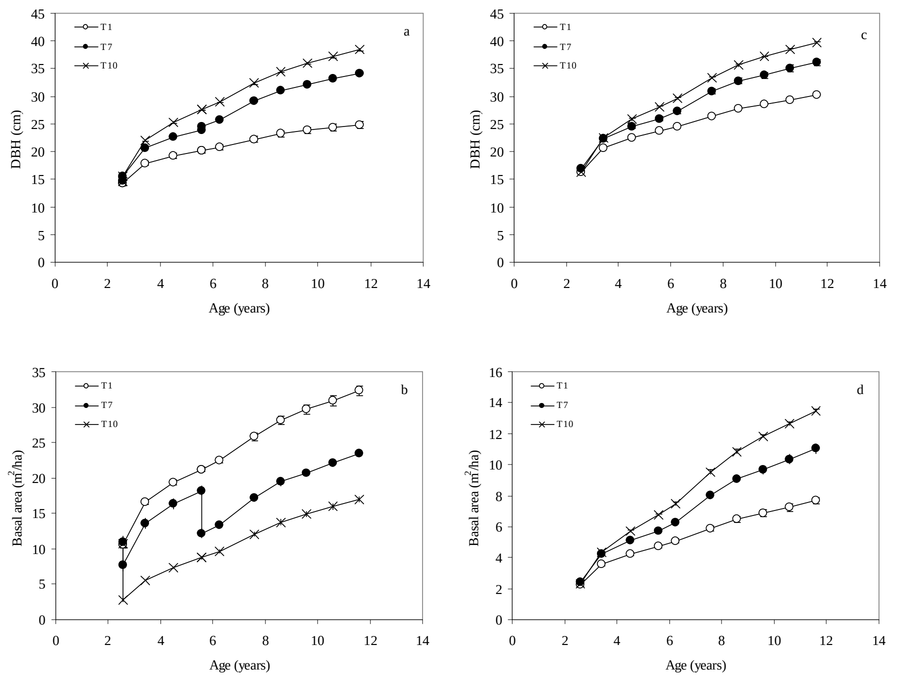

Figure 2 Development of mean DBH (a), mean basal area (b), DBH of the 100 thickest trees per hectare (c), and basal area of the 100 thickest trees per hectare (d) considering a low initial planting density (667 trees/hectare). Data is from trial 119, explanation on the treatments is available in Table 2. Error bars represent the standard error of means.

Thinning regimes with two thinning operations (T8 in Figure 1 and T7 in Figure 2) characterizes a multiproduct management scheme. In this type of regime, growth of the final crop trees are somewhat reduced, but thinning operations provide wood of commercial dimensions. Growth rate of the final crop dominant trees are still elevated, especially when a low initial density is practiced.

The choice of the best thinning regime for *Eucalyptus* clonal material will vary according to the objective of growing the plantation (PINKARD and

NEILSEN, 2003). For cellulose or energy, planting at high initial spacing with no thinning interventions will maximize standing basal area. The decision is more complex if growing wood for solid wood products. For instance, Medhurst, Beadle and Neilsen (2001) recommended a final density of 200 to 300 trees per hectare for thinning *Eucalyptus nitens* plantations, considering a rotation of 20 to 25 years. From the results of this study, shorter rotations (15 to 20 years) seem possible if early and intensive thinning regimes are used. Nutto et al. (2006) recommends wide initial spacing (500 to 800 trees per hectare) on sites of good to very good quality for high quality sawlog production for Brazilian *Eucalyptus* plantations. This assures that the high diameter increment potential of *Eucalyptus* for the first 3 years is maintained and enables short final rotations of 15 years.

The use of large logs for solid wood products is advisable, since they provide a greater proportion of sawn timber recovery (WARDLAW et al., 2004) and tend to be more stable during drying process (MCKENZIE and HAWKE, 1999) when compared to small diameter logs. For instance, the aforementioned authors recommend logs with minimum small-end diameter of 40 cm to reduce drying degrade in *Eucalyptus regnans*. The results presented in this study are still provisory, since a rotation of 15 years or more is required for many of the tested thinning treatments to produce considerable quantities of large scale timber. Economical analysis identifying the most profitable thinning regime once the trials reach a full rotation age will help elucidate the best thinning regime for the clones and sites tested.

4 Conclusions

With the above analysis and results of several different initial planting densities, timing, and severity of thinning treatments we may conclude that:

- Stands planted under high densities (1111 trees per hectare) presented a higher initial mortality proportion prior to thinning interventions than stands planted under low initial density;
- Diameter growth prior to canopy closure was influenced by genetic material (7% variation) as well as planting density, with low densities (under 617 trees per hectare) presenting the highest diameter growth (6 cm per year);
- Post thinning fertilization permitted a small but statistically significant growth advantage compared to treatment without post thinning fertilization;
- Thinning treatments conducted early in the life of the stand (2.5 years) and leaving a low number of trees (150 trees/ha) presented the highest values of mean DBH, DBH of the 100 and 200 thickest trees per hectare, mean height, height of the 100 and 200 thickest trees per hectare, and basal area of the 100 and 200 thickest trees per hectare.
- Unthinned treatments and thinning treatments conducted late in the life of the stand and leaving a high number of trees presented the highest values of total basal area.

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