UNIVERSIDADE FEDERAL DO PARANÁ

MÁRIO DOBNER JR.

IMPACTO DO MANEJO DE POVOAMENTOS NA PRODUTIVIDADE E QUALIDADE DA MADEIRA DE *Pinus taeda*

CURITIBA
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Tese apresentada como requisito parcial à obtenção do grau de Doutor em Ciências Florestais, Programa de Pós-Graduação em Engenharia Florestal do Setor de Ciências Agrárias da Universidade Federal do Paraná.

Orientador:
Prof. Dr. Antonio Rioyei Higa

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A banca examinadora, instituída pelo colegiado do Programa de Pós-Graduação em Engenharia Florestal, do Setor de Ciências Agrárias, da Universidade Federal do Paraná, após argüir o(a) doutorando(a) *Mário Dobner Junior* em relação ao seu trabalho de tese intitulado "***IMPACTO DO MANEJO DE POVOAMENTOS NA PRODUTIVIDADE E QUALIDADE DA MADEIRA DE Pinus taeda***", é de parecer favorável à *APROVAÇÃO* do(a) acadêmico(a), habilitando-o(a) ao título de *Doutor* em Engenharia Florestal, área de concentração em SILVICULTURA.

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RESUMO

IMPACTO DO MANEJO DE POVOAMENTOS NA PRODUTIVIDADE E QUALIDADE DA MADEIRA DE *Pinus taeda*

Espécies do gênero *Pinus* foram introduzidas no Brasil na primeira metade do século 20, com a perspectiva de fornecer matéria prima para indústrias de base florestal. Atualmente, plantios desde gênero totalizam 1.6 milhões de hectares e, embora a produção de madeira de pínus como biomassa desempenhe um importante papel, há uma crescente demanda por madeira serrada e laminada. O presente estudo teve como objetivo avaliar o crescimento de um povoamento podado de *P. taeda* ao longo de 30 anos, submetidos a desbastes pelo alto, com a intenção de produzir madeira para múltiplos usos. A área experimental estava localizada no planalto Sul do Brasil, onde o clima é úmido e subtropical. O experimento baseiou-se na seleção de 400 ‘árvores potenciais’ ha^{-1} e o seu favorecimento através da remoção de árvores concorrentes em diferentes intensidades. Um dos tratamentos foi mantido sem desbaste, como testemunha. O experimento foi instalado em blocos ao acaso, com quatro tratamentos (intensidades de desbastes), duas repetições e parcelas com 0,1 ha de área útil. Ao completar 30 anos de idade, árvores compreendendo toda a amplitude diamétrica foram selecionadas, derrubadas e cubadas. Discos transversais e toras foram amostrados para análises dos anéis de crescimento e do rendimento industrial, respectivamente. Árvores dominantes submetidas ao desbaste ‘extremo’ apresentaram crescimento diamétrico 40 % (67 cm) superior em comparação com indivíduos dominantes em povoamentos não desbastados (48 cm) aos 30 anos de idade. A produção em volume ha^{-1} não foi afetada pelo desbaste ‘extremo’, em relação ao volume obtido em povoamento não desbastado, desde a idade de 16 até 30 anos. Desbastes ‘moderado’ e ‘pesado’, resultaram em uma produção volumétrica 35 % maior que povoamentos não desbastados. Destaca-se, porém, que a superioridade na produção foi essencialmente a mortalidade observada em povoamentos não desbastados. Povoamentos sujeitos a desbastes ‘extremos’ foram mais eficientes na produção de toras de maiores dimensões (produziram mais e mais cedo). Entretanto, quando sortimentos de toras intermediários (>30 cm) são o objetivo do manejo, desbastes ‘moderados’ e ‘pesados’ combinam otimamente crescimento individual e a máxima produção por unidade de área (1.400 m^3 ha^{-1} aos 30 anos). Verificou-se que desbastes ‘extremos’ resultaram um atraso de cerca de quatro anos no início da produção de madeira adulta. Desbastes, independente da intensidade, resultam um perfil radial com densidade mais homogênea e, quando ‘moderados’, em máxima quantidade de madeira adulta. Para uma mesma idade de corte, desbastes não apresentam nenhum efeito sobre a densidade média da madeira colhida. A idade de corte, por sua vez, foi decisiva na obtenção de madeira de maior densidade. Resultados obtidos a partir da análise do rendimento industrial em serrarias e laminadoras indicam que toras de grandes dimensões proporcionam maiores rendimentos e benefícios econômicos, sendo uma opção interessante tanto para indústrias como para produtores de toras. A análise da performance financeira dos diferentes regimes mostra que povoamentos desbastados, independente da intensidade, resultam valor presente líquido, no mínimo duas vezes maiores (>13.000 US$ ha^{-1}) que povoamentos não desbastado (6.000 US$ ha^{-1}). Embora desbastes extremos resultem em idades de corte ótimas financeiras inferiores, são necessários pelo menos 22 anos para que todo o potencial de crescimento do povoamento seja aproveitado. Em conjunto, os resultados obtidos indicam que a produção de sortimentos de grandes dimensões através de desbastes orientados à 'árvores potenciais' é um objetivo de manejo factível, além de ser a opção mais rentável para povoamentos de *P. taeda* no Sul do Brasil. Embora desbastes 'extremos' tenham apresentado resultados interessantes, sua aplicação deve ser cuidadosamente avaliada considerando aspectos de manutenção inicial, estabilidade do povoamento e mercadológicos.

Palavras-chave: Desbaste. Poda. Silvicultura. Uso múltiplo.

RESUMO EXPANDIDO

O presente capítulo tem como objetivo fazer uma apresentação geral da tese na língua portuguesa. A motivação do estudo, bem como seus objetivos, métodos, principais resultados e considerações para a prática, são descritos.

1 INTRODUÇÃO

O estabelecimento de povoamentos de *Pinus sp.* no Brasil, objetivou primeiramente a produção de matéria prima para a indústria de polpa e papel. Sabia-se, porém, que madeira de melhor qualidade poderia ser produzida com práticas silviculturais como poda e desbaste. Entretanto, não havia informação disponível sobre como estas práticas afetam o crescimento de indivíduos e povoamentos de *Pinus taeda* no Sul do Brasil.

Atualmente, há 7,2 milhões de hectares de plantações florestais no país, 20 % dos quais com espécies do gênero *Pinus*. Apesar da importância das plantações florestais – 94 % da produção nacional de toras – as mesmas ocupam uma área inferior a 1 % do território nacional, indicando um enorme potencial de crescimento (ABRAF, 2013). Segundo a mesma fonte, a região Sul do país, onde estão mais de 80 % dos plantios de pínus, possui 17,8 mil empresas de base florestal, sendo responsável pela produção dos seguintes produtos e respectiva participação na produção nacional:

- Molduras: 100 % - 26 milhões de US$.
- Compensados: 99 % - 394 milhões de US$.
- Portas de madeira: 98 % - 170 milhões de US$.
- Móveis: 90 % - 469 milhões de US$.
- Painéis reconstituídos: 39 % - 132 milhões de US$.

O presente estudo considerou desbastes cujo objetivo principal é a seleção de ‘árvores potenciais’ (‘potential crop trees’ ou ‘Zukunftsbäume’) e o seu favorecimento através da remoção de indivíduos concorrentes. ‘Árvores potenciais’ são indivíduos dominantes, de boa qualidade e homogeneamente distribuídos no povoamento. Indivíduos concorrentes, por sua vez, são árvores também dominantes ou co-dominantes, que precisam ser removidas para que as ‘árvores potenciais’ possam desenvolver suas copas sem restrição de espaço.

Este tipo de intervenção é conhecido como ‘desbaste pelo alto’ (Colégio Florestal de Irati, 1986; Ribeiro *et al.* 2002), ou ‘desbaste por copa’ (‘crown thinning’) como é conhecido na língua inglesa (Sepherd, 1986; Smith *et al.*, 1997; Ministry of Forests, 1999; Kerr; Haufe, 2011). Ou ainda, em alemão, ‘Auslesedurchforstung’, que é o termo original, concebido por Schädelin (1934) na Suíça (Burschel and Huss 2003). Este tipo de desbaste é amplamente empregado na Europa, em função do grande potencial de favorecimento do crescimento individual de árvores selecionadas. Entretanto, é raramente aplicado aos povoamentos florestais no Sul do Brasil.

O termo em inglês ‘crown thinning’ caracteriza a intervenção que ocorre basicamente em função da análise da copa das árvores. Duas ou mais árvores dominantes cujas copas se tocam indicam competição mútua. Assim, uma ou mais precisam ser removidas para que as ‘árvores potenciais’ selecionadas possam expressar todo seu potencial de crescimento.

Deve-se atentar para certas particularidades da nomenclatura internacional:

- Selective thinning ≠ selection thinning.
- Thinning from above ≠ high thinning.
- Selection thinning = high thinning.

O termo ‘seletivo’ (selective), indica que o principal critério de seleção é a qualidade das árvores (fuste reto, galhos finos, entre outros), e não a classe sociológica das mesmas (grau de dominância) (Baker, 1934). Por isso, em desbastes seletivos, árvores intermediárias são muitas vezes selecionadas pois aparentam ter melhor ‘qualidade’. O que não acontece nos desbastes pelo alto, onde apenas árvores dominantes são selecionadas. Já a expressão ‘desbaste por seleção’ (selection thinning) pressupõe a remoção de todas as árvores dominantes de um povoamento visando o favorecimento das árvores intermediárias e suprimidas, o mesmo que ‘high thinning’ (Smith *et al.*, 1997, Ministry of Forests, 1999). Ambos (‘selective’ e ‘selection’) podem gerar um mal entendido com o termo ‘Auslese’, em alemão, cujo significado é seleção, porém indica outro tipo de intervenção, o desbaste pelo alto.

Diferentemente do desbaste seletivo, o desbaste pelo alto tem como premissa básica a análise da classe sociológica das árvores, selecionando indivíduos dominantes. Em última análise, conclui-se que os seguintes termos são sinônimos e expressam o tipo de intervenção realizada no presente estudo:

- Thinning from above = crown thinning = positive selection = Auslesedurchforstung.

2 HIPÓTESES, OBJETIVOS E ESTRUTURA DO ESTUDO

2.1 HIPÓTESES

P. taeda, em função de seu comportamento heliófilo, responde fortemente à desbastes pesados e precoces em termos de crescimento diamétrico e, consequentemente, de volume individual, enquanto que a resposta à liberação de espaço em idades avançadas é muito menor.

Considerando que a manipulação da densidade do povoamentos é uma das ferramentas mais importantes para silvicultores, sua aplicação em povoamentos de *P. taeda* no Sul do Brasil pode ser uma opção para a produção de madeira para múltiplos usos.

2.2 OBJETIVO GERAL

O objetivo do estudo foi avaliar o desenvolvimento de povoamentos podados de *P. taeda* com 30 anos de idade submetidos a diferentes intensidades de desbastes, com o objetivo de produzir madeira de alta qualidade.

2.3 OBJETIVOS ESPECÍFICOS

Os objetivos específicos do estudo foram determinar os efeitos de diferentes intensidades de desbaste:

- No crescimento:
    - do povoamento até os 30 anos de idade.
    - diamétrico de indivíduos em diferentes alturas.
    - em termos de produção de sortimentos de toras classificados de acordo com o diâmetro da ponta fina, podadas ou não podadas.

- Na qualidade da madeira.
- No rendimento industrial em serraria e laminadoras.
- Na performance financeira.

2.4 ESTRUTURA DA TESE

A tese está estruturada na forma de capítulos, cada um com o objetivo de avaliar um aspecto particular. Há uma introdução geral com as motivações do estudo, histórico da introdução e silvicultura de *Pinus spp.* no Brasil, descrição dos tipos de desbaste existentes com ênfase ao utilizado no presente estudo e, finalmente, uma apresentação do cultivo de *Pinus* ao redor do mundo.

No Capítulo 2 MATERIAL E MÉTODOS, apresenta-se a região onde o estudo foi estabelecido e o delineamento experimental utilizado. Maiores detalhes sobre a amostragem e análises realizadas são descritos em cada um dos respectivos capítulos.

No Capítulo 3 CRESCIMENTO DOS POVOAMENTOS, realiza-se uma primeira caracterização dos povoamentos e indivíduos aos 30 anos de idade. O desenvolvimento ao longo do tempo de variáveis como diâmetro das árvores dominantes (d_{100}), área basal e volume ha^{-1} são também apresentados.

No Capítulo 4 ESPESSURA DOS ANÉIS DE CRESCIMENTO, o foco é o crescimento diamétrico individual das árvores em resposta aos desbastes, e isso em diferentes alturas do fuste. O incremento diamétrico é avaliado em termos absolutos e relativos, medidos a partir de discos transversais, amostrados de forma a representar diferentes classes diamétricas.

No Capítulo 5 QUALIDADE DA MADEIRA, avaliou-se a qualidade da madeira produzida nas diferentes intensidades de desbaste. Foram abordadas características como homogeneidade de crescimento, densidade da madeira, proporção de lenhos juvenil e adulto, etc. A influência da idade de corte raso na densidade da madeira é também reportada.

No Capítulo 6 SORTIMENTO DE TORAS, a produção de madeira foi analisada na forma de sortimentos em função do diâmetro da ponta fina da tora e seu status em relação à poda (toras podadas e não podadas). A produção volumétrica total e de sortimentos >30 cm foi comparada entre os diferentes tipos de desbaste, considerando idades de corte raso entre 16-30 anos.

No capítulo 7 RENDIMENTO INDUSTRIAL, diferentes sortimentos de toras, incluindo dimensões acima das normalmente disponíveis, foram avaliados durante o processamento industrial em serraria e laminadoras. Rendimentos volumétrico e econômico são analisados.

O Capítulo 8, PERFORMANCE FINANCEIRA, apresenta a análise financeira dos diferentes regimes de desbaste avaliados. A quantidade de madeira produzida classificada em sortimentos, juntamente com os respectivos preços de mercado, foram empregados na construção de fluxos de caixa, a partir dos quais índices financeiros foram obtidos. Adicionalmente, análises de sensibilidade com diferentes cenários foram realizadas.

No Capítulo 9 DISCUSSÃO FINAL apresenta-se um resumo geral. Os resultados são apresentados em conjunto para permitir uma análise global dos mesmos, de forma a prover informações para o manejo de povoamentos de *P. taeda* no Sul do Brasil. Os regimes de manejo mais apropriados para objetivos de produção específicos são descritos, juntamente com considerações de interesse prático.

3 MATERIAL E MÉTODOS

3.1 LOCAL DO ESTUDO

A área experimental estava localizada no município de Campo Belo do Sul, Santa Catarina, Sul do Brasil, 950 m a.n.m. (lat. 27°59’33’’S, long. 50°54’16’’W) (Figura 2.1-1, página 24).

3.2 ESTABELECIMENTO DO POVOAMENTO

O preparo do terreno compreendeu as seguintes atividades:

(1) Corte raso de uma Floresta com *Araucaria* secundária.

(2) Queima dos resíduos.

(3) Plantio de mudas com 6 meses de idade e de raiz nua, no inverno de 1981, em uma densidade de 2.500 árvores ha^{-1} (espaçamento 2,5 x 1,6 m).

(4) Controle da vegetação concorrente durante os primeiros 2 anos após o plantio.

Nenhuma outra atividade foi realizada até a instalação do experimento, as 5 anos de idade, em 1986.

Não há informação sobre o material genético utilizado para o estabelecimento do povoamento. Suspeita-se, porém, que tenha sido importado da República do Zimbábue.

3.3 INSTALAÇÃO E DELINEAMENTO DO EXPERIMENTO

O delineamento experimental incluiu um gradiente de 4 intensidades de desbaste, nos quais 400 ‘candidatas a árvores potenciais’ ha^{-1} foram selecionadas e liberadas de competição em diferentes intensidades. Os tratamentos aplicados ao povoamento, caracterizados pelo número de árvores remanescentes e o número de árvores concorrentes que foram eliminadas com o objetivo de favorecer as ‘candidatas a árvores potenciais’ são demonstrados na Tabela 2.3-1. (página 28) O experimento foi delineado e instalado em 1986 pelo então diretor do Instituto de Silvicultura da Albert-Ludwigs Universität, Freiburg, Alemanha, Prof. Dr. Jürgen HUSS.

Os desbastes intermediários foram uma primeira tentativa de estabelecer um regime próximo aquele que seria empregado na prática, motivo pelo qual são denominados ‘orientados à prática’.

As diferentes intensidades de desbaste foram instaladas em parcelas com ~0,2 ha de área total, incluindo bordadura e uma área interna útil de ~0,1 ha, utilizada nas medições. Os tratamentos foram aleatoriamente estabelecidos em 2 blocos, caracterizando um delineamento em blocos ao acaso.

Os desbastes foram planejados ‘pelo alto’ (‘from above’ ou ‘crown thinning’). As ‘árvores potenciais’ foram selecionadas na primeira intervenção (1986, 5 anos de idade) e liberadas de competição removendo nenhuma, 1, 2 ou todas as concorrentes. Mais tarde, os desbastes continuaram removendo árvores concorrentes ou mesmo algumas das ‘árvores potenciais’ no tratamento ‘extremo’. Como demonstrado na Tabela 2.3-1, a principal diferença entre os tratamentos foi planejada para a primeira intervenção.

Todas as árvores foram podadas até 2,5 m de altura em 1986. Uma segunda poda foi realizada 2 anos mais tarde, quando apenas as 400 ‘árvores potenciais’ ha^{-1} foram podadas até 5,7 m em todos os tratamentos.

4 RESULTADOS E CONSIDERAÇÕES PARA A PRÁTICA

4.1 VISÃO GLOBAL DOS RESULTADOS

Os resultados encontrados demonstram que ‘desbastes pelo alto’ (‘from above’ ou ‘crown thinnings’) aumentaram substancialmente o diâmetro das árvores e, consequentemente, o volume individual das mesmas, sendo proporcional à remoção de árvores concorrentes. A altura das árvores, por outro lado, foi apenas levemente afetada pelos desbastes e diferenças foram observadas apenas entre tratamentos extremos. Reforça-se que as conclusões são fortemente dependentes do tipo de desbaste considerado.

Em geral, foi possível observar que

- Povoamentos não desbastados resultam
    - o menor crescimento diamétrico. As árvores dominantes atingiram 47 cm de diâmetro na idade de 30 anos, o menor valor entre os regimes avaliados.
    - área basal máxima aos 13 anos de idade (~70 m² ha^{-1}), sem aumento deste valor a partir de então.
    - uma perda significativa de madeira em função de mortalidade (~400 m³ ha^{-1}), mais de ⅓ de todo o volume produzido até o 30° ano, 70 % concentrado no período entre 20-30 anos.
- Povoamento sujeitos a desbastes ‘moderados’ e ‘pesados’ resultam
    - diâmetro de árvores dominantes 20 % superiores em relação ao obtido em povoamentos não desbastados.
    - a maior produção volumétrica (1.400 m³ ha^{-1}), 40 % superior ao verificado em povoamentos não desbastados.
    - a melhor combinação de produção volumétrica total e sortimentos de toras >30 cm quando períodos de produção maiores que 20-22 anos são considerados.
- Povoamentos sujeitos ao regime ‘extremo’ resultam

  - o maior diâmetro médio das árvores dominantes (67 cm aos 30 anos de idade), 40 % maior que os obtidos em povoamentos não desbastados.
  - volume individual das árvores dominantes 90 % superior (5,3 m³) em relação as árvores dominantes em povoamentos não desbastados (2,8 m³), e 30 % maior que naqueles com desbastes orientados à prática.
  - a mesma produção volumétrica observada em povoamentos não desbastados,

    700 m³ ha^{-1} aos 16 anos de idade, ou

    1.000 m³ ha^{-1} aos 30 anos.
  - a melhor estratégia para a produção de sortimentos de toras de grandes dimensões (>50 cm). Produz mais e mais cedo. É a única opção quando almeja-se a produção de sortimentos >50 ou mesmo >60 cm em períodos de produção menores que 30 anos.

As respostas das árvores aos desbastes em crescimento diamétrico são observadas primeiramente na base da árvore. Em maiores alturas, aumentos no crescimento diamétrico demoram mais tempo para serem verificados e necessitam desbastes mais intensos para tal. Entretanto, uma vez observados, maiores taxas de crescimento permanecem por mais tempo que na base da árvore. Assim, embora as árvores tornam-se mais cônicas após desbastes, a conicidade tende a diminuir com o tempo. Além disso, verificou-se que

- quando desbastes são aplicados a povoamentos com 5 anos de idade e 32 m² ha^{-1} de área basal, aumento imediato no crescimento diamétrico das ‘árvores potenciais’ somente é observado com a remoção de 2 ou mais árvores concorrentes por árvore potencial. Após pelo menos 2 desbastes consecutivos com a remoção de 1 árvore concorrente por ‘árvore potencial’ por intervenção, há um aumento significativo no crescimento comparado aquele observado em povoamentos não desbastados.
- Imediatamente após desbastes ‘extremos’, aumentos no crescimento diamétrico na ordem 60 % são obtidos a 1,3 m de altura, em comparação com o incremento de árvores em povoamentos não desbastados. Árvores sujeitas ao regime ‘extremo’ apresentam os maiores incrementos por, pelo menos, 10 anos após a

primeira intervenção. Incrementos >300 % superiores em comparação a árvores em povoamentos não desbastados foram verificados.

- Árvores dominantes respondem mais aos desbaste que árvores intermediárias ou suprimidas, e isto de uma forma mais duradoura, tanto em termos absolutos como relativos.

Em relação à qualidade da madeira, resultados indicam que os desbastes aplicados não somente promoveram um maior crescimento diamétrico das árvores, mas também

- um ritmo de crescimento mais homogêneo,
- uma densidade da madeira mais homogênea ao longo do perfil radial,
- uma quantidade de madeira adulta proporcionalmente maior, quando não ‘extremo’.

O regime ‘extremo’ postergou o início da produção de madeira adulta em cerca de 4 anos, em comparação a povoamentos não desbastados. Mesmo assim, o maior ritmo de crescimento das árvores neste tratamento durante a maior parte do período avaliado, principalmente durante a segunda metade do período de produção, resultou em quantidade semelhante de madeira adulta àquela observada nos desbastes ‘moderado’ e ‘pesado’, os quais foram ótimos neste sentido.

O rendimento industrial das toras foi maior quanto maior o diâmetro na ponta fina das mesmas. Com relação à serraria, verificou-se

- um rendimento industrial médio de 57 % para toras com diâmetros entre 20-57 cm. São necessários 2,5-1,3 m³ de toras para produzir 1 m³ de madeira serrada, dependendo do sortimento utilizado.
- uma tendência de aumento linear no rendimento industrial com o aumento do diâmetro das toras. Ganhos significativos no rendimento foram observados em toras com mais de 35 e 45 cm, indicando potencial para aumento no valor comercial destes sortimentos, especialmente >45 cm.
- que, em relação ao benefício econômico, classes diamétricas intermediárias (25-35 cm) são menos atrativas que classes inferiores (20-25 cm) e superiores (>45 cm).

Para a laminação com torno, foi observado

- um rendimento médio de 54 % para toras com diâmetro entre 21-67 cm. O rendimento industrial aumenta 0,6 % com o aumento de 1 cm no diâmetro da ponta fina das toras.
- que toras com diâmetro entre 30-45 cm são as que resultam o maior benefício econômico.
- que os preços praticados para os sortimentos mais grossos e podados refletem apenas o potencial de toras cuja poda foi ineficiente. A análise do potencial teórico de toras com núcleo nodoso ≤15 cm indicou que há potencial para maior rendimento industrial e ambos, indústria e produtores de tora, podem ser beneficiados.

Com relação à laminação por facas, verificou-se

- um rendimento industrial médio de 21 % para toras com diâmetro entre 30-65 cm na ponta fina. De acordo com o modelo linear para o rendimento, um aumento de 3,7 m^2 na produção de lâminas é esperado para cada aumento de 1 cm na ponta fina das toras.
- toras de grandes dimensões não resultam necessariamente nos maiores benefícios econômicos. Entretanto, esta conclusão foi fortemente afetada pela má qualidade da poda aplicada ao povoamento estudado.

Os resultados foram influenciados por poda inadequada das árvores. Por isso, o real potencial de toras de grandes dimensões e podadas não pôde ser apropriadamente determinado. Assim, uma análise do potencial teórico foi necessária. Os resultados de tal análise são apresentadas no item 9.2.7 Potencial teórico de toras podadas (página 227).

A performance financeira dos povoamentos sujeitos às diferentes intensidades de desbaste foi analisada. Verificou-se que

- a produção de toras de grandes dimensões é uma opção de manejo viável. Quando a base do fuste é podada (6 m), aos 30 anos de idade, este segmento representa ~30 % do volume das árvores, porém 50 % do valor das mesmas.
- desbastes que liberam ‘árvores potenciais’ da competição de forma ‘extrema’ resultam não apenas o melhor resultado financeiro (VPL = ~15.000 US\$ ha^{-1}), mas

o faz antes (aos 24 anos) que desbastes orientados à prática (30 anos) ou nenhum desbaste (26 anos).

- povoamentos sujeitos a desbastes, independente de intensidade, resultam no mínimo duas vezes maior retorno financeiro (>13.000 US$ ha^{-1}) que aqueles não desbastados (~6.000 US$ ha^{-1}).
- de acordo com a taxa interna de retorno (TIR) dos diferentes regimes avaliados (10-17 % ano^{-1}), a idade ótima de corte variou entre 16-18 anos. Entretanto, considerando uma perspectiva de longo prazo (VPL ou VET), o período de produção precisa ser estendido. Mesmo em povoamentos sob o regime 'extremo', onde uma tendência de antecipação da idade ótima de corte foi observada, o corte final deve ser ≥22 anos, considerando os atuais valores de mercado para os sortimentos de tora.
- Os melhores resultados financeiros foram obtidos nos povoamentos desbastados. Simulações indicam, porém, que resultados financeiros ainda melhores podem ser obtidos. Considerando um sortimento de tora adicional >50 cm para toras podadas e não podadas, o VPL de povoamentos sob regime 'extremo' aumenta em ~30 %, enquanto apenas pequenas diferenças são verificadas em povoamentos sob regimes 'moderados', 'pesados' ou não desbastados.

4.2 CONSIDERAÇÕES PARA A PRÁTICA

Alguns proprietários de terras podem hesitar em aceitar que a produção de toras de grandes dimensões e podadas é um objetivo de manejo factível e uma opção economicamente viável. Pelo menos no Sul do Brasil, há uma demanda crescente por toras de maiores dimensões, não podadas e podadas.

Embora oscilações de mercado podem ser observadas ao longo do tempo, o fato de que toras de grandes dimensões e podadas abasteciam originalmente apenas indústrias voltadas para a exportação não é mais uma verdade absoluta. Diversos produtos são fabricados atualmente a partir da madeira de pínus, visando também abastecer o mercado interno, os quais requerem um amplo leque de sortimentos para atender eficientemente diferentes linhas de produção.

A realização dos desbastes demonstrou ser uma abordagem promissora para os povoamentos de *P. taeda* no Sul do Brasil. Assim, aspectos relevantes à prática são discutidos em detalhe a seguir.

4.2.1 Densidade de plantio

No presente estudo, os povoamentos analisados foram estabelecidos com uma densidade inicial de 2.500 árvores ha^{-1}. Em função do alto percentual de sobrevivência, do rápido e homogêneo crescimento inicial, a densidade de plantio atualmente utilizada em plantios de *P. taeda* no Sul do Brasil são menores, ~1.600 árvores ha^{-1}. Tal densidade é aparentemente apropriada para a maioria das condições e resulta em menores níveis de competição nos primeiros anos, de forma que os desbastes podem ser postergados, sem, contudo, afetar o crescimento diamétrico das árvores.

Além disso, foi demonstrado que árvores de *P. taeda* possuem um grande potencial de utilizar maiores espaços produtivos – neste caso disponibilizados pelos desbastes – o que sugere que as densidades iniciais poderiam ser até inferiores a 1.600 árvores ha^{-1}. No caso do regime ‘extremo’, faz pouco sentido plantar um povoamento relativamente denso e, aos 5 anos, reduzir para 400 árvores ha^{-1}, como foi realizado na área experimental aqui avaliada. Muito mais apropriado seria estabelecer o povoamento com um número menor de indivíduos.

Não se deve esquecer, porém, que quanto maior a densidade de plantio, maior a possibilidade de seleção das ‘árvores potenciais’. Adicionalmente, os custos de controle da vegetação concorrente podem aumentar em função do maior tempo necessário para o fechamento do dossel. Não se recomenda, portanto, estabelecer povoamentos com menos de 1.000 indivíduos ha^{-1}.

4.2.2 Seleção de ‘árvores potenciais’

A seleção de ‘árvores potenciais’ envolve questões relacionadas ao critério de seleção, ao momento e ao número de indivíduos por hectare.

O principal critério de seleção é a posição sociológica da árvore. Somente árvores dominantes são capazes de formar grandes indivíduos. Árvores dominantes, entretanto, produzem normalmente galhos maiores. Assim, e em função da desrama natural ineficiente de *P. taeda*, a poda artificial é uma necessidade se a produção de madeira livre de nós é almejada.

Deve-se tomar cuidado, porém, pois indivíduos codominantes ou mesmo intermediários são frequentemente selecionados como ‘árvores potenciais’ por aparentarem ser de melhor ‘qualidade’. Mais tarde, porém, tais indivíduos não crescem satisfatoriamente para atingir os objetivos de produção.

4.2.2.1 Momento da seleção

A seleção de ‘árvores potenciais’ no experimento analisado foi realizada aos 5 anos de idade, quando a altura média do povoamento era de 8-9 m. Presumia-se ser este um momento apropriado para selecionar e favorecer o crescimento individual das árvores. De fato, respostas em crescimento diamétrico foram verificadas imediatamente após desbastes extremos.

Ao se reduzir a densidade do povoamento de 2.500 para 1.600 árvores ha^{-1}, entretanto, desbastes podem ser postergados em 2-3 anos, permitindo uma primeira seleção e remoção de competidores às ‘árvores potenciais’ aos 7-8 anos, otimamente, quando a altura do povoamento está em torno de 12-14 m e há uma melhor distinção dos indivíduos em termos de classificação sociológica, como verificado no Capítulo 3, item 3.3.9.

Entretanto, a necessidade de uma seleção precoce permanece em função da poda das árvores, preferencialmente, aos 3-4 anos. Por isso, recomenda-se iniciar a seleção de ‘árvores potenciais’ em quantidade 2 vezes superior à densidade final do povoamento – são, portanto, denominadas ‘candidatas a árvores potenciais’ – de forma a permitir uma seleção definitiva mais tarde.

4.2.2.2 Número de ‘árvores potenciais’ ha^{-1}

A definição do diâmetro final almejado das árvores é um ponto fundamental na escolha do regime de manejo a ser utilizado, pois somente então pode-se estabelecer o número de ‘árvores potenciais’ ha^{-1} para a colheita final. Para tal, uma possibilidade é dividir a ocupação máxima possível (área basal do sítio) pela área transversal do diâmetro meta estabelecido. Os resultados desta análise são apresentados na Tabela 9.2-1 (página 224).

Os resultados devem ser analisados com cuidado, uma vez que equações ajustadas para as 100 árvores mais grossas ha^{-1} foram empregadas e, assim, os períodos de produção podem estar subestimados.

A área basal máxima atingida pelos povoamentos analisados no presente estudo foi ~70 m² ha^{-1}. Para comparação, foi também considerada uma área basal de 60 m² ha^{-1}, mais realista para sítios de qualidade intermediária.

A partir da Tabela 9.2-1 é possível verificar que árvores com grandes diâmetros podem ser obtidas em povoamentos com desbastes 'extremos' na metade do tempo necessário para se obter os mesmos diâmetros em povoamentos não desbastados. Importante destacar que diâmetros >50 cm são praticamente impossíveis em povoamentos não desbastados. Mesmo para povoamentos sujeitos a desbastes orientados à prática, diâmetros meta >60 cm não são realistas em função do longo período de produção necessário. Desta forma, quando diâmetros >60 cm são o objetivo de produção, os desbastes precisam ser necessariamente 'extremos'.

Como já mencionado, recomenda-se selecionar inicialmente 2 vezes o número de 'árvores potenciais'. Por exemplo, para 200 'árvores potenciais' ha^{-1}, a primeira seleção deve considerar 400 indivíduos ha^{-1}. Isto significa uma distância média de 5 m entre indivíduos selecionados. Mais tarde o número de 'árvores potenciais' é reduzido.

4.2.3 Intensidade do desbaste

Foi demonstrado ao longo do trabalho que, quando 'desbastes pelo alto' são aplicados, o crescimento diamétrico das árvores é suficiente para compensar perdas de produção mesmo quando a área basal é extremamente e precocemente reduzida.

Em comparação com povoamentos não desbastados, desbastes 'extremos' não apresentaram perda de produção volumétrica em períodos de produção de 16-30 anos. Isso significa que a enorme capacidade de crescimento de indivíduos precocemente e extremamente liberados de competição resulta, ao mesmo tempo, máximo crescimento individual sem nenhuma perda de produção. Entretanto, ocupações do espaço produtivo de 70-80 % da área basal máxima (desbastes 'moderado' e 'pesado') mantidas a partir dos 10 anos de idade, resultam na máxima produção volumétrica ha^{-1} (35 % a mais que os anteriores aos 30 anos de idade).

Quando diâmetros meta de até 50 cm são almejados, desbastes orientados à prática são a melhor opção de manejo pois

- podem ser obtidos em períodos de produção de ~25 anos, que é também a idade ótima do ponto de vista financeiro.
- entregam uma produção volumétrica adicional de madeira em relação às outras estratégias de manejo.

Entretanto, se o objetivo é produzir árvores com diâmetros >50 cm, dentre os tratamentos testados, a opção recomendada é o regime de desbaste ‘extremo’. É preciso lembrar que um diâmetro alvo de 50 cm (a 1,3 m) significa 2 toras podadas (2,5 m de comprimento) >40 cm. Com isso em mente, e considerando que o mercado está disposto a pagar mais por toras podadas e de grandes dimensões (cenário ‘novos sortimentos’), pode-se afirmar que, do ponto de vista financeiro (VPL e VET), a melhor estratégia de manejo é obtida

- com a produção de toras >50 cm – diâmetros alvo a 1,3 m ≥60 cm.
- sob o regime ‘extremo’
- em períodos de produção não inferiores a 22 anos.

4.2.4 Qualidade da madeira

Do ponto de vista prático, e considerando os requisitos do mercado da madeira de pínus no Sul do Brasil, não foram detectadas limitações à qualidade da madeira em função da aplicação de desbastes em povoamentos de *P. taeda*, mesmo quando regimes ‘extremos’ foram considerados.

Em termos de área, a camada externa de madeira adulta produzida nos povoamentos desbastados é 2 vezes superior à obtida no povoamento sem desbaste (0,12 m²). Em termos radiais, porém, o ganho em crescimento diamétrico obtido no regime ‘extremo’ é, em grande parte, madeira juvenil.

4.2.5 Idade de corte

A análise da taxa interna de retorno (TIR) dos diferentes regimes de manejo indicam que a idade de corte final ótima é de 18 anos. Entretanto, a característica de longo prazo de investimentos florestais requer uma análise mais conservadora. Uma abordagem sólida é realizada com índices como Valor Presente Líquido (VPL) e Valor Esperado da Terra (VET). De acordo com esses últimos dois critérios, o resultado financeiro ótimo é obtido em idades de corte ≥22 anos.

Esta conclusão difere da ideia comum que períodos curtos de produção resultam sempre as melhores performances financeiras.

Quando o experimento foi concluído, após um período de produção de 30 anos, supunha-se que a idade ótima financeira havia sido atingida em todos os diferentes regimes de desbaste. Entretanto, os maiores valores de VPL para povoamentos com desbastes ‘moderados’ e ‘pesados’ foram obtidos na idade de 30 anos. O que significa que valores ainda maiores poderiam ser verificados se períodos de produção superiores a 30 anos fossem considerados. Deve-se atentar ao fato do tratamento ‘moderado’ ter apresentado valores praticamente constantes nos últimos 3 períodos avaliados (26 a 30 anos).

Embora evidências suficientes demonstrem que um taxa de juros real anual de 4 % seja uma taxa alternativa realista, o aumento do período de produção foi consequência, principalmente, desta pré-suposição. Ao empregar taxas de juro superiores, resultados financeiros ótimos são obtidos com idades de corte menores.

4.2.6 Silvicultura sustentável

Em função da instabilidade das conclusões obtidas com as diferentes taxas de juro, uma análise adicional foi considerada, na qual povoamentos florestais totalmente regulados foram avaliados em termos de receitas e custos anuais. A discussão relacionada a esta abordagem é descrita abaixo.

Povoamentos florestais regulados são caracterizados por:

- Uma quantidade de madeira semelhante é colhida anualmente.
- A quantidade de madeira colhida anualmente é igual ao crescimento volumétrico dos povoamentos no mesmo período.

Isto significa que a área colhida anualmente pode variar, sendo dependente da qualidade dos sítios colhidos. Após a colheita, o povoamento é reestabelecido e, assim, a sustentabilidade da produção é assegurada.

Para um exemplo prático, o regime de desbastes ‘extremo’ foi selecionado, juntamente com as seguintes suposições:

- Diâmetro alvo: 60 cm.
- Período de produção: 25 anos.

Como os povoamentos estão totalmente regulados, todas as atividades relacionadas ao manejo ocorrem anualmente em $^{1}/_{25}$ da área sob manejo. Neste caso, a análise financeira pode desconsiderar taxas de juros. Ao final do ano, o resultado financeiro é simplesmente as receitas menos os custos que ocorrem durante o ano. Os resultados desta análise são apresentados na Tabela 8.3-3 (página 206).

A vantagem desta abordagem é que todos os esforços são concentrados na produção de povoamentos valiosos, a partir do mínimo custo. Em outras palavras, a silvicultura é o ‘motor’ principal da análise, ao invés de fatores externos, como é o caso da taxa de juros.

A simplicidade da análise demonstra claramente o predomínio das receitas sobre os custos. Pode-se supor que há outros custos relacionados à produção, os quais não foram considerados na análise acima. De fato, uma reflexão relevante é o fato de povoamentos sob regimes de manejo mais elaborados como é o caso dos analisados no presente estudo possuirem uma gestão mais complexa e dispendiosa que povoamentos não desbastados e podados. A seleção de ‘árvores potenciais’, a realização de poda, desbastes, etc., requerem pessoal treinado e controle. O mesmo é verdade para a colheita de diferentes sortimentos de tora, mais ainda para sortimentos podados de grandes dimensões, os quais precisam ser encaminhados à indústria em um curto período de tempo antes que a ação de fungos manchadores prejudique a qualidade dos produtos.

De qualquer forma, o excedente de receitas é suficiente para absorver custos adicionais que eventualmente não foram considerados sem comprometer a viabilidade econômica do manejo.

4.2.7 Potencial teórico de toras podadas

A análise do rendimento industrial (Capítulo 7) foi afetada pela má qualidade da poda aplicada às árvores do presente estudo – núcleo nodoso acima dos valores considerados aceitáveis (15 cm). Isto foi particularmente verdade para o processo de laminação por facas, no qual apenas 20 % do volume das toras foi transformado em lâminas.

Embora a produção de toras de grandes dimensões e podadas foi a opção de manejo de maior performance financeira dentre as analisadas, supõe-se que o resultado possa ser ainda melhor.

O baixo rendimento obtido no Capítulo 7, item 7.4 ‘Laminação por facas’ pode não ter sido apenas resultado da má qualidade de poda. Adicionalmente, o processo industrial utilizado pode não ter sido o mais apropriado para toras de grandes dimensões. Entretanto, e por motivos de simplicidade, a discussão a seguir considerou o mesmo processo industrial, porém avaliando o potencial teórico de toras otimamente podadas.

Como descrito no Capítulo 7, previamente ao faqueamento, as toras foram serradas em blocos. O número potencial de blocos por tora com diferentes diâmetros na ponta fina são demonstrados na Figura 9.2-1 (página 227). Comparações entre o rendimento teórico e potencial, bem como o benefício econômico das toras, são descritos na Tabela 9.2-3 (página 227).

Os resultados assumem que os blocos puderam ser inteiramente transformados em lâminas, mantendo apenas o resíduo padrão do equipamento.

A partir da Figura 9.2-1 e Tabela 9.2-1 verifica-se que, enquanto toras com 30 cm resultam somente 4 blocos de 5 cm de espessura, toras com 70 cm entregam 16 blocos de 7 cm e 11 blocos de 11 cm. Resultados indicam que toras com diâmetro ≤30 cm não são aptas para este processo de faqueamento. Com o aumento do diâmetro das toras, porém, um aumento exponencial no rendimento das mesmas é observado.

Comparando o rendimento teórico e o medido em m² de lâmina, verificou-se que toras de pequenas dimensões, 30-40 cm de diâmetro foram eficientemente processadas pelo processo industrial analisado. Entretanto, quando toras de maiores dimensões foram consideradas, quanto maior a tora, maior a perda de madeira. Toras com 70 cm possuem um rendimento teórico 130 m² maior que os estimados com o modelo de regressão ajustado. Em termos de benefício econômico, isto significa um aumento de 100 US$ por tora, ou mais de 50 %.

Os resultados suportam a ideia de que a produção de toras de grandes dimensões com núcleos nodosos restritos (no máximo 15 cm) resultam ganhos substanciais à indústria e, por isso, maiores preços podem ser obtidos na comercialização das mesmas.

Adicionalmente, toras de grandes dimensões permitem a produção de lâminas com os anéis de crescimento paralelos uns aos outros (tipo ‘linheiro’), o que, em comparação com o tipo ‘catedral’, considerado no presente estudo, possuem valores de mercado 20 % superiores. No passado, esta diferença já foi de 70 %.

Em conjunto, os resultados indicam que a produção de sortimentos de toras de grandes dimensões e podados é uma opção de manejo altamente viável e beneficiaria ambos, produtores de toras e indústrias. Entretanto, verificou-se que a introdução de um novo sortimento, simulado no Capítulo 8 para toras podadas >50 cm ao preço de 140 US$ m^{-3} pode ser desproporcional ao seu real potencial industrial. O benefício econômico teórico foi apenas 10 US$ $tora^{-1}$ maior que o valor medido. De qualquer forma, há certamente espaço para maiores preços caso toras >60 ou >70 cm sejam consideradas.

SUMMARY

CROWN THINNING EFFECTS ON GROWTH AND WOOD QUALITY OF *Pinus taeda* STANDS IN SOUTHERN BRAZIL

Pine species were introduced in Brazil in mid-20th century with the perspective of supplying raw material for forest-based industries. Currently, pine plantations cover ~1.6 million hectares, and although biomass production plays an important role in Brazil, there is an increasing need for sawtimber, and even high quality timber is demanded. With the study it was aimed to evaluate the growth of 30-years-old loblolly pine stands submitted to crown thinnings and with the goal of producing timber for multiple uses. The experimental area was located in southern Brazil, where climate is humid and subtropical. The research design included 4 thinning variants, in which 400 potential crop trees ha^{-1} were selected and released from competition in different intensities by removing competitor trees (crown thinning). Thinning variants were established in ~0.1 ha plots of effective area. There were 2 replicates in block form with random distribution of variants. Trees were annually measured and, at age 30 years, the experiment was finalized. Selected trees were harvested and scaled. From them, cross-sectional discs and logs were taken for growth ring and industrial analyses, respectively. It was verified that loblolly pine trees, when early released from competition, showed a remarkable diameter growth in response to thinnings, which were the higher the more growing space was provided, up to 40 % (67 cm) in top diameter of trees in the ‘extreme’ variant, compared to the trees in the stands ‘without’ thinning (48 cm) at age 30 years. As a result of the great capacity of young trees to make use of the provided growing space, the production in volume ha^{-1} between ‘extreme’ and unthinned regimes was similar (~1,000 m³ ha^{-1}). Since the stands were 16 years old, there was no difference in volume production. Moreover, practice oriented variants, where thinnings were less intensive and more frequent, delivered more volume than unthinned stands, up to 35 %. The surplus was essentially the amount of timber loss due to mortality in the unthinned stand. Altogether, findings proved that extremely thinned stands are the most efficient approach in producing big-sized assortments. However, when these big log assortments are not required, intermediate thinnings combine best individual growth and maximum volume production per area unit (up to 1,400 m³ ha^{-1}). Site occupations of 70-80 % of the maximum basal area from age 10 years onwards are optimal for the maximum volume production ha^{-1}. Early and extreme release from competition resulted in a ~4-years postponement of the mature wood production. Nevertheless, thinnings improved the homogeneity of wood density and, when moderately and frequently applied, resulted in greater amounts of mature wood, in absolute and relative terms. For the same rotation length, thinning had no effect on wood density, but rotation length itself was determinant for obtaining wood of higher density. Results clearly showed that extreme and early release from competition of loblolly pine trees led not only to a better financial outputs, but does it earlier than other thinning intensities and no thinning at all. Thinned stands, independently of intensity, resulted in at least twice as greater financial performance (>13,000 US$ ha^{-1}) than unthinned ones (~6,000 US$ ha^{-1}). The achievement of optimum financial performance needs pruning and harvest ages longer than the ones currently used in southern Brazil. Although very heavy thinnings have a shortening effect on the optimal financial harvest age, it should be at least 22 years for utilizing the whole growth potential of the stands. Thinnings are a profitable silvicultural option even when no pruning is carried out. Altogether, results indicate that the production of big-sized log assortments due to crown thinning is a feasible management goal and is the most profitable alternative for loblolly pine stands in southern Brazil. Although ‘extreme’ regimes showed interesting results, their applicability need a careful analysis of tending costs, stand stability and demand of big-sized log assortments.

Keywords: Thinning. Pruning. Silviculture. Multiple-use.

ZUSAMMENFASSUNG

DER EINFLUSS UNTERSCHIEDLICHER AUSLESEDURCHFORSTUNGSINTENSITÄTEN AUF *PINUS TAEDA*-BESTÄNDEN IN SÜDBRASILIEN

In der Mitte des 20. Jhdts. wurden mehrere Kiefernarten in Brasilien mit dem Ziel, die Papier- und Zellstoffindustrie des Landes mit Rohstoffen zu versorgen, eingeführt. Mittlerweile gibt es in Brasilien rund 1,6 Mio. ha Kiefernplantagen. Obwohl die Massenproduktion nach wie vor eine wichtige Rolle spielt, steigt der Bedarf nach sägefähigem Holz und sogar Wertholz wird zusehends nachgefragt. Mit der vorliegenden Untersuchung soll die Entwicklung von 30 jährigen *P. taeda* Beständen unter verschiedenen Durchforstungsintensitäten im Hinblick auf eine vielfältige Nutzung des erzeugten Holzes, auch Wert- und Starkholzproduktion, bewertet werden. Es werden Bestandesentwicklung, Zuwachs, Holzqualität, industrielle Ausbeute und ökonomische Erfolge unter verschiedenen Szenarien untersucht. Die Versuche wurden 1986 in fünf Jahre alten *P. taeda* Beständen im Süden Brasiliens angelegt. Das Klima ist feucht subtropisch mit rund 1.800 mm Niederschlägen, die gleichmäßig über das Jahr verteilt sind. Bei dem Versuch handelt es sich um eine Blockanlage mit zweifacher Wiederholung und 0,1 ha großen Parzellen. Es wurden vier Durchforstungsintensitäten erprobt und die Varianten zufällig verteilt. Zu Beginn wurden in jeder Parzelle 400 Zukunft-Bäume ha^{-1} ausgewählt und nach dem zugrundeliegenden Durchforstungskonzept unterschiedlich stark freigestellt. Es folgten weitere Durchforstungen und auch die Anzahl der Z.-Bäume wurden in der Extremvariante auf 150 St. ha^{-1} reduziert. Es konnte gezeigt werden, dass die frühe und starke Freistellung der Kiefern erfolgreich war. In Südbrasilien zeigten die Kiefern eine beachtliche Steigerung des Durchmesserwachstums, welche umso größer war, je größer der zur Verfügung stehende Wuchsraum war – um bis zu 40 % gegenüber der undurchforsteten Variante. Junge Bäume nutzen aufgrund ihres ausgeprägten Kronenwachstums den ihnen zur Verfügung gestellten Wuchsraum bestens. Demzufolge waren die Gesamtwuchsleistungen sowohl der undurchforsteten wie auch der extrem durchforsteten Bestände ab einem Alter von 16 Jahren gleich hoch. Bestände mit praxisorientierten Durchforstungsstärken, mit häufigeren, dafür aber schwächeren Eingriffen, zeigten um bis zu 35 % höhere Gesamtwuchsleistungen als undurchforstete. Über alle Varianten hinweg hat sich gezeigt, dass extrem starke Durchfortungen am besten dazu geeignet sind, möglichst viel und möglichst schnell Starkholz zu erzeugen. Sie sind darüber hinaus die einzige Möglichkeit, wenn Sortimente mit mehr als 50 cm oder gar 60 cm in Brasilien noch akzeptierten Produktionszeiträumen erreicht werden sollen. Wenn hingegen keine so großen Dimensionen benötigt werden, fördern mittlere Durchforstungsstärken das Einzelbaumwachstum und die flächenbezogene Produktions am besten. Bei Grundflächenhaltungen von 70-80 % zeigte sich ab einem Alter von 10 Jahren der höchste volumenmäßige Flächenertrag. Auch die Varianten mit einer Grundflächenreduktion auf bis zu 50 % hatten noch keine nennenswerten Einbußen hinsichtlich der Wuchsleistung und erbrachten noch Volumina, die denjenigen der undurchforsteten Varianten vergleichbar waren. Demnach sind Bedenken, dass starke Durchforstungen zu Einbußen bei der Wuchsleistung führen, unbegründet, jedenfalls solange nicht Durchforstungsintensitäten angewendet werden, die weit über die praxisüblichen hinausgehen. Die beachtlichen Zuwächse hatten auch einen gewissen Einfluss auf die Holzqualität. Obwohl nur wenige Unterschiede in der Holzdichte festgestellt werden konnten, führte eine frühe und extreme Freistellung dazu, dass adultes Holz erst mit vierjähriger Verzögerung im Vergleich zu den schwächer oder undurchforsteten Varianten gebildet wurde. Die schwächeren aber häufigeren Freistellungen führten jedoch zu einer homogeneren Holzdichte und sowohl relativ wie auch absolut zu höheren Adulteholzvolumina. Bei gleicher Umtriebszeitlänge hatten Durchforstungen keinen Einfluss auf die Holzdichte. Bei einer längeren Umtriebszeit hingegen, war die Holzdichte höher. Aus praktischer Sicht und unter Berücksichtigung der Anforderungen des brasilianischen Kiefernholzmarktes, dürften die geringfügigen negativen Auswirkungen auf die Holzqualität für die meisten Verwendungen des Holzes ohne Bedeutung sein. Betrachtet man die ökonomischen Auswirkungen des Versuches, so zeigte sich, dass die starke und frühe Freistellung der Z.-Bäume nicht nur zu einem besseren finanziellen Ergebnis führte, sondern dieses auch früher erreicht wurde. Durchforstete Bestände waren – unabhängig von der Durchforstungsintensität – mindestens doppelt so wertvoll wie undurchforstete. Um das finanzielle Ergebnis weiter zu verbessern, muss man zukünftig die Ästung intensivieren und die Ästungsqualität verbessern. Zusätzlich müssen die Umtriebszeiten auf ein bisher in Brasilien nicht übliches Maß hinaus verlängert werden. Auch, wenn sehr starke Durchforstungen die Umtriebszeiten aus ökonomischer Sicht etwas verkürzen, sollten diese – um das volle Potenzial der Kiefernbestände zu nutzen – nicht unter 22 Jahren liegen. Zusammenfassend zeigen die Auswertungen, dass die Starkholzproduktion ein lohnendes Ziel der Kiefernwirtschaft in Südbrasilien ist und sich mit Hilfe der Auslesedurchforstung als waldbaulicher Methode auch erreichen läst. Dazu müssen die Z.-Bäume allerdings sorgfältig ausgewählt, konsequent freigestellt und sachgerecht geästet werden.

Schlusswörte: Durchforstung. Ästung. Waldbau. Mehrfachnutzung.

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1 GENERAL INTRODUCTION

1.1 PROBLEM STATEMENT

With the establishment of pine plantations in Brazil it was firstly aimed to produce raw material for the pulp and paper industry. As a normal market development it was supposed that there would be potential for high quality timber production. It was known that timber of better quality could be produced with silvicultural treatments like thinning and pruning, but no information was available about how these practices influence the growth and development of *Pinus taeda* (loblolly pine) trees in southern Brazil.

Currently, there are 7.2 million ha of plantation forestry, of which 20 % with pine species. Despite of the importance of the planted forestry sector, it occupies less than 1 % of the country area and, therefore, there is an enormous potential for growth.

Crown thinning should be introduced because of its individual tree approach and potential for favouring selected potential crop trees, already known in central Europe. However, at the moment the experiment was established, there was no available knowledge about loblolly pine stands development, especially in the conditions of southern Brazil. Thus, the present study was designed aiming at evaluating the growth response of trees under different crown thinning intensities:

- practice oriented variants of thinning intensities.
- two extremes for comparison: no thinning at all and extremely heavy and early thinning.

The practice oriented variants were an early attempt of testing regimes for the praxis by applying two different schedules with different intensities and timing.

However, it was important to understand the growth behaviour of trees under extreme conditions. The one in which trees grow free of competition since early in the stand life allows the definition of basic rules for the practice, i.e. how is the relationship of individual tree size *versus* production per area unit over time. For this purpose, the extremely heavy variant was designed beyond the limit that would be commercially practicable.

Lack of information about the diameter growth of loblolly pines favoured by crown thinnings made it impossible to define the rotation length at the moment the experiment started. In so far, perceptions about how long the study should be carried out was only possible after two decades. By finishing the experiment at an age of 30 years, it was presumed that the optimum rotation length for the tested regimes had been reached.

Before entering into the study, some context information is needed.

1.2 DEVELOPMENT OF THE BRAZILIAN FOREST SECTOR

Large-scale silviculture of exotic tree species in Brazil is quite recent (20th century), but the forest-based industry dates back to colonial times (16th century) and is expressed even on the lands name – taken from brazil-wood.

Native forests have been exploited to meet the population demands and to establish agricultural fields as well as pastures since earlier times. However, deforestation grew enormously during the last century, since even the brazil-wood exploration preserved a good part of the Atlantic Forest until the end of 19th century.

Southern Brazil includes 3 states: Paraná, Santa Catarina and Rio Grande do Sul (Figure 2.1-1), comprising ~60 million ha. Originally, the plateau areas were covered by ~20 million ha of mixed forests dominated by *Araucaria angustifolia* (Bertol.) Kuntze (MAACK, 1950). After ~100 years of exploitation, only 1-2 % of the original forests have remained (CASTELLA; BRITEZ, 2004).

For the state of Santa Catarina, a new study made by Vibrans *et al.* (2013) utilizing satellite image-based maps and ground inventory concluded that, from the original area, 24 % remain, although highly fragmented and in different successional phases. The majority of the fragments (80 %) are smaller than 50 ha.

One important milestone of the over-exploitation in Santa Catarina and Paraná forests was the so called ‘march to the west’, which intended to open up the interior for colonization in the beginning of the 20th century. Thus, a railway linking the Atlantic coast to the west was constructed. According to Miranda (2007), great extensions of the *Araucaria* dominated forests were donated by the Republic to the British-American railway constructors, along with the surrounding areas (15 to 30 km each railway side), which were completely explored. Better transportation and new harvest facilities increased exploitation exponentially.

The over-exploitation scenario in the southeast and south led to some concerns about the future wood supply. The first expressive exotic tree introduction for production aims is accredited to Edmundo Navarro de ANDRADE. At the final of 19th and beginning of 20th centuries, there were already some difficulties in supplying the timber demand for maintenance and construction of railways. For this purpose and in 1914, Andrade introduced >130 species of *Eucalyptus* (ANDRADE, 1941).

Pines species were introduced in 1948 by the Forest Service of São Paulo. However, commercial planting started only 20 years later (SHIMIZU; SEBBENN, 2008).

Since the institution of the new Forest Code, law n° 4,771 of 1965, a new political approach took place encouraging the afforestation activity in Brazil. With the law 5,106 of 1966, afforestation investments could be deducted from the annual income statement. Thus, instead paying taxes to the government, it was allowed to partially invest in plantation forestry, first by natural persons, and from 1970 onwards also by legal persons. It proved to be an important incentive for the forest sector, since only in the period between 1966-1979, ~700,000 ha were afforested in the state of Paraná, mainly with pines (BREPOHL, 1980). The taxes benefits persisted until the year 1981.

Parallel to this, and in 1967, the Brazilian Forest Institute was created (IBDF). Its responsibilities were to implement the regulation brought about the Forest Code (IORIS, 2008).

It was also during the 1960's that a first Forest Science Faculty in Brazil was established. The faculty was a product of a mission of the Food and Agriculture Organization (FAO), which in 1960 officially started in the Viçosa Federal University, Minas Gerais. However, due to political and infrastructural questions, the so called 'School of Forests' was transferred to the Paraná Federal University, in the city of Curitiba (MACEDO; MACHADO, 2003).

During the 1970's, little was known about silviculture practices and even less about the future perspective of timber production. In fact, much of these plantations were carried out without any clear objectives, as there were 'no costs' since taxes were allocated. Because of the low requirements and fast return of investment, almost all of the investors aimed at producing pulpwood in short rotations.

Although mass production for the pulp industry still plays an important role in Brazil, market conditions have developed. There is an increasing need for sawtimber, and even high quality timber is demanded. Thus the management practices of the plantations have been changed gradually and are still under way.

In the meantime Brazil became an important player in world plantation forestry. In 2012, planted forests covered 72,000 km², of which 22 % were pine plantations (ABRAF, 2013). Despite its importance, it still means less than 1 % of the country's area. According to the same source, the domestic roundwood consumption in 2011 was 170 million m³. Solid wood industry accounted for 32 million m³, 85 % provided by the pines.

Pinus plantations are 80 % concentrated in the southern States (ABRAF, 2012), and *P. taeda* is the most important one with approximately 1 million ha (SBS, 2005).

1.3 SPECIES *Pinus taeda*

Pinus taeda L. (loblolly pine) is an introduced species in southern Brazil, where it has been intensively planted during the past ~50 years.

The species natural range is the southeast United States of America, occurring from Texas eastward to Florida (28° N) and northward to Delaware (39° N) (Figure 1.3-1). It occurs naturally in 15 southern and mid-Atlantic states and has one of the widest geographic range within the southern pines (SCHULTZ, 1997). The climate in its natural region is characterized as humid, warm-temperate with long and hot summers and mild winters (BAKER; LANGDON, 1991; SCHULTZ, 1997). Characteristics of the climate in the natural region of loblolly pine is shown in Table 1.3-1.

TABLE 1.3-1: CHARACTERISTICS OF THE CLIMATE IN THE LOBLOLLY PINE NATURAL REGION

range	mean annual **precipitation** mm	mean annual **temperature** °C	period without **snow** month
from	1,000	13	5
to	1,500	24	10

SOURCE: BAKER and LANGDON 1991

According to Walker and Oswald (2000), the optimum growth occurs along the Atlantic Coast at the Virginia-North Carolina line. There, night and day temperatures differ more than elsewhere in the species' range.

FIGURE 1.3-1: NATURAL DISTRIBUTION OF LOBLOLLY PINE IN THE UNITED STATES
SOURCE: adapted from USDA 2013

Loblolly pine grows naturally in various combinations with longleaf pine (*Pinus palustris* Mill.), shortleaf pine (*Pinus echinata*), slash pine (*Pinus elliottii* Engelm.) and with most southern hardwoods (*Quercus spp*.; *Carya spp.*, *Sassafras albium* Nutt., *Acer rubrum* L., *Salix nigra* Marsh., *Liriodendron tulipifera* L., *Fagus grandiflora* Ehrh., *Fraxinus spp.*, i.a.). The maturity is reached by age 80 and rarely lives beyond age 300 years even under the best conditions. In absence of disturbance, succession results in nearly complete elimination of loblolly pine and formation of mixed hardwood forests (SCHULTZ, 1997).

It is an early successional species (SCHULTZ, 1997). However, according to Walker and Oswald (2000), loblolly pine may survive with 50-60 % of full sunlight on better sites, but often this shade-tolerance diminishes when seedlings reach heights of 2-3 m. According to the same authors, the species prefers wetter sites, attaining maximum growth on poorly drained clay and clay loam soils.

The name ‘loblolly’ was probably given to the species because it often grew in low spots or swales along the coast of Virginia and the Carolinas. These wet areas were commonly referred to as ‘loblollies’ by early colonials. Until the early 1900’s, loblolly pine was often called ‘North Carolina pine’ or ‘old-field pine’, reflecting the species’ ability to regenerate rapidly on abandoned cultivated land or home-sites. The scientific name of loblolly pine was somewhat controversial. The word ‘*taeda*’, meaning torch, which was bestowed on loblolly by LINNAEUS in 1753, is more appropriate for longleaf pine (*P. palustris*). Torches were made primarily from resin-soaked longleaf pine heartwood, called 'lightwood'. They provided an important source of light at night in colonial homes throughout the southern Coastal Plain. Longleaf pine, which commonly grows in pure stands on the drier sites and mixed with loblolly pine on intermediates sites, was given the species name *palustris* (from the Latin word '*palus*' or '*paluster*') meaning swamp. In retrospect, these two southern pines should more appropriately have had the other's species name (SCHULTZ, 1997).

The utility of loblolly pine, the large area at which it grows, and its broad genetic base make it one of the most useful and valuable forest tree species (ZOBEL, 1982). It is the most important timber-producing along the southern Atlantic Coast (WALKER; OSWALD, 2000), and probably the most intensively studied among the forest tree species, at least in the U.S. (BALDWIN *et al.*, 2000).

Although loblolly pine grows reasonably well in a great variety of conditions, soil nutrient availability is the dominant driver of productivity across its natural range (JOKELA *et al.*, 2004). Thus, and according to the same authors, intensive management practices that include use of genetically improved seedling stock, mechanical and chemical site preparation, and fertilization are commonly used to increase forest productivity.

1.4 SILVICULTURE OF PINES

1.4.1 Competition between trees and responses to its release

As stands develop and inter-tree competition intensifies, some trees become supressed and may die, while others become dominant (LEWIS; FERGUSSON, 1993). According to Shepherd (1986), competition between trees begins when two or more trees are growing in close proximity and fighting for the same resources. Tree growth will be checked when any one of those resources becomes limiting, for example water or other vital nutrient elements, or light due to mutual shading by the tree crowns. According to the same author, trees exist often in a state where several vital resources are at, or close to, critical limits which can change from time to time throughout the year depending on weather patterns.

The understanding of how and when competition within trees begins is important, since it affects individual trees and stand growth. The crown development is an important indicator for the silviculturists in this context. Since it is well established that silvicultural practices that aim at accelerating the growth of trees have a direct effect on the crown development, and only indirect on diameter (LARSON, 1972).

Differences in growth rate of loblolly pine individuals are evident already at early ages when competition between trees begins. The differentiation process begins at earlier ages on better sites or at higher levels of stocking. Because growth in height is a critical factor in the occupation of available space, the result is separation of trees into height classes. The most vigorous individuals become dominants as the stand ages (HARMS; LANGDON, 1976).

At least with light-demanding species, which is the case of most pines, it is often best to allow the trees to grow without competition when they are young so that they will develop crowns large enough to maintain high growth rates at later stages.

A good indicator of ability to respond to silvicultural treatments is the live crown ratio. Blackwelder (1983) reported for loblolly pines that stands should be managed by avoiding live crown ratios below 35 %. Below this value, trees will not be able to response satisfactorily to thinnings. Moreover and for practical purposes, dominant and co-dominant trees are more capable to response and to do it faster due to the bigger crown already formed (LEWIS; FERGUSON, 1993; PELTOLA *et al.*, 2002).

1.4.2 Thinning

Thinning is the operation that artificially reduces the number of trees growing in a stand (EVANS; TURNBULL, 2004). The objectives are (BURSCHEL; HUSS, 2003):

- Harvest of wood or by-products,
- Removal of low quality individuals,
- To concentrate the growth on selected remained trees,
- Regulation of tree species.

The objectives of thinning vary according to local circumstances, depending on the nature and growth rate of the crop, the availability of labour and finance, and demand of markets for the production (SHEPHERD, 1986).

Historically, thinning has been frequently used as an emergency measure to generate wood rather than as a silvicultural treatment (BLACKWELDER ,1983). According to Puettmann *et al.* (2009), beginning in the fourteenth century, small trees were in great demand for firewood, fence construction, or to support grapevines. Thus, it was the demands for specific wood products, rather than ideas about increasing growth and vigour of remaining trees, that led to implement thinning practices in young, dense stands.

According to Burschel and Huss (2003), the exceptional meaning of silvicultural practices applied early in the stand life was not recognized until the 20th century. Only in 1934, with Schädelin, the intervention on young stands started being faced as an indispensable practice.

The term 'Durchforstung', meaning 'thinning' in German, is, however, known since 1791, when was used for the first time by Georg Ludwig HARTIG (MAYER, 1984).

1.4.2.1 Types of thinnings

The exact type of thinning, can only be classified when the quality of the affected trees are regarded. With tree quality it is meant the canopy classification, or sociological classes. Kraft (1884 *apud* MAYER, 1984; SMITH *et al.*, 1997) was the first one who prescribed thinning procedures based on them, suggesting the following classification:

(1) Pre-dominant: trees with crowns extending above the general level of the crown cover and receiving full light from above and partially from the sides: larger than the average trees in the stand.

(2) Dominant: their crowns extend above the general level, but are slightly smaller than the previous class, occupy the majority of the stand area.

(3) Co-dominant: trees with crowns forming the general level of the canopy cover and receiving full light from above, but comparatively little from the sides; usually with medium-sized crowns, more or less crowded on the sides.

(4) Intermediate: trees shorter than those in the preceding classes but with crowns extending into the crown cover formed by them.

(5) Supressed: trees with crowns entirely below the general level of the crown cover, receiving no direct light; also named 'overtopped'.

From the practical perspective, and because the empiric approach of KRAFT's classification, some overlapping between canopy classes are possible, especially between classes (1) x (2) and (3) x (4).

The main features of this crown classification were the placement of each tree in relation to its neighbouring ones due to crown formation (BURSCHEL; HUSS, 2003). According to the same authors, this classification has been widely utilized in the praxis as a support during thinning selections, even when done unconsciously by silviculturists.

According to Shepherd (1986), Smith *et al.* (1997) and Kerr and Haufe (2011), there are four distinct types of thinning:

- Low thinning: trees are removed from the lower crown classes;
- Crown thinning: also named 'from above' or 'selective' although these terms may be easily confused with selection thinning; this method was the basis of the present study and is described in detail in the following topic.
- Selection thinning: dominant trees are removed in order to estimulate the growth of trees of the lower crown classes;
- Geometric thinning: trees to be cut or retained are chosen on the basis of some predetermined spacing or other geometric pattern, with no regard for their position in the crown canopy; also named 'mechanical' referred to the mechanistic mode of choices and not to any use of machinery, 'systematic' and 'schematic'.

In the first three methods, the choices are based on the development status of the trees and their position within the crown canopy structure. In the fourth, spacing or arrangement of trees in the stand is the first consideration. It is also useful to recognize a fifth method, free thinning, which can be any combination of the other four simultaneously applied in a single operation (SMITH *et al.*, 1997).

1.4.2.2 Crown thinning

The concept of this type of thinning was first developed by the Swiss Schädelin in 1934, called 'Auslesedurchforstung', based on the development of light-demanding species, and regarding three stages (BURSCHEL; HUSS, 2003):

(1) Re-spacing: during this phase the management objective is to provide a sufficient number of good-quality trees as candidates for subsequent selection process. Only needed when natural regeneration was used in the stand formation.

(2) Potential crop trees selection: a defined number of potential trees is identified and promoted through the removal of direct competitors. After a number of interventions, these selected trees form the dominant part of the stand.

(3) Light-growth-phase: the management focuses on creating and maintaining free growth conditions for the crowns of the potential crop trees in order to guarantee persistent high increment in volume and value.

According to Smith *et al.* (1997), in crown thinnings, trees are removed from the upper crown classes in order to open up the canopy and favour the development of the selected trees of these same classes. Any pre-dominant, dominant or intermediate interfering with the development of potential crop trees are also removed.

The selection of potential crop trees is of great importance since the production will be concentrated on a relative small number of trees ha^{-1}. According to Abetz (1975 *apud* Röhrig *et al.*, 2006) the selection of potential crop trees define the basis of this thinning concept and regard the following criteria:

(1) Vitality: the most important one; only vital trees of the upper canopy classes are able to substantially respond to increases in the growing space.

(2) Quality: the second priority is given to the quality of trees, firstly the form of the stem and secondly the amount and size of branches.

(3) Distribution: only after fulfilling the previous criteria attention to the distribution of trees within the stand should be taken.

The amount and size of branches are of secondary importance. This is because, according to the thinning concept, the potential crop trees selection is carried out when trees have reached 7-8 m of branch-free stem (14-16 of tree total height). Therefore, the most valuable butt part of the stem will not be affected by increasing knottiness.

One modification of the Schädelin method is used when the potential crop trees are selected even earlier in the rotation. This is always the case if pruning is adopted (BURSCHEL; HUSS, 2003).

Crown thinnings are also called ‘low-density thinning’ in the United States, when selected trees are early and heavily released from competition (GUITERMAN *et al.*, 2011).

1.4.3 Silviculture of pines: a global overview

Pines are the most planted tree in the world, accounting for more than 46 million ha or ⅓ of the world productive planted forests (FAO, 2006). The planted area of the most important pines in the world are shown in Table 1.4-1.

Plantations with *P. taeda* are widely present in the United States, Brazil and Argentina.

TABLE 1.4-1: THE MOST IMPORTANT CULTIVATED PINES SPECIES AND THEIR PLANTED AREA

Species	Planted area million ha
P. taeda	11.3
P. sylvestris L.	9.0
P. massoniana Lamb.	6.0
P. radiata D. Don	4.3
P. elliottii	3.2

SOURCE: adapted from FAO 2006

P. sylvestris and *P. massoniana* are the main species in planted semi-natural forests in Europe and in China (FAO, 2006).

The largest plantations of *P. radiata* are located in Chile and New Zealand. This species is also planted in Australia (~800,000 ha), Spain (~300,000 ha) and South Africa (~60,000 ha) (MEAD, 2013).

Together with *P. radiata*, *P. patula* is widely planted in South Africa, where tree breeding and management have substantially influenced the silviculture of pines in Brazil.

Although Schultz (1999) reported that 200-300 million seedlings year^{-1} of *P. taeda* trees are planted in China, no further information about this impressive afforestation program was found.

1.4.3.1 Southern United States

In the U.S., large-scale plantings and direct seeding have extended the commercial range of loblolly pine (SCHULTZ, 1997), mostly following World War II, when artificial planting was increased to supply the growing forest industry (BROOKS; BAILEY, 1992).

According to Schultz (1997), there were probably no more than 2 million ha of predominantly loblolly pine forests in the south of United States before the arrival of Europeans. Currently, the species is by far the most planted, predominating on more than 13 million ha of Southern lands, followed by *P. elliottii* (SCHULTZ, 1997). This planted area might be smaller depending on source, as shown above from FAO (2006).

The silviculture of *P. taeda* in the U.S. has been widely studied and reported. Over the last three decades, considerable investments have been made in applied research programs, emphasizing site preparation, understory competition control, fertilization, growth and yield. Intensive silvicultural practices have been commonly applied to both increase stand productivity and reduce rotation lengths throughout its native range (MARTIN; JOKELA, 2004). Originally, however, site preparation and planting were considered to be marginal forestry activities. (ZOBEL, 1982).

Thinning of loblolly pine stands is a widely used management practice in the south-eastern U.S. (PETERSON *et al.*, 1997). Blackwelder (1983) reported that thinning intensities removing from 35-45 % of the basal area generally improve the harvesting economics and final product profile. Sawtimber production and stand value over the rotation are increased by heavier thinning. According to the same author, maximum growth is generally obtained by thinning at early, typically pre-commercial ages of 8-10 years.

Because of initial fast-growth characteristic, pre-commercial thinning are commonly prescribed for dense naturally regenerated stands. Mann and Lohrey (1974) recommended that stocking should reduce to 1,200-1,700 trees ha^{-1} by age 5 years to ensure the optimal volume production.

Stands are commonly managed in production periods of 20-35 years. (ZOBEL ,1982; BLACKWELDER, 1983; SENFT *et al.*, 1985; CUBBAGE *et al.*, 2010).

In general, a mean annual volume increment (MAI) of 10-15 m^3 ha^{-1} year^{-1} is reported (HARMS; LANGDON, 1976; CLASON, 1994; CUBBAGE *et al.*, 2007, CUBBAGE *et al.*, 2010). However, in Hawai, MAI easily reaches 24 m^3 ha^{-1} year^{-1} (HARMS *et al.*, 1994).

The most serious pests in its natural range are bark beetles, particularly the southern pine beetle *(Dendroctonus frontalis),* whose attack may result in extensive mortality. Most infestations originate in stands that are under stress because of poor site, adverse weather, over stocking, or over maturity. Once the southern pine beetle population has been build-up, adjacent well-managed stands may also be attacked. Preventive measures include avoidance of planting outside the natural range of the species and maintenance of vigorous stands through controlling density by thinning (THATCHER *et al.*, 1980; WALKER; OSWALD, 2000). According to Walker and Oswald (2000), the pine beetle cause more damage to southern forests than fires. According to the same authors, leaf-cutting ants (*Atta texana*) are also considered as a plague.

1.4.3.2 Chile

Radiata pine was introduced in Chile in 1885 for ornamental purposes. Currently it is the base of industrial forestry, third in the ranking of Chilean export products (LISBOA, 1993).

There were ~1.4 million ha of radiata pine plantations in Chile in 2003 (INFOR, 2004), located from 33° S to 42° S (LISBOA, 1993), mostly owned by large, vertically integrated companies (MEAD, 2013).

Rotation lengths of 18-28 years are most common (MEAD, 2013).

Mean annual increment is 10-24 $m^3 ha^{-1} year^{-1}$ (CUBBAGE *et al.*, 2007), however values as high as 34 were reported (MEAD, 2013).

Most of the resource is managed for maximum volume production - pulplogs. However, high pruning is some times regarded to obtain clear veneer logs (MEAD, 2013).

1.4.3.3 New Zealand

Wood products are New Zealand’s third largest export good, behind dairy and meat. The forest-based industry is supported by managed plantation forests, covering 1.7 million ha. (~7 % of the country’s land area). Radiata pine comprises 90 % of the plantation area (Ministry of Primary Industries - New Zealand, 2012), accounting for ~1.5 million ha.

Over 90 % of plantations in New Zealand are privately owned, although growers generally do not own the land (MEAD, 2013).

In New Zealand, radiata pine is usually grown over 25-32-year of production period (MEAD, 2013).

The mean annual increment in volume is 25-30 $m^3\ ha^{-1}\ year^{-1}$ (LAMPRECHT, 1990, CUBBAGE *et al.*, 2007, PALMER *et al.*, 2010). However, growth rates of up to 50 $m^3\ ha^{-1}\ year^{-1}$ have been recorded on the best sites (BURDON; MILLER, 1992).

The main goals of the plantations are: sawlogs, pulplogs, posts and poles and energy (MEAD, 2013).

Lewis and Fergusson (1993) pointed out that it is commonly aimed with the management to produce trees with a final breast height diameter of 50-60 cm, or butt logs with 45 cm under bark. Because artificial prune is used, the regime is called 'clear-wood' management.

About 58 % of the planted forest are expected to be pruned to a height of at least 4 m. However, there is a general trend within the industry in avoiding intensively managed pruned regimes to unthinned and unpruned regimes (Ministry for Primary Industries, 2012), and rotation lengths are likely to increase (Ministry of Agriculture and Forestry, 2009).

Cown (2005) reported that one important characteristic aimed by the industry in this country is wood density. And that there are concerns that the currently 25-years rotation length might not deliver suitable wood for end-uses of solid timber.

1.4.3.4 South Africa

Fast-growing trees were introduced into southern Africa following European colonization in the 1650s (VAN WILGEN; RICHARDSON, 2012). According to Hurley *et al.* (2012), the small natural forest resource was the main reason and led to the introduction of non-native tree species in the 18th and 19th centuries. Species of *Pinus*, *Eucalyptus* and *Acacia* were used to establish plantations aiming to service the demand for wood and wood products.

In 2011, plantation forestry covered ~1.3 million ha, of which ~650,000 ha were with pines. The most important species is *P. patula* (~50 %), planted in the summer-rainfall areas, followed by radiata pine, planted in winter-rainfall areas (Forestry South Africa, 2011). According to the same source, the forest-based industry demanded 7.6 million m^3 of softwood in 2011, mainly for sawtimber production (52 %), while pulpwood was the second most important sector (47 %).

A decrease of ~200,000 ha in the planted area was observed in the last decade, when *Eucalyptus* and *Acacia* were more afforested than pines (Forestry South Africa, 2011).

P. patula shows annual volume increments with 30-40 year rotations varying between 8-40 m^3 ha^{-1} $year^{-1}$, depending on site factors and treatments (FAO, 2001). Cubbage *et al.* (2007) reported a more narrow increment amplitude of 10-25 m^3 ha^{-1} $year^{-1}$.

Pine stands are thinned and pruned intensively to improve quality and value. Planned rotation age is 30 years and the goal is to produce trees with an average diameter at breast height (dbh) of 42 cm over-bark pruned to 9.5 m (KOTZE; MALAN, 2007).

Loblolly pine is planted in a smaller scale. It is grown at rotation lengths of 18-35 years. Mean annual increment is 18 m^3 ha^{-1} $year^{-1}$, but can exceed 28 m^3 ha^{-1} $year^{-1}$ on the best sites. Trees can reach a height of 30 m and a DBH of 45 cm at age of 35 years (SCHULTZ, 1997). Similar to Brazil, the most serious pest is the woodwasp – *Sirex noctilio* (HURLEY *et al.*, 2012).

1.4.3.5 Argentina

In Argentina, plantation forestry exceeded recently 1 million ha (Ministerio de Agricultura, Ganaderia y Pesca, 2011), of which 650,000 ha was planted with pines. According to the same source, loblolly pine is the most widely planted tree species in Argentina, mainly in the north-eastern subtropical area (CUBBAGE *et al.*, 2007).

Loblolly pine plantations have been managed in production periods of 20-25 years delivering mean volume increments of 18-30 m^3 ha^{-1} yr^{-1} (BAEZ; WHITE, 1997; CUBBAGE *et al.*, 2007; RIU, 2011).

In the past years plantations have been established at densities of 1,800 trees ha^{-1} and managed for 20-25 year rotations. In 1996 *Sirex noctilio* was detected for the first time in some plantations and the density was lowered to 1,400-1,100 trees ha^{-1} as a sanitary decision. Commercial thinning is normal practice with commonly 2 during the rotation (BAEZ; WHITE, 1997).

1.4.3.6 Overview

An overview in tabular form is shown (Table 1.4-2). It was intended to present a currently used management schedule and, therefore, recent sources were consulted.

However, because practice oriented data could hardly be found, some inaccuracies might have occurred.

1.5 SILVICULTURE OF LOBLOLLY PINE IN SOUTHERN BRAZIL

Loblolly pine was introduced in Brazil in 1948, together with *P. palustris*, *P. echinata* and *P. elliottii* (slash pine). However, expressive plantings have started only 20 years later. Both loblolly and slash pine were the most promising ones, and were intensively planted in the south and southeast regions of the country (SHIMIZU; SEBBENN, 2008). Currently, the area occupied by pines in Brazil is about 1.6 million hectares (ABRAF, 2013), including the tropical varieties that have been introduced later. Notwithstanding, loblolly pine is the most important one (CUBBAGE *et al.*, 2007) with approximately 1 million ha (SBS, 2005).

In Brazil, loblolly pine is adapted to acidic soils (KRONKA *et al.*, 2005) and nutritional deficiencies are not considered a limiting factor to its growth, since shortage symptoms were not yet observed (REISSMANN; WISNIEWSKI, 2000).

According to Reissmann and Wisniewski (2000), loblolly pine has an extraordinary capacity of managing nutritional resources, and even growing in poor sites, does not show visual symptoms of deficiency. However, recent studies reported the need for fertilization on poor sites, as a result of nutrient exportation due to successive rotations (BELLOTE *et al.,* 2003; MORO *et al.,* 2008). VOGEL *et al.* (2005) found a linear trend of loblolly pine growth by improving phosphorus supply. Bellote *et al*. (2003) recommended beyond phosphorus, potassium fertilizing.

In Brazil, and according to the Brazilian Enterprise for Agricultural Research (EMBRAPA, 2005), site preparation is an important silvicultural means. When plantation takes place in abandoned agricultural fields, it is recommended to eliminate the compaction of the soil sub-layer, normally with help of rippers 50 cm depth.

At the beginning of the pine cultivation in Brazil, commonly bare roots seedling were planted, with densities up to 2,500 trees ha^{-1}. In the last 20 years, however, the production of seedlings in containers (~60 cm^3) became the most applied method (CARNEIRO, 1995).

Loblolly pine resists frosts and provides high yields (SHIMIZU; SEBBENN, 2008). In the cold highlands of southern Brazil, it growths better than any other tree. On average, values around 37 m³ ha-1 year-1 are described (Abraf 2011). However, values varying from 15-57 are reported (MAINARDI *et al*., 1996).

Leaf-cutting ants are considered the most important pest of Brazilian plantation forestry (NICKELE *et al.,* 2010). However, ants damage is only a problem until age 2 years (CANTARELLI *et al.,* 2008), and can be easily controlled by chemicals.

The initial success of loblolly pine as wood source in Brazil was mainly due to the absence of natural constrains. However, from the beginning of the 1980ies onwards, some pests emerged causing problems. Among them, the most notorious

TABLE 1.4-2: CURRENTLY USED SCHEDULES IN MANAGING PINE STANDS FOR THE DIFFERENT COUNTRIES AND SPECIES AS OVERVIEW

COUNTRY (species)	AGE years	OPERATION	STOCKING trees ha^{-1}	OBSERVATIONS	MAI m^3 ha^{-1} year^{-1}
United States (*P. taeda*)	0	planting	1,090		10-15
	22	thinning	500		
	30	thinning	250		
	35	clear cut	-		
Chile (*P. radiata*)	0	planting	1,250		10-24
	5	pruning to 2.2 m	700	>4.5 m crown	
	8	pruning to 4 m	450	6 m crown	
	8	thinning	600		
	9	pruning to 5.5 m	400		
	10	pruning to 7.9 m	250		
	13	thinning	400		
	25	clear cut	-		
New Zealand (*P. radiata*)	0	planting	1,000		25-30
	6	pruning to 3.5 m	375	4 m crown	
	7-8	pruning to 5.6 m	375		
	7-8	thin to waste	750		
	10	thin to waste	375		
	30	clear cut	-		
South Africa (*P. patula*)	0	planting	1,111		10-25
	3-4	pruning to 2 m			
	4-6	pruning to 4 m			
	5-7	pruning to 6 m		might continue up to 9.5 m	
	8-10	thinning	500	selective from below	
	12-15	thinning	300		
	30	clear cut	-		
Argentina (*P. taeda*)	0	planting	833-1,666		18-30
		pruning to 2 m	600-800		
	3-4	thinning	800	trees 6 m height	
		pruning to 4 m	400	trees 7-8 m height	
	6-7	thinning	600	basal area = 32 m² ha^{-1}	
		pruning to 6 m	300		
	8-10	thinning	450		
	14-16	thinning	250		
	20-29	clear cut	-		

SOURCE: adapted from KURTZ; FERRUCHI, 2004; WEST, 2006; KOETZE; MALAN, 2009; CUBBAGE *et al.,* 2007; CUBBAGE *et al.,* 2010; RIU, 2011 one was the wood-wasp (*Sirex noctilio* F., *Hymenoptera, Siricidae*), which represented a strong threat to the pine forest sector in Brazil. It is known that the must adequate prophylaxis is to thin the stands, keeping only vital individuals (IEDE et al., 2008).

There are no available data about the plantation area with pines that is subject to thinning and pruning in Brazil. However, as the majority of plantations belongs to big companies' (pulp and paper and reconstituted panel industries) it is supposed that, most of the planted area is being managed without thinning and pruning, since the production goal is the maximum volume per area unit.

Thinnings, when carried out, are commonly a combination of schematic thinning (3rd-9th row), which allow stand access. Furthermore, and completing the thinning intensity, thinnings from below removing malformed individuals (i.a. forked) are used. These types of thinnings are also most oftly reported in domestic scientific studies (ANDRADE *et al.,* 2007, ELESBÃO; SCHNEIDER, 2011).

Moreover, several studies regarding mathematical approaches for modelling stand growth and determination of the most profitable option (SANQUETTA *et al.,* 2000; SCOLFORO *et al.,* 2001; EISFELD *et al.,* 2005). They are interesting approaches, but fail to capture the biological processes and consequences of thinnings on individual tree growth.

For illustrative purpose, 3 different examples of management regimes are shown in Table 1.5-1.

The pulpwood regime is the most used management schedule, and is the simplest one, as the maximum volume in the shortest period is intended. The regime reported by Mainardi *et al.* (1996) reported an intermediate scheme, in which thinnings are regarded. The regime called 'Florestal Gateados' is a reference to the enterprise where it is commercially applied. This example is relative well known within the Brazilian forest sector as a success case of multiple-use management, from which the most valuable pine logs in the country are produced.

Ahrens (1992) reported that although not frequent, some landowners in Brazil use to thin loblolly pine stands 4-5 times during the rotation period. Thinnings are light and from below. The author also reported that pre-commercial thinnings are not common.

Table 1.5-1: Management regimes commonly applied in the Brazilian pine stands

Regime	Age years	Operation	Stocking trees ha^{-1}	Observations
Pulpwood	0	planting	1,600-1,800	
	15-20	clear cut	-	
Mainardi *et al.* 1996	0	planting	1,666	
	~8	thinning[1]		BA = 40 m^2 ha^{-1}
	~12	thinning[2]		BA = 40 m^2 ha^{-1}
	15-16	clear cut		
Florestal Gateados	0	planting	1,666	
	3	prune to 1 m	1,600	
	4	prune to 2.5 m	1,600	
	5	prune to 3.5 m	1,000	
	6	prune to 5.7 m	1,000	
	~7	thinning[3]	1,100	BA = 40-45 m^2 ha^{-1}
	~10	thinning[3]	750	
	~13	thinning[3]	450	
	~16	thinning[3]	350	
	~20	thinning[3]	250	
	25-30	clear cut	-	

Source: The author (2014)

[1] basal area is reduced to 25 m^2 ha^{-1}. Thinning type is a combination of mechanical (3rd row) and thinning from below

[2] basal area is reduced to 25 m^2 ha^{-1}.

[3] all thinnings aim at reducing the basal area from 40-45 to 30 m^2 ha^{-1} and, more important, by reducing competitor trees to future-crop selected individuals – crown thinning.

There is a trend over the last years of stagnation or even decrease in the area occupied with pine plantations in Brazil. This fact is attributed to an increase in eucalypt plantation where pine have been clear-felled (ABRAF, 2011). However, especially in southern Brazil, recently planted *Eucalyptus* stands have not been growing as expected. The cold winter with high temperatures fluctuations during the day (over 25 °C span) are the reasons for some plantation failures (Dobner *et al.,* 2009). Moreover, planting *Eucalyptus* requires higher investment (intensive site preparation, fertilizing and weed control) in comparison to pines. Therefore, the trend of planting eucalypts instead of pines might not continue, at least by small and medium sized landowners, where loblolly pine is well established, successfully cultivated and with a well-developed market.

Different moments during a rotation of intensively managed loblolly pine stands in southern Brazil are shown in Figure 1.5-1.

With the introduction of pines in Brazil it was aimed, at first, to supply the pulp and paper industry. However, within the last decades, it became an important source for the solid wood industry (Moro *et al.,* 2008). According to Camargo (2008) the wood of loblolly pine produced in Brazil is currently used as:

- Sawtimber: as direct applications, mainly in constructions.
- Plywood: Brazil is the fifth largest world producer of softwood plywood, for the construction, furniture and packaging industries. The majority of softwood plywood is exported.

FIGURE 1.5-1: DIFFERENT ASPECTS DURING THE PRODUCTION PERIOD OF INTENSIVELY MANAGED LOBLOLLY PINE STANDS IN SOUTHERN BRAZIL: (A) SEEDLINGS PRODUCED IN CONTAINER; (B) THINNING PROCEDURE IN A 10-YEAR-OLD PRUNED STAND; (C) A 20-YEARS-OLD STAND; (D) CLEAR-CUT OF A 30-YEARS-OLD STAND; (E) LOGS OF A CLEAR-CUT

SOURCE: The author (2014)

- Value added products: include blocks, blanks, moulding, panels, doors, and others. These products add more value to the primary product chain. Moulding (profiles obtained from the reprocessing of timber blocks and blanks) is used primarily by the construction industry overseas.

The consumption of pines roundwood in Brazil by segment in 2010 is shown in Table 1.5-2.

From Table 1.5-2 it can be seen that, in 2010, the half of the demand for pine wood was used for solid-wood end-uses. Pulp and paper also play an important role, just as big as the reconstituted panels (fibre and particle boards).

TABLE 1.5-2: BRAZILIAN CONSUMPTION OF PINE ROUNDWOOD BY SEGMENT DURING THE YEAR OF 2010

SEGMENT	ROUNDWOOD CONSUMPTION million m³	%
Solid wood¹	29.1	*52*
Industrial firewood	9.4	*17*
Pulp and paper	8.6	*15*
Reconstituted panels	8.8	*15*
Others	0.3	*<1*
Total	**56.2**	*100*

SOURCE: adapted from ABRAF, 2011

[1] sawtimber, plywood and processing of high value added products (floor, door, window, framework, tools and edge glued panel.

1.6 STUDY HYPOTHESES, OBJECTIVES AND STRUCTURE

1.6.1 Study hypotheses

Loblolly pine, as a light-demanding species, responds strongly to early and intense thinnings with regard to diameter growth and single tree volume production, whereas they do not react much when released at an advanced age.

Low initial stand density or early and intensive thinnings may cause, however, the development of big branches which may deteriorate the quality of the stems. Therefore, artificial pruning is a must for high quality timber production. Whether other disadvantages may follow intensive thinning is contradictory.

If stand density manipulation is one of the most important available tool for silviculturists, then applying it to loblolly pine stands in southern Brazil might be an option when the production of timber for multiple purposes is intended.

1.6.2 General objectives

The aim is to study and evaluate the development of a 30-years-old loblolly pine stand that was treated with different intensities of crown thinning, with the goal of producing high quality timber.

1.6.3 Specific objectives

Specific objectives of the research were to evaluate the effects of crown thinning intensities on:

- Growth:
    - Stand development until age 30 years.
    - Individual tree growth as response to thinnings at different height levels.
    - Log assortments production classified by small-end diameter and pruning.
- Wood quality.
- Industrial yield of logs in sawmills and veneer industries.
- Financial performance according to different thinnings regimes and harvest ages.

1.6.4 Structure of the thesis

The following chapters are dedicated to particular aspects of the study. Each of the chapters contains the description of the special methods, results and discussions concerning the respective aspect. It is structured in the following way:

In Chapter 2 MATERIAL AND METHODS, information is given about the study site and the design and establishment of the experiment.

Chapter 3 GROWTH OF STANDS provides a first evaluation of the stand and trees characteristics at age 30 years and over time as affected by the different thinning intensities. The development of top diameter, basal area and volume ha^{-1} are reported.

Chapter 4 RING WIDTH addresses an individual tree approach, regarding growth responses following thinnings at different heights. The growth rate in absolute and relative terms, obtained from cross-sectional discs, are compared between thinning variants and diameter classes.

In Chapter 5, the WOOD QUALITY produced under the different management regimes is evaluated. Features as growth homogeneity, wood density and the proportion of juvenile and mature wood are assessed. The influences of harvest age on wood quality are also reported.

In Chapter 6 LOG ASSORTMENTS the volume production is classified according to log diameter and whether they are pruned or not. Comparison between thinning variants are carried out, regarding harvest ages from 16-30 years.

Chapter 7 INDUSTRIAL YIELD aims at evaluating the industrial output of logs assorted by diameter and pruning. Sawmill and veneer processes are analysed from the perspective of volume and economic yield.

In Chapter 8 FINANCIAL PERFORMANCE, stands subjected to different thinning regimes are analysed from the financial perspective. The amount of timber assorted according to logs diameter, together with their prices, are used for cash flow analysis, from which financial indexes are obtained. Additionally, sensibility analysis with different scenarios are evaluated.

Chapter 9 FINAL DISCUSSION provides a summarising approach. The main results are put together in order to assess a holistic view of managing loblolly pine stands in southern Brazil. Silvicultural regimes for specific productions goals are outlined and considerations to the praxis presented.

2 MATERIAL AND METHODS

2.1 STUDY SITE

2.1.1 Location

The study was located in the municipality of Campo Belo do Sul, Santa Catarina state (SC), southern Brazil, about 950 meters a. s. l. (lat. 27°59’33’’S, long. 50°54’16’’W) (Figure 2.1-1).

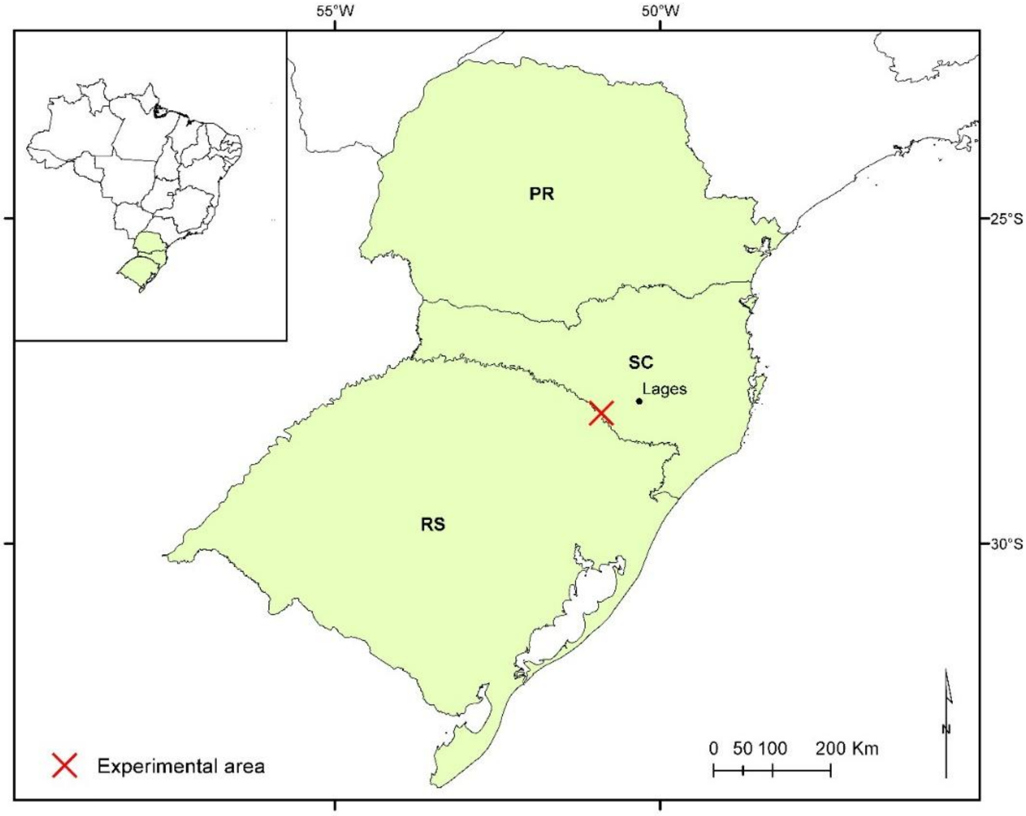


FIGURE 2.1-1: SOUTHERN BRAZIL (GREEN HIGHLIGHTED): THE STATES OF PARANÁ (PR), SANTA CATARINA (SC) AND RIO GRANDE DO SUL (RS). EXPERIMENTAL AREA LOCATED ~60 KM APART FROM THE MUNICIPALITY OF LAGES

SOURCE: The author (2014)

The experimental area is called ‘Pedras Brancas’, which means ‘white stones’ in Portuguese and refers to their dominance in the area.

2.1.2 Climate

The climate is humid and subtropical. According to Köppen, Cfb. Frosts occur between 2 and 29 events year^{-1} (EMBRAPA, 1998). For local climate description, meteorological data during the experiment period (1980-2011) were taken from a meteorological station owned by the National Meteorological Institute (INMET), located in the municipality of Lages (Figure 2.1-2).

From Figure 2.1-2 it can be seen that, the studied site is characterized by

- well distributed rainfall during the whole year, i.e. there is no water-deficit period.
- mild mean temperature during year, 16° C in average, even when mean minima reaches ~0 °C in Jun-Jul-Aug. A constant ~20 °C variation amplitude between minima and maxima can also be observed.

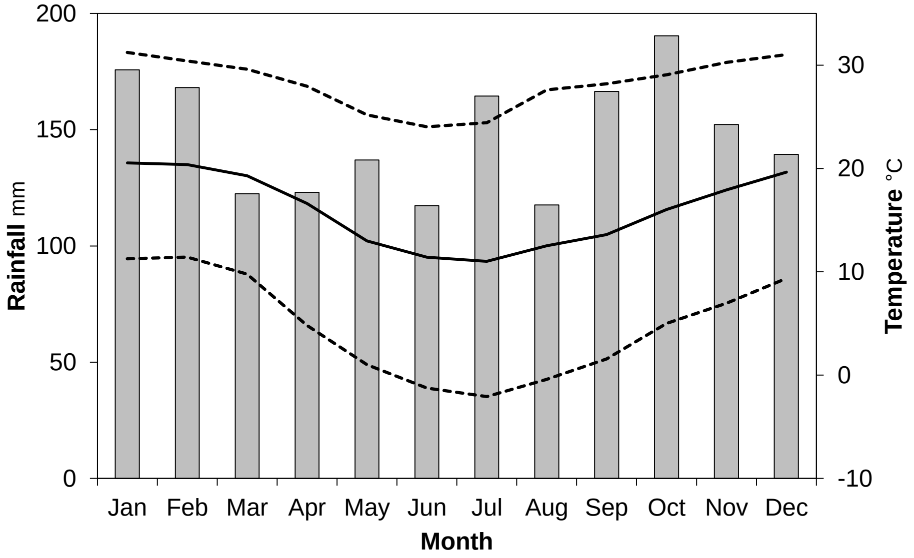


FIGURE 2.1-2: COLUMNS SHOW THE AVERAGE MONTHLY RAINFALL; LINES THE TEMPERATURE: MEDIUM (FULL LINE), MINIMUM AND MAXIMUM (DASHED LINES) TEMPERATURES, FOR THE STUDIED PERIOD (1980-2011)

SOURCE: The author (2014)

During the studied period (1980-2011), the average annual rainfall was ~1,800 mm, ranging from 1,200 in 1985, to 2,400 mm in 1983. The lowest absolute temperature was -6 °C, registered in July of 2000.

In general, it can be seen that rainfall and temperature conditions are optimal and allow vegetative activity during most of the year.

2.1.3 Soil

Soils developed from sedimentary material (EMBRAPA, 1998). According to Guedes (2005) they are not hydromorphic, clay rich, well drained, typically dark-coloured.

Oliveira (2012) found near to the study area the following soil types:

- clayey loam structured soil (Hapludox – Nitossolo háplico),
- well drained Leptossols (Neossolo Litólico), and
- dusky Latossol (Latossolo Bruno).

All soil types developed from Rhyodacites, a volcanic and acid rock from the 'Serra Geral' formation (TRUFFI; CLEMENTE, 2002), and had a total porosity varying from 50-67 % (OLIVEIRA, 2012).

The area had been covered by an *Araucaria* dominated forest until 1980. Previous to this date, *Araucaria* individuals and other valuable species (i.a. *Cedrela sp.*) were harvested. In 1980, the remained forest was cleared and, at the beginning of 1981, burned.

Soil analyses in 2011 confirmed its chemical quality (Table 2.1-1).

TABLE 2.1-1: SOIL CHEMICAL ANALYSIS FOR THE STUDY SITE 'PEDRAS BRANCAS'

PARAMETER	UNIT	VALUE	GRADE
pH		5.1	low
Al - Aluminium	cmolc dm^{-3}	3.7	high
Clay	%	28.0	high
Ca - Calcium	cmolc dm^{-3}	3.1	medium
Mg - Magnesium	cmolc dm^{-3}	0.9	medium
P - Phosphorus	mg dm^{-3}	16.0	high
K - Potassium	mg dm^{-3}	98.0	medium
Cu - Copper	mg dm^{-3}	1.3	high
Zn - Zinc	mg dm^{-3}	1.0	high
Fe - Iron	mg dm^{-3}	58.5	high
Mn - Manganese	mg dm^{-3}	4.2	medium
CEC	cmolc dm^{-3}	7.9	high

CEC = cation exchange capacity.

SOURCE: The author (2014)

Values were graded according to the Fertilizing and Liming Manual (2004) for the states of Santa Catarina and Rio Grande do Sul, Brasil.

Loblolly pine is well adapted to acid soils, thus the high aluminium saturation and the low pH values are no constraints.

The analysed macronutrients (Ca, Mg, P and K) and micronutrients (Cu, Zn, Fe and Mn) were present in medium or high levels, which, together with the high cation exchange capacity (CEC), evidenced the high chemical quality of the soil.

2.1.4 Original vegetation

The area is located within the Mixed Ombrophylous Forest (MOF), mountain formation (400-1000 m a. s. l.), which is also called Araucaria Forest (IBGE, 2012). A primary Araucaria forest is shown in Figure 2.1-3.

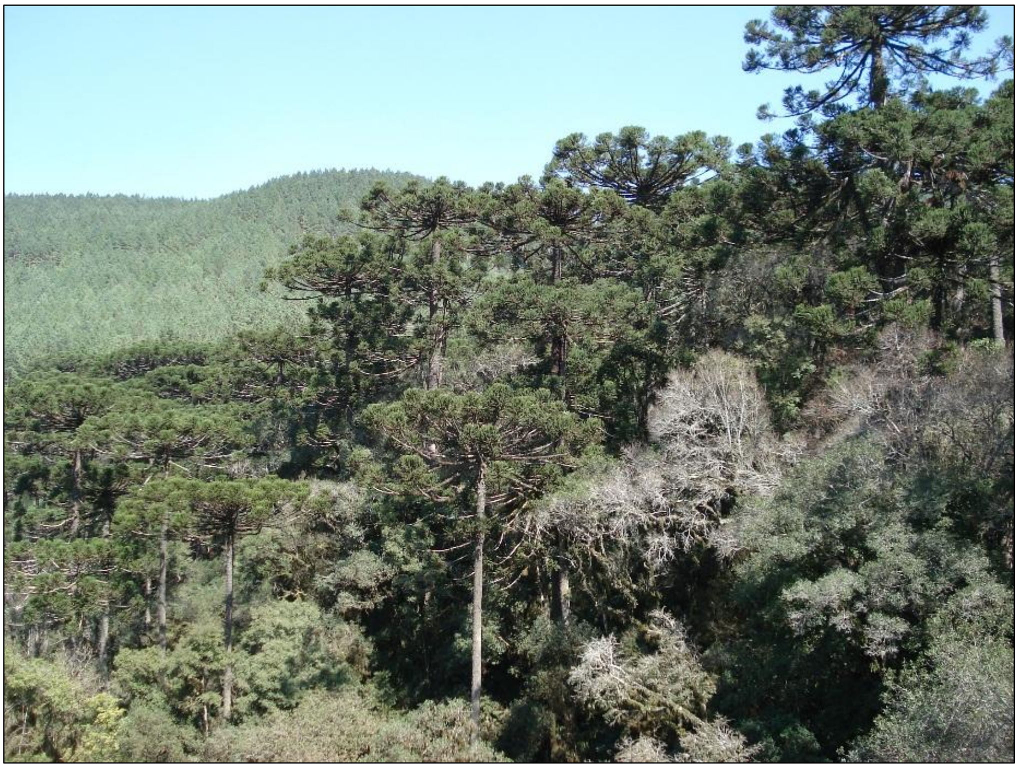


FIGURE 2.1-3: PRIMARY ARAUCARIA FOREST WITH *ARAUCARIA ANGUSTIFOLIA* EXEMPLARS OCCUPYING THE HIGHER CANOPY. LOBLOLLY PINE PLANTATION IN THE BACKGROUND

SOURCE: The author (2014)

2.2 SITE PREPARATION AND PLANTING

Site preparation comprised the following activities:

(1) Clear-cut of a degraded *Araucaria* forest.

(2) Slash burning.

(3) Planting of six month old bare-root seedlings in winter 1981, at a density of 2,500 trees ha^{-1} (spacing: 2.5 x 1.6 m).

(4) Weeding in the first 2 years.

(5) No tending procedure took place before the establishment of the experiment.

2.3 EXPERIMENT ESTABLISHMENT AND DESIGN

In 1986, a 5-year-old loblolly pine plantation was used for the thinning experiment.

The research design included a gradient of 4 thinning intensities, in which 400 potential crop tree candidates ha^{-1} were selected and released from competition in different intensities. The proposed thinning variants, characterized by the number of remaining trees and the number of competitors that were eliminated in order to favour the potential crop trees, are shown in Table 2.3-1. The concept of the experiment was designed by Prof. Dr. Jürgen HUSS in 1986.

TABLE 2.3-1: THINNING PROGRAM AS CHARACTERISED BY THE NUMBER OF REMAINING TREES (REMAIN.) AND THE NUMBER OF COMPETITORS (COMP.) THAT WERE ELIMINATED IN ORDER TO FAVOUR THE POTENTIAL CROP TREES CANDIDATES.

	THINNING VARIANT							
Age	WITHOUT		MODERATE		HEAVY		EXTREME	
year	remain.	comp.	remain.	comp.	remain.	comp.	remain.	comp.
0	2,500		2,500		2,500		2,500	
5	all	-	2,100	1	1,700	2	400	all
7	all	-	1,700	1	1,300	1	400	-
10	all	-	1,300	1	900	1	250	0.4
13	all	-	800	1	500	1	150	0.4
15	all	-	400	1	500	-	150	-

SOURCE: Prof. Dr. J. HUSS (1986)

Small inconsistencies in the number of trees per hectare after thinning is due to some differences in stand initial density and rouded values. Although some supressed tree might have died, resulting in differences in the stand initial density previous to thinning, the most important is the number of competitor trees removed per potencial crop one.

The thinning variants were established in ~0.2 ha large plots (divided in a total plot including edge rows and an inner part of ~0.1 ha used for measurements). There were 2 replicates in block form with random distribution of variants.

Thinning procedures were planned as crown thinning. The potential crop trees were selected at the first intervention (1986) and liberated differently by eliminating none, 1, 2 or all competitors. Later on, thinnings continued by removing a certain number of competitors, and by reducing the number of potential crop trees in the 'extreme' variant. As shown in Table 2.3-1, the main difference in thinning intensity was planned for the first intervention.

All the trees were pruned up to 2.5 m height in 1986. A second pruning procedure took place 2 years later, when the 400 potential crop trees ha^{-1} were pruned up to 5.7 m high.

3 GROWTH OF *Pinus taeda* STANDS SUBJECTED TO CROWN THINNING IN SOUTHERN BRAZIL

3.1 INTRODUCTION

The silviculture of loblolly pine stands in southern Brazil has been remarkable intensified. As a result of more productive genetic materials, production periods have been shortened throughout the years. Currently, there is a great effort to suit specific clones to different sites in order to increase even more the productivity of stands.

Breeding programs have been led by pulp and paper industries and are responsible for impressive increments up to 57 m^3 ha^{-1} $year^{-1}$ (MAINARDI *et al.,* 1996). Only recently concerns have channelled into wood density and other qualitative characteristics at the expense of maximum volume growth. However, aiming at increasing cellulose production per area unit instead of improving solid-wood performance.

Although initially inexpressive, the solid-wood industry based on pines have developed and, in 2010, accounted for more than half of the domestic round wood consumption (ABRAF, 2011). Even though, the majority of pine plantations still belongs to pulp and paper industries, which commercialize the big-sized bottom logs for better prices, obtaining small-sized and cheaper ones from independent log producers. It means that the solid-wood industry have been supplied with ‘by-products’ of pulp-wood regimes rather than being the main management objective.

Pulp-wood schedules are simpler in comparison to regimes aiming at solid end-uses, especially when the production of high quality wood is intended. Therefore, it is quite logic that the production of timber for solid end-uses could be optimally done by changing the management goals and silvicultural practices. Indeed, aiming at producing big-sized logs, possibly free of knots (artificially pruned) could be an interesting option for independent log producers. The production of multiple log assortments, of diverse sizes and quality, has the advantage of reducing risks and dependence of an specific industrial segment, at the same time that more valuable niches may be supplied. Moreover, small-sized logs of poorer quality will be anyway produced at upper parts of the stem.

According to Hennessey *et al.* (2004), thinning is the principle tool for silviculturists to manipulate the growth of a stand. It is commonly used to ensure that only trees of good form and vigour will be left to grow on to become valuable, final crop trees – thinnings essentially concentrate the growth potential of the site onto the crop trees (MAKINEN; ISOMAKI, 2004; MEAD 2013).

Although not applied to the majority of loblolly pine stands in Brazil, thinnings are regarded in punctual cases. When at all, thinnings are carried out ‘from below’. It is the easiest way to thin a stand because it simply anticipate the natural mortality of trees. However, by removing suppressed and intermediate trees from a stand, little or no improvement is to be expected on the growth of the dominant trees.

Differently, with the crown thinning method it is aimed to favour selected individuals of greater vitality and quality by removing direct competitors. Thus, dominant individuals are removed when they compete with a selected potential crop tree, allowing the remaining ones to develop even greater crowns and to achieve, and maintain for longer periods, an enhanced diameter growth rate.

The present study evaluated the growth responses of loblolly pine, individually and as stands, grown in southern Brazil subjected to different crown thinning intensities.

3.2 MATERIAL AND METHODS

The present analysis is part of several evaluations of the Pedras-Brancas-thinning trial. Details about site, experiment design and thinning variants are described in Chapter 2 MATERIAL AND METHODS.

3.2.1 Data collection

Trees have been annually measured between 1985-2001, in 2003 and, finally, in August 2011:

(1) Diameter at breast height (1.3 m) of all trees with diameter tape (millimetre exact).

(2) Total height (h_t) and crown basis height with hypsometer. However, at age 30 years, survey was carried out with measurement tape after tree felling. In total, 13 trees plot^{-1} regarding all diameter range (4 small, 5 medium sized and 4 large).

Trees were scaled in detail after felling in August 2011. Diameter data were collected with diameter tapes:

(1) at 0.2, 0.5 and 1.0 m above ground,

(2) from 1.0 m onwards, measurements were done every 5 % of total height,

(3) totalling 19 d_i x h_i paired data per tree.

In total, 105 trees were scaled, regarding all thinning variants and diameter range. Scaling provided 2,403 d_i x h_i measurements, which allowed the adjustment of models for estimating tree height, crown basis height, individual volume and stem taper.

3.2.2 Modelling

The evaluation of different silvicultural practices commonly requires the assessment of quantity and quality of the wood produced, which is frequently obtained with help of volumetric or taper equations. For this purpose, models are fitted with scaling data (diameter measurements over the total stem length), and are used to estimate both the volume of individual trees and diameter values along the stem, using the diameter at breast height and total tree height values as independent variables.

Because not all trees height were measured, hypsometric models were fitted and used for estimating the height of unmeasured individuals.

3.2.2.1 Tested models

Based on the inventory data, hypsometric models were adjusted to estimate total height and crown basis height (CBH). Models for individual volume and stem taper estimation were also fitted (Table 3.2-1). Adjustments were carried out by linear regression methods, mostly with the data obtained at the final forest inventory, age 30 years. Nevertheless, for a more accurate estimation of the volume obtained at the different thinnings, hypsometric models were also adjusted for the ages 11 and 14 years. According to a standard growth model the estimated heights were corrected for the years different than 11 and 14. Because of the same reason, a taper model at age 14 years was also adjusted and used for volume calculation harvested on thinnings.

The Hradetzky model was adjusted with the best potencies selected by stepwise method from 43 different options (range 0.005-99). Non-linear models were logarithm transformed previous to adjustment.

Table 3.2-1: Tested models for hypsometric, individual volume and stem taper estimation.

Hypsometric	
Trorey (1932)	$h_t = \beta_0 + \beta_1 dbh + \beta_2 dbh^2 + \varepsilon_i$
Stoffels (1953)	$\ln(h_t) = \beta_0 + \beta_1 \ln(dbh) + \varepsilon_i$
Curtis (1967)	$\ln(h_t) = \beta_0 + \beta_1 \left(\frac{1}{dbh}\right) + \varepsilon_i$
Individual volume	
Husch (1963)	$\ln(v_i) = \beta_0 + \beta_1 \ln(dbh) + \varepsilon_i$
Spurr (1952)	$v_i = \beta_0 + \beta_1 \left(dbh^2 h_t\right) + \varepsilon_i$
Schumacher-Hall (1933)	$\ln(v_i) = \beta_0 + \beta_1 \ln(dbh) + \beta_2 \ln(h_t) + \varepsilon_i$
Taper	
Kozak *et al*. (1969)	$\frac{d_i}{dbh} = \sqrt{\beta_0 + \beta_1 \left(\frac{h_i}{h_t}\right) + \beta_2 \left(\frac{h_i}{h_t}\right)^2} + \varepsilon_i$
Schöpfer (1966)	$\frac{d_i}{dbh} = \beta_0 + \beta_1 \left(\frac{h_i}{ht}\right) + \beta_2 \left(\frac{h_i}{ht}\right)^2 + \beta_3 \left(\frac{h_i}{ht}\right)^3 + \beta_4 \left(\frac{h_i}{ht}\right)^4 + \ldots$ $\ldots + \beta_5 \left(\frac{h_i}{ht}\right)^5 + \varepsilon_i$
Hradetzky (1976)	$\frac{d_i}{dbh} = \beta_0 + \beta_1 \left(\frac{h_i}{ht}\right)^{p1} + \beta_2 \left(\frac{h_i}{ht}\right)^{p2} + \ldots$ $\ldots + \beta_n \left(\frac{h_i}{ht}\right)^{pn} + \varepsilon_i$

Where: h_t = total height (m); dbh = diameter at breast height (1.30 m; cm); $\beta$is = parameters; ln = neperian logarithm; d_i = diameter at different heights (cm) measured at height h_i; h_i = height along bole (m); $p$is = selected powers for the Hradetzky model; ε_i = error.

3.2.2.2 Best model selection

The selection of the best adjusted model was done through the respective model statistics:

- coefficient of determination ($R_{adj.}^2$),
- standard error of the estimate (S_{yx}),
- residues analysis.

The coefficient of determination shows the variation proportion of the dependent variable which is explained by the independent variables. The closer to one, the better is the adjustment. When comparing models which had a different number of coefficients, it was necessary to adjust the R^2 value, as follow:

$$R^2_{adj} = 1- \left\{(1- R^2)\left(\frac{n-1}{n-p-1}\right)\right\}$$

Where: n = number of cases; p= number of coefficients.

The standard error of the estimate (S_{yx}) is a statistic which expresses the average dispersion between the observed and estimated values. The lower this value, the better is the adjusted model.

When a logarithm transformation of the model was used, the estimated values are subjected to logarithm discrepancy. In these cases, each estimated value need to be corrected by the Meyer factor (MF).

$$MF = e^{0,5\ S_{yx}^2}$$

Where: e = 2.718; S_{yx} = standard error of the estimate.

After conducting the Meyer correction, the standard error of the estimate has to be recalculated:

$$S_{yx} = \sqrt{\frac{\sum_{i=1}^{n}(x_i-x)^2}{n-p}}$$

Where: x_i = real value; x = estimated value; n = number of cases; p = number of coefficients.

The graphical residues analysis is a method which, although visual, it is crucial for the choice of the best adjusted model. It shows the dispersion of estimated values in relation to the measured one. The lower and more uniform the dispersion of residues, the better is the adjustment.

3.2.3 Data analysis

Values were typed into electronic spreadsheets (Microsoft Excel ®), and later analysed.

Measured values directly or indirectly averaged and compared between thinning variants. The following variables were analysed:

- quadratic mean diameter (d_g): mean transversal area converted to diameter; this approach is commonly used because its average value is less sensitive to extreme observations than simply the mean value of diameter at breast height,
- top diameter (d_{100}): mean diameter of the 100 thickest trees ha^{-1},
- coefficient of variation for d_{100} (CV_{100}): shows the dispersion of observations in relation to the mean value,

- transversal area (g): obtained by dividing the basal area by the number of trees ha^{-1},
- top transversal area (g_{100}): the top diameter transformed into transversal area,
- total height (h),
- top height (h_{100}): the height of the 100 thickest trees ha^{-1}, also called dominant height,
- crown length: obtained by subtracting crown basis height from total height,
- h:d ratio: height of a tree divided by its diameter at the breast height, as an indicator of tree stability.
- basal area (b.a.): sum of tree's transversal areas within one hectare,
- individual tree volume (v_i), estimated with the models shown in Tab. 3.2-1,
- top volume (v_{100}): mean volume of the 100 thickest trees ha^{-1}, also named the volume of the dominant trees,
- thinned volume: volume obtained from thinnings,
- standing volume (V_{stand}): the volume ha^{-1} of the standing trees at age 30 years,
- total volume (V_{total}): total produced volume ha^{-1},
- mean annual increment (MAI): total produced volume divided by the number of years.

Only few tree height data of previous years were available, and manly average data instead of individual values. Thus, the adjustment of growth models was not possible. However, mean values for height and top height from age 3 years onwards were presented. Values were compared with related published studies (YOSHITANI JR., 2009).

Individual tree volume and volume ha^{-1} were quantified throughout the adjusted models.

Volume increments were also graphically analysed as relative values plotted over the percentage value of the periodic mean basal area in 5-years periods. Thus evaluating the efficiency of growing space use according to stand basal area.

The development of diameter growth was assessed through time series of paired diameter and age values, used to fit Chapman-Richards growth models (PRETZSCH, 2009) for the diameter of the 100 thickest trees ha^{-1} (d_{100}). A total of 1,426 paired values were regarded. Chapman-Richards growth models were also fitted for the volume ha^{-1} development along the years.

The accuracy of potential crop trees selection was carried out by comparing the correlation between the diameter of the selected trees at different initial ages (5, 8 and 10 years) with the diameter of trees at age 20 years. Thus, indicating how strongly the thickest trees at a given age maintain this diameter superiority later on. Coefficient of determination of linear regressions between values was utilized as a criterion of accuracy.

The design of the experiment allowed statistical evaluations with analysis of variance (ANOVA) and mean test (TUKEY). Results of the ANOVA for each tested parameter are shown in Appendix, while in results, the following criteria expressed the significant levels:

- n.s. = not significant.
- * = $p < 5$ %.
- * * = $p < 1$ %.
- * * * = $p < 0.1$ %.

After detecting significant differences with ANOVA, means were classified with letters according to TUKEY test, in which values with the same letter do not significantly differed. The lowest value received the letter ‘a’.

3.2.4 Experimental area along the years

Some disturbances occurred during the 30 years of observation. In one of the plots, 5 potential crop tree candidates (equivalent to ~50 trees ha^{-1}) were broken by storm in 1988/89, at age 8 years. They were easily replaced by some neighbouring dominant trees and the gaps closed within a short period. Early losses do not cause big problems when there are enough pruned trees for replacement (in this case 2 times the planed final number).

A clear-cut surrounding the experimental area took place in 2007. Although an additional buffer zone was kept to protect the plots, one of them (plot 5, ‘extreme’ variant) was severely damaged by a summer storm. Because another part of the whole stand was managed similarly as the ‘extreme’ variant, it was possible to establish a new plot just beside the older one for the final measurement in 2011.

3.3 RESULTS

3.3.1 Stand density development

Thinnings began when the stand was 5 years old (1986), being replicated at ages 7, 10, 13 and 15. Only treatment 'moderate' was thinned all the times. The other treatments were thinned at none (without) or some of the indicated ages. The real development of the number of trees ha^{-1} is shown in Figure 3.3-1, similar to the planed one (Chapter 2, Table 2.3-1).

From the Figure 3.3-1 it can be verified that the numbers of trees ha^{-1} have been gradually reduced in the 'moderate' and 'heavy' thinned stands with different intensities, mainly in the first intervention. Whereas the 'extreme' variant resulted in an early and very heavy reduction which was even intensified in the following years.

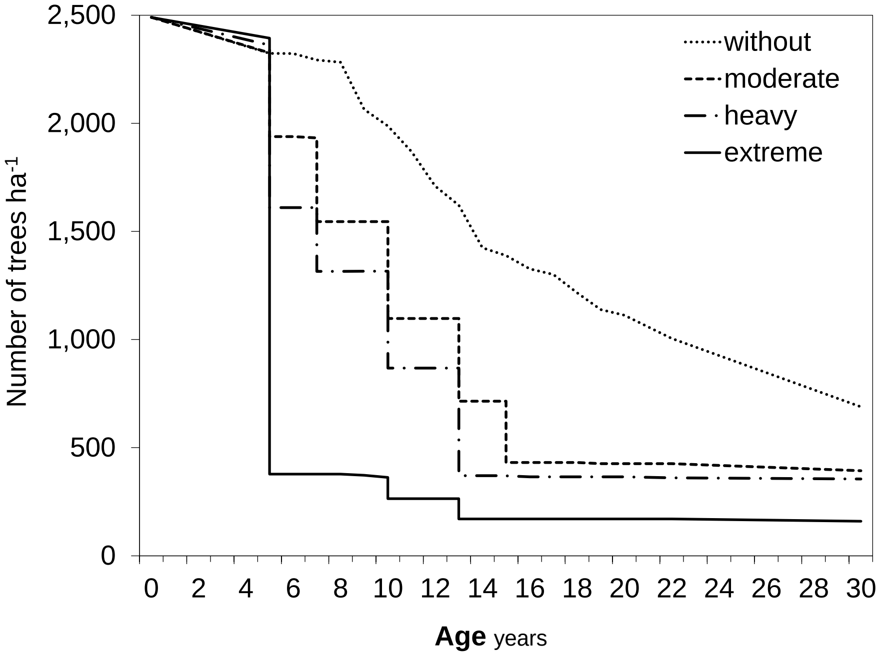


FIGURE 3.3-1: DEVELOPMENT OF TREE NUMBER HA^{-1} FOR THE DIFFERENT THINNING VARIANTS DURING THE 30 YEARS PERIOD. REDUCTION IN TREE NUMBER HA^{-1} IN THE STAND 'WITHOUT' THINNINGS IS ONLY DUE TO MORTALITY

SOURCE: The author (2014)

The reduction of trees ha^{-1} in the stand 'without' thinning is solely the result of tree mortality (self-thinning).

3.3.2 Diameter at age 30 years

Comparisons of diameter at breast height (dbh, 1.3 m) between thinning treatments describe the tree's response to the growing space provided by the interventions. The diameter of the tree with the mean transversal area, or quadratic mean diameter (d_g), mean diameter of the 100 thickest trees ha^{-1} (d_{100}), the coefficient of variation for d_{100}, transversal area (g) values and the transversal area of the dominant trees (g_{100}) are shown in Table 3.3-1.

The analysis of quadratic mean diameter (d_g) between treatments showed a remarkably difference, almost 30 cm between the extreme variants. Thinning variant 'extreme' reached a value over 70 % higher than the one observed in the stand 'without' thinning. Treatments 'moderate' and 'heavy' were similar to each other, and about 30 % higher than the unthinned variant. However, this comparison is affected by the removal of all small trees in the 'extreme' variant. Even though some small trees were kept in the practice oriented variants ('moderate' and 'heavy'), the ones that did not directly concurred with the selected potential crop trees, the differences might have distortions and might be not only due to the thinning treatments.

Table 3.3-1: Quadratic mean diameter (d_g), diameter of dominant trees (d_{100}), coefficient of variation for D_{100} (CV_{100}), transversal area (g) and top transversal area (g_{100}) for the different thinning variants at age 30 years

Thinning variant	**d_g**		**d_{100}**		**CV_{100}**	**g**		**g_{100}**	
	cm	%	cm	%	%	m²	%	m²	%
without	35.6 a	*100*	47.6 a	*100*	11.4	0.10 a	*100*	0.18 a	*100*
moderate	45.8 b	*129*	55.9 b	*117*	7.8	0.16 b	*160*	0.24 b	*133*
heavy	48.8 b	*137*	57.8 b	*121*	6.9	0.19 b	*190*	0.26 b	*144*
extreme	61.9 c	*173*	66.6 c	*140*	6.0	0.30 c	*300*	0.35 c	*194*
Statist. signific.	* * *		* *		n.s.	* *		* *	

Percent values indicate the increase in relation to the control value (100).

Source: The author (2014)

A fairer comparison is possible by the top diameter, which includes only the 100 dominant trees ha^{-1} (d_{100}). The trend among treatments verified with top diameter was the same described for d_g. However, the difference amplitude between treatments was reduced. 'Extreme' thinning led to a top diameter 40 % bigger in relation to the control one. 'Moderate' and 'heavy' thinnings were similar and about 20 % bigger than the stand ‘without’ thinning. In absolute values, it was observed that the diametric gain was, respectively, 10 and 20 cm for the dominant trees in the intermediate variants (practice oriented) and ‘extreme’ thinned stands.

Although a smaller coefficient of variation was expected for the thinned treatments, meaning a more homogeny diameter distribution, no significant differences were detected.

The differences between treatments were even higher when the transversal area (g) of the individual trees was regarded. The quadratic effect of ‘g’ led to an over 200 % increase of the values observed in the ‘extreme’ treatment in comparison to the unthinned stand.

By regarding only the dominant trees and their transversal area (g_{100}), the higher growth of trees subjected to practice-oriented thinnings resulted values 30-40 % greater than the unthinned stand. While in the ‘extreme’ variant trees reached values almost 2-times greater than the stand ‘without’ thinning.

3.3.3 Diameter development along time

The assessment of diameter development along time provides a better understanding on the growth responses of trees. In order to accurately evaluate the differences on diameter development affected exclusively by the thinning variants, growth models were fitted considering the diameter of the 100 thickest trees ha^{-1} (d_{100}). Regression curves are shown in Figure 3.3-2.

From Figure 3.3-2 it can be seen that the top diameter development of trees in the ‘extreme’ variant showed a remarkably higher growth rate in comparison to the other treatments, and this since early ages. Trees in the variants ‘moderate’ and ‘heavy’ had an intermediate and similar pattern of growth, while trees in the stand ‘without’ thinning showed the lowest top diameter development level.

Lower coefficient of determination (R^2) of the different equations indicated that there was a higher variation within top diameter values, evident in the stand ‘without’ thinning.

The top diameters at different ages and the statistical analysis are shown in Table 3.3-2. Measured values were used in the statistical comparisons.

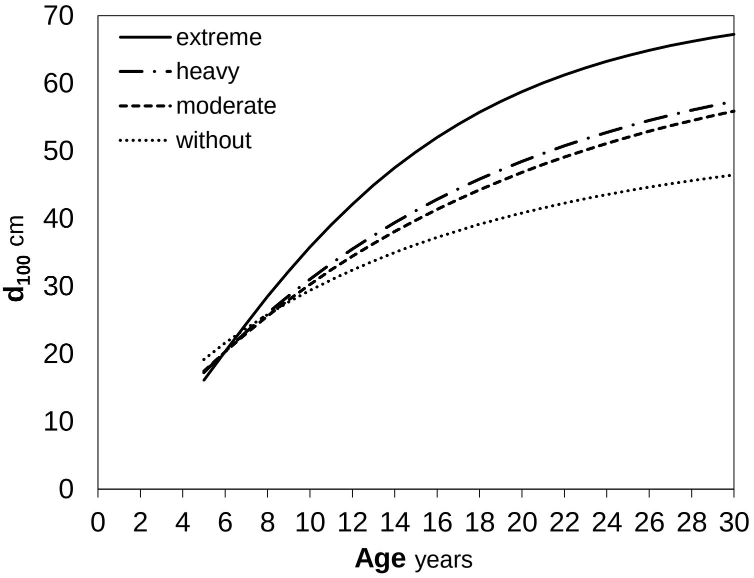


FIGURE 3.3-2: DEVELOPMENT OF TOP DIAMETER (D_{100}) ACCORDING TO AGE, DURING THE STUDIED PERIOD AND FOR THE DIFFERENT THINNING VARIANTS. CURVES REPRESENT ADJUSTED CHAPMAN-RICHARD GROWTH MODELS SHOWN BELOW:

$$\text{without} = 52.4\left(1-e^{-0.06\ \text{Age}}\right)^{0.78}$$
$R^2 = 0.87$

$$\text{moderate} = 66.9\left(1-e^{-0.06\ \text{Age}}\right)^{0.99}$$
$R^2 = 0.91$

$$\text{heavy} = 66.2\left(1-e^{-0.07\ \text{Age}}\right)^{1.10}$$
$R^2 = 0.95$

$$\text{extreme} = 71.5\left(1-e^{-0.11\ \text{Age}}\right)^{1.77}$$
$R^2 = 0.95$

SOURCE: The author (2014)

No statistical analysis was carried out for the age 25 years because of lack of field measurements. Age 30 years is shown again in order to facilitate comparisons between treatments.

It was observed that, at age 5 years, dominant trees had a mean diameter of ~18 cm. At that moment, at which thinning interventions were applied, trees in the area ‘without’ thinning had a d_{100} greater than the ‘heavy’ and ‘extreme’ variants. This difference is considered to be purely by chance and in absolute terms means only ~1 cm.

However, at age 10 years, only 5 years after the first intervention, trees on the area ‘extremely’ thinned were already significantly thicker than the others. This top diameter superiority even increased in the following years.

Table 3.3-2: Top diameter (d_{100}) at different ages for the different thinning variants.

Thinning variant	d_{100} at age:					
	5	10	15	20	25	30
without	18.6 b	30.0 a	35.9 a	40.3 a	44.1	47.6 a
moderate	17.6 a b	30.1 a	39.1 b c	46.8 a b	52.0	55.9 b
heavy	17.4 a	31.2 a	41.0 b	48.5 b	53.7	57.8 b
extreme	17.4 a	35.8 b	49.3 c	59.0 c	64.1	66.6 c
Statist. signific.	*	* *	* *	* *	-	* *

No statistical analysis were carried out for age 25 years because no fiel measurement took place. Values were estimated from annual ring measurements.

Source: The author (2014)

The practice oriented treatments were similar to each other during the whole period. However, from age 15 onwards, the top diameter on the ‘moderate’ one resembled the value observed on the unthinned stand.

As mentioned, differences between treatments increased with time and, by age 30 years, there was three distinct groups where trees in the stand ‘without’ thinning were the thinnest ones, trees in the ‘extreme’ were the thickest, while the practice-oriented variants resulted in an intermediate group.

3.3.4 Height and crown length

The average total height at age 30 years was 35 m. Average height, top height and crown length of the trees subjected to the differently thinned variants are shown in Table 3.3-3.

Table 3.3-3: Total height (h), top height (h_{100}) and crown length of the different thinning variants at age 30 years.

Thinning variant	h m	h_{100} m	Crown m
without	35.5 b	37.4 b	9.4
moderate	36.1 b	36.4 a b	11.3
heavy	35.1 b	35.9 a b	11.3
extreme	33.6 a	33.9 a	12.9
Statist. signific.	*	*	n.s.

Source: The author (2014)

Significant differences were detected for tree total heights (h). The trees in the 'extremely' thinned stand were shorter than the others.

In relation to top height (h_{100}), differences between treatments were verified only between stands 'without' and 'extreme' thinning (3.5 m or 10 %).

No significant differences were found for the crown length between thinning variants.

The adjusted equations for estimating total height and crown basis height were obtained through the model of TROREY, and are both plotted in Figure 3.3-3 for the different treatments.

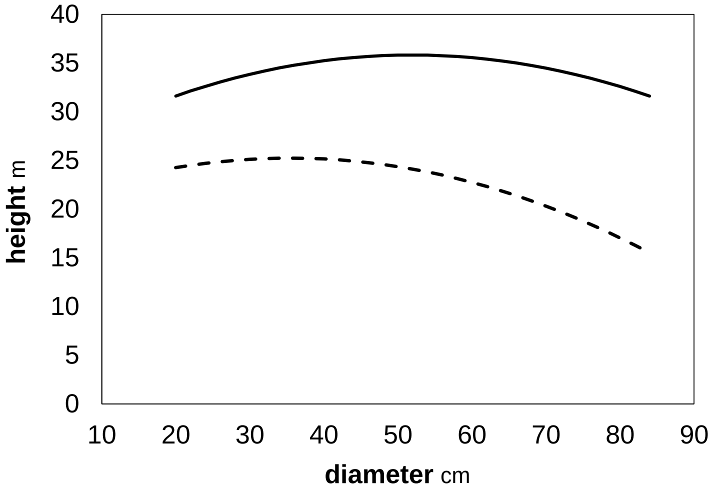


FIGURE 3.3-3: HYPSOMETRIC CURVES FOR TOTAL HEIGHT (FULL LINE) AND FOR CROWN BASIS HEIGHT (DASHED LINE)

Values obtained through adjusted TROREY models:

$\text{total height} = 24.7 + 0.4(\text{dbh}) - 0.004(\text{dbh})^2$
$R^2 = 0.16$, $S_{yx} = 5.9$ %

$\text{crown basis} = 20.1 + 0.3(\text{dbh}) - 0.004(\text{dbh})^2$
$R^2 = 0.23$, $S_{yx} = 12.6$ %

SOURCE: The author (2014)

Despite some variation between the height of trees subjected to different treatments, it was opted for a single hypsometric model, one for total height and one for crown length. It was judged that there would be no substantial advantage of employing distinct hypsometric equations per thinning variant.

Although low coefficients of determination (R^2) were obtained, standard errors of estimate (S_{yx}) show the equations suitably estimate values. Moreover, low 'R^2' values are common for hypsometric equations.

From the Figure 3.3-3 a slight decrease in tree height after diameter values of 50-60 cm can be verified. However, and also after the same diameter values, crown basis height decreased even more pronouncedly, indicating the tendency of longer crowns in big-sized trees. Nevertheless, no differences between thinning variants for this variable were detected as shown in Table 3.3-4.

3.3.5 Height development

Data related to height were not profusely available as was the case for diameter. Height measurements were infrequently carried out along the 30-years period and even when, only average values were kept instead individual tree values.

This scarcity of data may have led to some inaccuracy. However, an average height development could be built both for the whole stand (h) and for the dominant trees (h_{100}). Values per year are shown in Table 3.3-4.

TABLE 3.3-4: TOTAL HEIGHT (H), TOP HEIGHT (H_{100}) AND CROWN LENGTH DURING THE 30 YEARS-PERIOD

Age	h m	h_{100} m
3	5.0	5.2
4	6.5	7.1
5	**8.1**	**8.9**
6	9.6	10.7
7	**11.0**	**12.5**
8	12.4	14.1
9	13.8	15.7
10	**15.1**	**17.3**
11	16.4	18.7
12	17.6	20.1
13	**18.8**	**21.4**
14	20.0	22.7
15	**21.1**	**23.9**
20	26.2	28.9
25	30.6	32.7
30	34.4	35.5

Highlighted values indicate the year at which thinnings took place.

SOURCE: The author (2014)

This approximation was important in order to discuss the timing of thinning and pruning not only regarding to age, but also height.

From Table 3.3-4 it can be seen that, in general, the mean annual height increment was ~1.5 m during the first 10-years period. Later on, this rate obviously decreased, having been ~1.0 m year^{-1} during the period 11-20, and even lower after this.

The presented results are important for a critical evaluation of the applied management schedule, with valuable insights for the praxis, especially for thinning intervals and pruning.

3.3.6 Height:diameter-ratio

The ratio between total height and diameter at breast height is an important indicator of tree stability. The mean ratio for all trees and treatments was 78, ranging between 42-138. The height:diameter-ratio (h:d) for the different thinning variants are shown in Table 3.3-5.

TABLE 3.3-5: HEIGHT: DIAMETER-RATIO (H:D) PER THINNING VARIANT AT AGE 30 YEARS

THINNING VARIANT	**h:d**
without	97 b
moderate	82 ab
heavy	76 ab
extreme	58 a
STATIST. SIGNIFIC.	*

SOURCE: The author (2014)

Differences in h:d values were verified only between treatments ‘without’ and ‘extreme’. The practice oriented variants showed intermediate values, similar to both ‘without’ and ‘extreme’.

3.3.7 Basal Area

The mean stand basal area at age 5 years, previous to the first thinning procedure, was 31.8 m² ha^{-1}, ranging between 31-33 m² ha^{-1}, which shows that the stand was quite homogeneous. The remaining basal area after the first intervention (age 5 years) and the basal area reached at age 30 years for the different treatments are shown in Table 3.3-6.

Basal area immediately after thinning (age 5 years) was extremely reduced by the treatments. The stand with ‘extreme’ thinning showed the lowest value, far beyond a practice oriented interventions. The basal area after the first thinning was statistically similar for the treatments 'moderate' and 'heavy', although 2 competitors were taken in the 'heavy' variant, instead of 1 in the 'moderate'.

TABLE 3.3-6: REMAINING BASAL AREA AFTER THE FIRST THINNING (AGE 5 YEARS) AND BASAL AREA AT AGE 30 YEARS FOR THE THINNING VARIANTS

THINNING VARIANT	BASAL AREA m² ha⁻¹ at age years: **5**		BASAL AREA m² ha⁻¹ at age years: **30**	
without	32.7	c	68.4	b
moderate	25.2	b	64.9	ab
heavy	20.2	b	66.5	b
extreme	7.2	a	47.7	a
STATIST. SIGNIFIC.	* * *		*	

SOURCE: The author (2014)

The 'moderate' and 'heavy' thinned stands, even after 5 and 4 interventions, respectively, reached a basal area similar to the control at age 30 years. Treatment 'extreme' showed a lower value, although already similar to the 'moderate' one, demonstrating the remarkably growth potential of loblolly pine trees after extreme and early release from competition.

The development of the basal area immediately after the first intervention for the different thinning variants and during the 30 years period is shown in the Figure 3.3-4.

According to Figure 3.3-4 the basal area of the stand 'without' thinning reached values over 70 m² ha^{-1}. This may represent the possible maximum value for high productive sites of loblolly pine in southern Brazil. The maximum value was verified at age 22 years (71.7 m² ha^{-1}). However, similar values (69.1 m² ha^{-1}) had already been reached at age 13 years and, since then, no substantial increase was observed. In fact, a slight decrease in basal area was verified at age 14 years, which can be associated with woodwasp attacks.

Treatment called 'moderate' was the only one where 5 thinning procedures were carried out. The first 4 interventions were always less intense in comparison to the 'heavy' one. However, at age 15 years, when the 5th thinning was applied, the intensity was higher than the previous ones, enough to reduce the basal area just at the same level observed in the 'heavy' one at the same age. Thus, the difference between these 2 variants was concentrated at the first rotations half, mainly due to different intensities at the first intervention. After that and during the last 15 years, both developed in a similar way, including the number of trees ha^{-1} (Figure 3.3-1). The 4th and last thinning applied in treatment 'heavy' was also the more intense one.

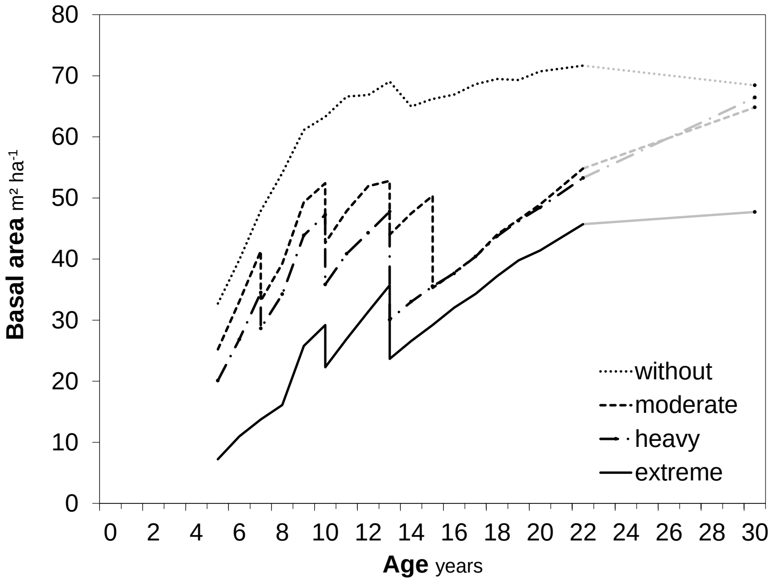


FIGURE 3.3-4: BASAL AREA DEVELOPMENT AFTER THE FIRST INTERVENTIONS OF THE DIFFERENT THINNING VARIANTS ALONG YEARS. NO MEASUREMENTS WERE DONE BETWEEN YEARS 23 TO 29 - GREY SEGMENT

SOURCE: The author (2014)

In the 'extreme' variant, basal area at age 30 years was lower than the ones verified in the 'heavy' and 'without' variants. It is important to note that there were only 200 trees ha^{-1} in the 'extreme' treatment since age 13 years. At age 30 years, this variant had the half of trees ha^{-1} present in the 'moderate' and 'heavy' ones, and less than one third of the stand 'without' thinning. Altogether, this information shows the impressive capacity in occupying the growing space when trees are early and heavily released from competition.

3.3.8 Volume

3.3.8.1 Individual volume

It is not possible to scale every single tree in an experiment in order to obtain its volume. Therefore, the analysis of individual tree volume and the quantification of the total produced volumes demand estimation methods. The most used one is the adjustment of models which can estimate, in this case, individual volume, so that with help of easy-to-measure variables (diameter at breast height and total height), tree volume can be assessed.

The individual volume models were adjusted with paired d_i x h_i data of 103 trees and the results of the best fitted model (SCHUMACHER-HALL) are shown in Figure 3.3-5. The results obtained for the other models are presented in Appendix.

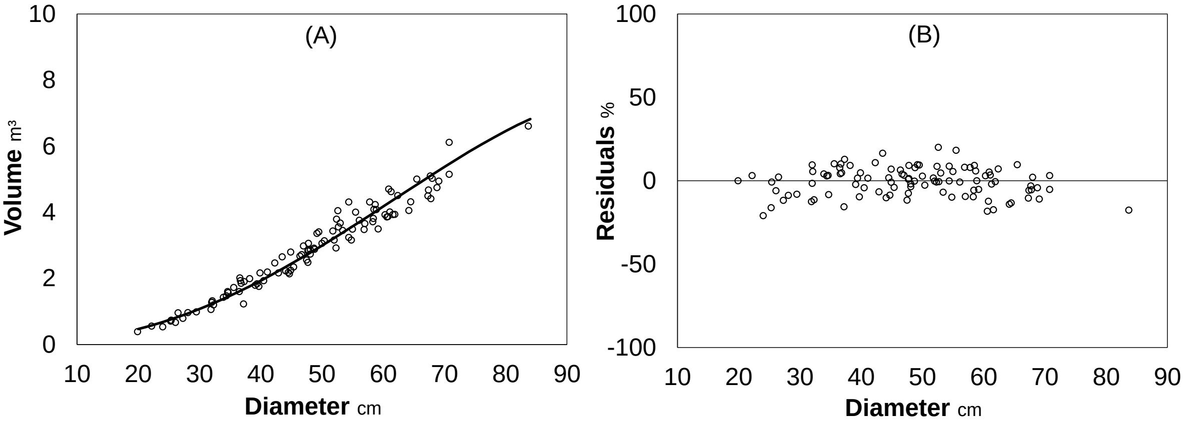


FIGURE 3.3-5: (A) OBSERVED INDIVIDUAL VOLUME (CIRCLES) AND ESTIMATED REGRESSION CURVE (LINE) WITH SCHUMACHER-HALL MODEL DEPENDING ON DIAMETER AT BREAST HEIGHT AT YEAR 30. (B) ESTIMATION RESIDUALS ACCORDING TO TREE DIAMETER. EQUATION IS PRESENTED BELOW

$\ln(v_i) = -10.430 + 1.873 \ln(dbh) + 1.174 \ln(h) + \varepsilon_i$ $R^2_{adj.} = 0.96$ $S_{yx} = 9.8\ \%$

Where: v_i = tree individual volume; dbh = diameter at breast height; h = total height; ln = neperian logarithm and ε_i = error.

SOURCE: The author (2014)

From the Figure 3.3-5 the strong influence of diameter on tree volume can be seen. Residual plot shows that the estimation did not present any relevant bias, thus providing a satisfactory estimation when the independent variable is kept within the ranges of the data used for estimating the model parameters (Ø = 20-90 cm). Nevertheless, it is important to note that there was only one value over 80 cm. Besides this, the residual of estimating the volume of the tree with diameter over 80 cm was similar to the other ones.

Mean individual volume was 2.9 m³, ranging from 0.4-6.6 m³. The mean individual volume and the individual volume of the 100 thickest trees ha^{-1} (v_{100}) per variant is shown in Table 3.3-7.

TABLE 3.3-7: MEAN INDIVIDUAL VOLUME (v_i) AND MEAN INDIVIDUAL VOLUME OF THE TOP TREES (v_{100}) WITH THE RESPECTIVE PERCENTUAL GAIN IN RELATION TO CONTROL (100)

THINNNIG VARIANT	v_i				v_{100}			
	m³			%	m³			%
without	1.5	a		*100*	2.8	a		*100*
moderate	2.5	b		*171*	3.8	b		*137*
heavy	2.9	b		*194*	4.1	b		*146*
extreme	4.6		c	*309*	5.3		c	*190*
STATISTIC. SIGNIF.	* *				* *			

SOURCE: The author (2014)

The effect of selective thinnings on the development of individual tree volume was impressing:

- The trees in the plots ‘without’ thinning reached a mean individual volume (v_i) of only 1.5 m³. Trees subjected to the practice oriented variants (‘moderate’ and ‘heavy’) had almost twice as much volume as the ones in the ‘without’, whereas, those having been early and ‘extremely’ released from competition, showed 3-times as much. Finally, the relation was roughly 1:2:3.
- The absolute differences between treatments were smaller for the volume of the dominant trees (v_{100}). Although, statistical differentiation remained the same.

3.3.8.2 Volume ha^{-1}

Total volume ha^{-1} was assessed due to the quantification of tree segment volumes (logs, 2.5 m length), which were obtained through fitted taper models. The sum of all segments resulted in individual tree volumes per plot, which were transformed to hectare according to plot area.

Diameter values at different heights were estimated with help of the selected taper equation (HRADETZKY). Coefficients and statistics are shown in Table 3.3-8 and Figure 3.3-6.

As expected, taper was more abrupt at the tree basis. Between 20-60 % of tree total height, the trend became smoother. Then, at the crown height, taper increased again (Figure 3.3-6 A).

It could be seen on the residual plot (Figure 3.3-6 B), that the fitted equation delivered accurate estimations over 10 cm in diameter, while inaccurate ones under this value, reaching standard errors over 100 %. While it could be argued for the inefficiency of this equation, it is important to note that these diameters are in the non-commercial range, up high in the tree, not regarded in the present analysis.

TABLE 3.3-8: ADJUSTED COEFFICIENTS (β_i), SELECTED POWERS AND STATISTICS FOR THE HRADETZKY TAPER EQUATION AT AGE 30 YEARS

Equation	Model coefficients					
	β_0	β_1	β_2	β_3	β_4	β_5
HRADETZKY	30.505	0.740	-0.115	-30.023	-1.166	0.125
Selected powers		1	10	0.005	2	35
	R² = 0.98			Syx = 6.5 %		

SOURCE: The author (2014)

Another reason why volume quantification considered diameters no lower than 10 cm over bark, was the difficult utilization of logs from these diameter class since it occurs in a segment of the tree bole which commonly breaks at the moment of tree felling.

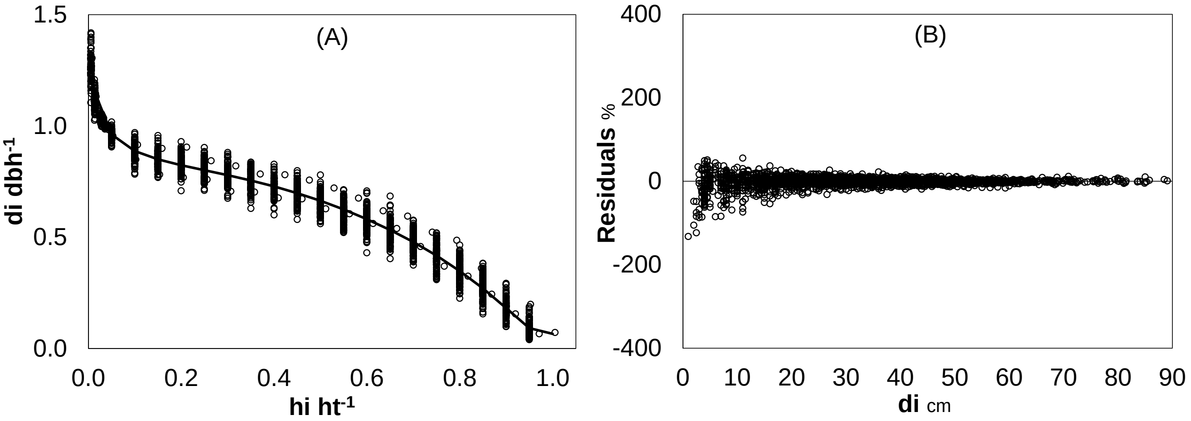


FIGURE 3.3-6: OBSERVED D_I X H_I (CIRCLES) AND ESTIMATED TREE TAPER (LINE) FOR THE HRADETZKY TAPER EQUATION AT YEAR 30 (A). RESIDUAL PLOTS (B)

SOURCE: The author (2014)

The total volume production during a rotation period comprises the volume of the standing trees at the final cut and the volume harvested in the thinnings. The volume harvest in the different thinning procedures is shown in Table 3.3-9.

No statistical comparison were carried out for individual thinning procedures, in which there were certainly differences. Especially in the first one (age 5 years), when ~2,100 trees ha^{-1} were cut in the 'extreme' variant, which even being of small size, delivered twice as much volume than the one obtained in the 'heavy'.

Table 3.3-9: Harvest volume per thinning and treatment (m^3 ha^{-1}), total per treatment and its proportion (%) in relation to the total volume produced during the 30 years period

Thinning variant	Volume						
	5	7	10	13	15	Total	%
without	-	-	-	-	-	-	-
moderate	30	48	70	112	155	416	*30*
heavy	48	34	81	173	-	337	*25*
extreme	93	-	51	141	-	284	*28*
Statistic. signif.						n.s.	

5, 7, 10, 13 and 15 years: age at which thinning took place

Source: The author (2014)

However, when the total volume obtained through thinnings was regarded, no significant differences between treatments were observed.

In general, and for all thinned variants, about one third of the produced volume was harvested through thinnings.

The standing volume at age 30 years, the total produced volume (including thinning) and mean annual increment (MAI) in volume for the different thinning intensities are presented in Table 3.3-10.

Table 3.3-10: Standing volume ($V_{stand.}$), total produced volume (V_{total}), and mean annual increment (MAI) in volume at age 30 years for the different thinning variants.

Thinning variant	V_{stand}			V_{total}			MAI	
	m^3 ha^{-1}		%	m^3 ha^{-1}		%	m^3 ha^{-1} $year^{-1}$	
without	1,022	b	*100*	1,022	a	*100*	34	a
moderate	996	b	*98*	1,412	b	*138*	47	b
heavy	1,025	b	*100*	1,362	b	*133*	45	b
extreme	727	a	*71*	1,012	a	*99*	34	a
Statistic. signif.	*			*			*	

% in relation to without = 100

Source: The author (2014)

From Table 3.3-10, it can be observed:

- Stands moderately and heavily thinned, after 4 or 5 interventions, were capable to reach a similar standing volume (V_{stand}) in relation to the control area, ‘without’ thinning. Only the treatment ‘extreme’ showed a ~30 % lower value.

- However, when the total produced volume (V_{total}) was regarded, including thinnings, treatment ‘extreme’ surprisingly resembled the value observed in the full-stocked area, ‘without’ thinning. Yet, treatments ‘moderate’ and ‘heavy’ reached even higher production levels, being over 30 % more efficient in total volume production than the other 2 extreme variants.
- Mean annual increment (MAI) in volume showed, obviously, an identical trend as verified for total produced volume. Its evaluation, however, is important to give an idea about the site production potential.

The remarkably growth potential observed in the thinned stands, which resulted in more volume than the stand ‘without’ thinning showed that the management of the stand density had positive effects on the total volume production. The volume development along time is plotted on Figure 3.3-7.

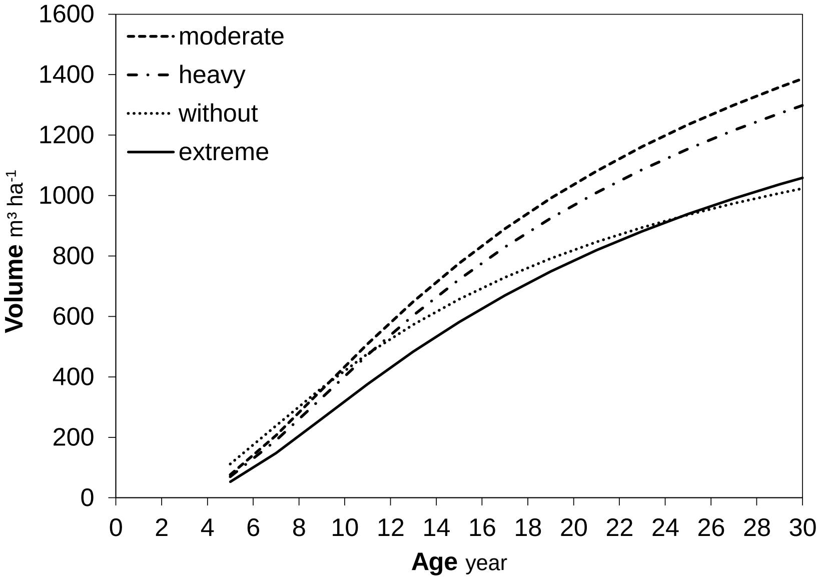


FIGURE 3.3-7: VOLUME DEVELOPMENT OF THE DIF-FERENT THINNING VARIANTS ALONG TIME. CURVES OBTAINED WITH THE EQUATIONS SHOWN BELOW AND WITH HELP OF AGE.

$$V_{without} = 1{,}593.2\ e^{-\frac{13.284}{age}}$$
$R^2 = 0.99$

$$V_{moder.} = 1{,}593.2\ e^{-\frac{13.284}{age}}$$
$R^2 = 0.99$

$$V_{heavy} = 2{,}329.8\ e^{-\frac{17.551}{age}}$$
$R^2 = 0.99$

$$V_{extreme} = 1{,}926.4\ e^{-\frac{17.962}{age}}$$
$R^2 = 0.97$

SOURCE: The author (2014)

From Figure 3.3-7 it can be seen that the volume production of the stand ‘moderately’ thinned was highest after age 10 years onwards. The production observed in the ‘heavy’ variant was slightly lower than the one verified in the ‘moderate’. Surprisingly, the variant ‘extreme’ resembled the volume production of the unthinned stand by the age 18-20 years, or maybe earlier, and showed an increasing trend at age 30 years, while the unthinned stand levelled off.

For a better understanding of these relationships, the volume increments were plotted as percentages over the percentage values of the periodic mean basal area (Figure 3.3-8). The values of the unthinned stand have been set equal to 100. The values of the ‘x’ axis, which decreased from left to right, thus representing the different degrees of stocking in relative terms, corresponding to increasing thinning intensity. Different periods were considered.

From the Figure 3.3-8, the **optimum** and **critical basal area** values could be determined. The optimum basal are is the one by which the highest possible increment in volume can be achieved during a given period, while the critical one is the stoking value beyond which the volume increment is lower than the one verified in a full-stocked stand (100).

(1) The period between **5-10 years** showed that no basal area reductions were able to produce as many volume as the full-stocked one. However the ‘moderate’ variant still produced ~ 95 % of the full-stoked area. Thus, the removal of one competitor tree does not compromise the total volume production in this period. In absolute terms, the volume increment was ~60 m^3 ha^{-1} $year^{-1}$ for both ‘without’ and ‘moderate’ variants, while 54 and 30 for the ‘heavy’ and ‘extreme’ ones.

(2) During the **10-15 years** period, it was verified that a site occupancy of ~70 % (‘moderate’) showed the maximum periodic increment in volume, ~30 % more than the one verified on the stand ‘without’ thinning. Moreover, even the most intense variant (‘extreme’), with ~40 % of the site occupancy capacity, was more productive than the unthinned one. In absolute values, the ‘moderate’ variant produced 53 m^3 ha^{-1} $year^{-1}$, while the ‘without’ one reached only 40 m^3 ha^{-1} $year^{-1}$.

(3) Between ages **15-20 years**, a site occupancy of ~70 % continued to delivered the highest periodic increment in volume, reaching values ~40 over the ones observed in the stand ‘without’ thinning. In this period, all thinned treatments showed

increment values over 50 m³ ha^{-1} $year^{-1}$, while the unthinned stand kept the previous growth rhythm of ~40 m³ ha^{-1} $year^{-1}$.

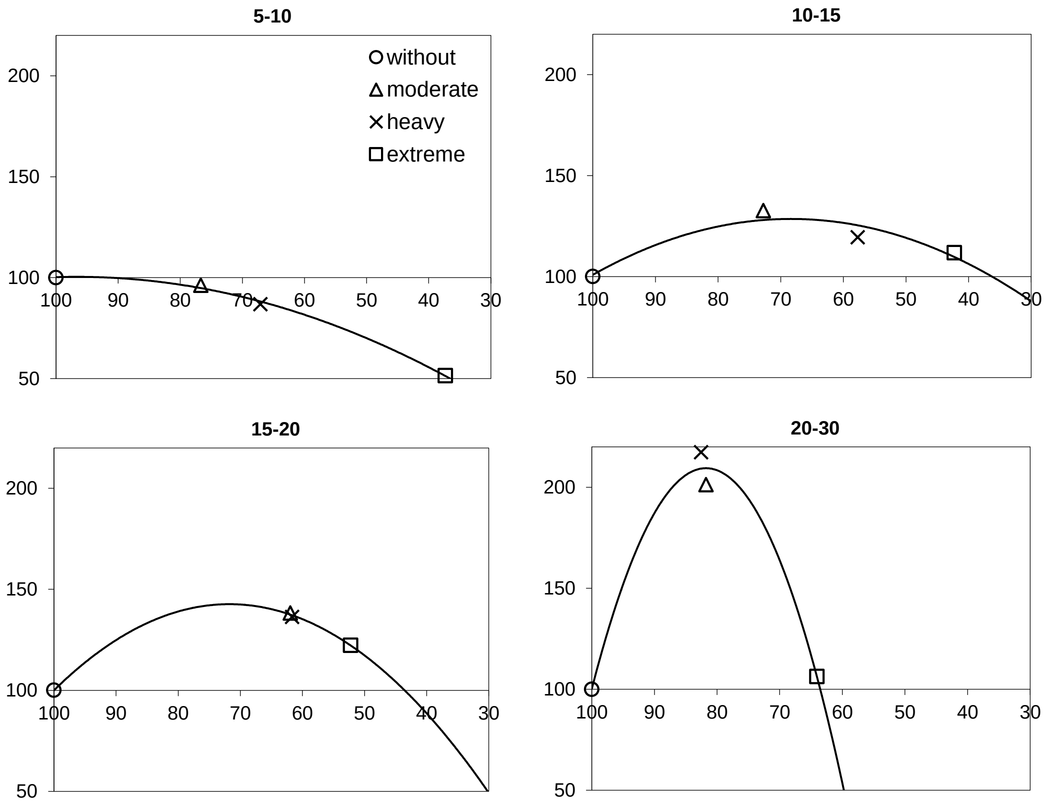


FIGURE 3.3-8: VOLUME INCREMENTS ('Y' AXIS) PLOTTED AS PERCENTAGE OVER THE PERCENTAGE VALUE OF THE PERIODIC MEAN BASAL AREA ('X' AXIS). VALUES FOR THE UNTHINNED STAND WERE SET EQUAL TO 100

$v_{5\text{-}10} = -29.83 + 2.69\ (x) - 0.014\ (x)^2$ $R^2 = 0.99$

$v_{10\text{-}15} = -0.84 + 3.78\ (x) - 0.028\ (x)^2$ $R^2 = 0.89$

$v_{15\text{-}20} = -133.14 + 7.68\ (x) - 0.054\ (x)^2$ $R^2 = 0.99$

$v_{20\text{-}30} = -1{,}987.8 + 53.74\ (x) - 0.33\ (x)^2$ $R^2 = 0.99$

SOURCE: The author (2014)

(4) Because of lack of information between ages 23-29, the last analysed period was longer, **20-30 years**. At this period, the thinned stands showed remarkably higher increments in relation to the unthinned one. Although the absolute values of the thinned stands were lower than the one verified during the 15-20 years, the stand 'without' thinning showed a negative basal area growth and a very low volume growth. In absolute terms, treatments 'moderate' and 'heavy' showed periodic

increments of ~40 m^3 ha^{-1} $year^{-1}$ while ‘without’ and ‘extreme’ reached only ~20 m^3 ha^{-1} $year^{-1}$.

3.3.9 Accuracy of the crop trees selection

The selection of potential crop trees involves questions about the criteria, the time and number of individuals that should be selected.

Tree competition starts relatively early in fast-growth plantations, which is the case for loblolly pine. Therefore, a gradual differentiation into canopy classes is an expected consequence. From this point of view, the potential crop trees should be selected only after it is possible to identify the dominant and well-formed trees. However, while early selections are necessary, the earlier the potential crop tree are selected the more uncertain is the selection.

For comparison purposes, potential crop trees were also selected in the control area, but were not liberated from competition of their neighbours, as was the case for the thinned variants. Therefore, they can be regarded as ‘virtual’ potential crop trees only. For reasons of clearness only the variants ‘without’ and ‘heavy’ are shown in Table 3.3-11.

From the determination coefficients (R^2), it can be noted that the prognosis about the development of the diameters is very weak when trees are selected at age 5 years. Later on the selection accuracy improved remarkably, over 0.7 at age 10 years. For a better understanding, determination coefficients are shown in Figure 3.3-9, for all treatments and from age 5-10.

TABLE 3.3-11: CORRELATION BETWEEN THE DIAMETERS (DBH) OF SELECTED POTENTIAL CROP TREES AT AGE 5, 8 AND 10 AND THEIR DIAMETER AT AGE 22 YEARS.

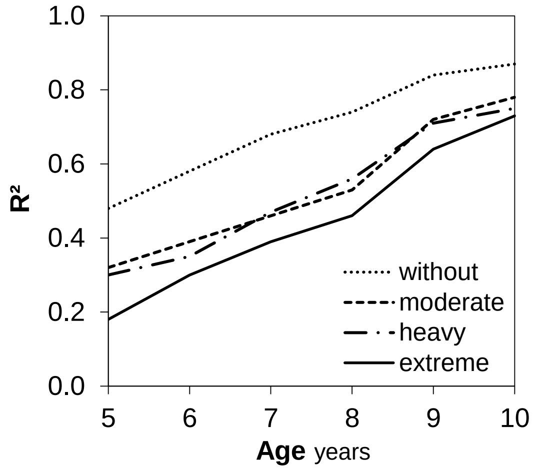
THINNING VARIANT	AGE FRAME	REGRESSION LINE	R^2
without	5 : 20	$dbh_{20} = 2.140\ dbh_5 - 3.691$	0.48
	8 : 20	$dbh_{20} = 1.826\ dbh_8 - 7.961$	0.74
	10 : 20	$dbh_{20} = 1.532\ dbh_{10} - 5.968$	0.87
heavy	5 : 20	$dbh_{20} = 2.193\ dbh_5 + 7.288$	0.30
	8 : 20	$dbh_{20} = 1.877\ dbh_8 - 0.249$	0.56
	10 : 20	$dbh_{20} = 1.544\ dbh_{10} - 0.327$	0.75

Equations and correlation coef-ficients are given.

SOURCE: The author (2014)

FIGURE 3.3-9: CORRELATION BETWEEN THE DIAMETER AT AGE 5-10 YEARS WITH THE ONE VERIFIED AT AGE 20 YEARS FOR THE DIFFERENT THINNING VARIANTS

SOURCE: The author (2014)



From Figure 3.3-9 it can be seen that the values observed in the thinned variant were always lower than the one obtained in the stand 'without' thinning. While one could suppose the selection on thinned stands is of lower accuracy, it may rather means the opposite. The lower values verified on the thinned variants express the great growth response of the trees to the release from competition. Whilst one tree, on the unthinned stand, with 25 cm of diameter at age 5 years, reached on average 38 cm at age 10 years (varying between 30-42 cm), a tree with the same initial diameter on the 'heavy' variant, reached 47 cm at age 10 years (varying between 35-55). This logic resulted in lower correlations between diameter values of age 5-10 with the ones observed at age 30 years.

In general, it can be concluded that any selection made before age 8 years should consider a safity margin, at least, 2:1 – to select and favour 2 times de number of trees intended to form the final stand.

Still about the selection of potential crop trees, and even with the low correlation between diameter at age 5 and 20 years, it proved to be feasible by appropriately selecting the trees and releasing them from competition. Which was not the case for the unthinned stand. The frequency of trees per diameter class at age 5 and 10 years are plotted in the Figure 3.3-10. Selected potential crop trees are highlighted.

In Figure 3.3-10 it turned clear that only selecting trees at age 5 years has a very low accuracy and, already at age 10 years, the selected trees were not able to maintain its dominancy. Although only trees thicker than the average were selected at age 5 years in the 'without' variant, the diameter distribution at age 10 years showed that some of the trees lost their vitality and were overlapped by surrounding ones.

In the thinned stands, on the other hand, where trees were selected and favoured by removing the direct competitors, it was much more efficient and sufficient to keep the selected trees on the right side of the frequency distribution (dominant position). All other trees were removed from the ‘extreme’ variant, and therefore it is not possible to compare the potential crop trees with the removed ones. However, the shift to the right side of the diameter distribution demonstrate a satisfactory result.

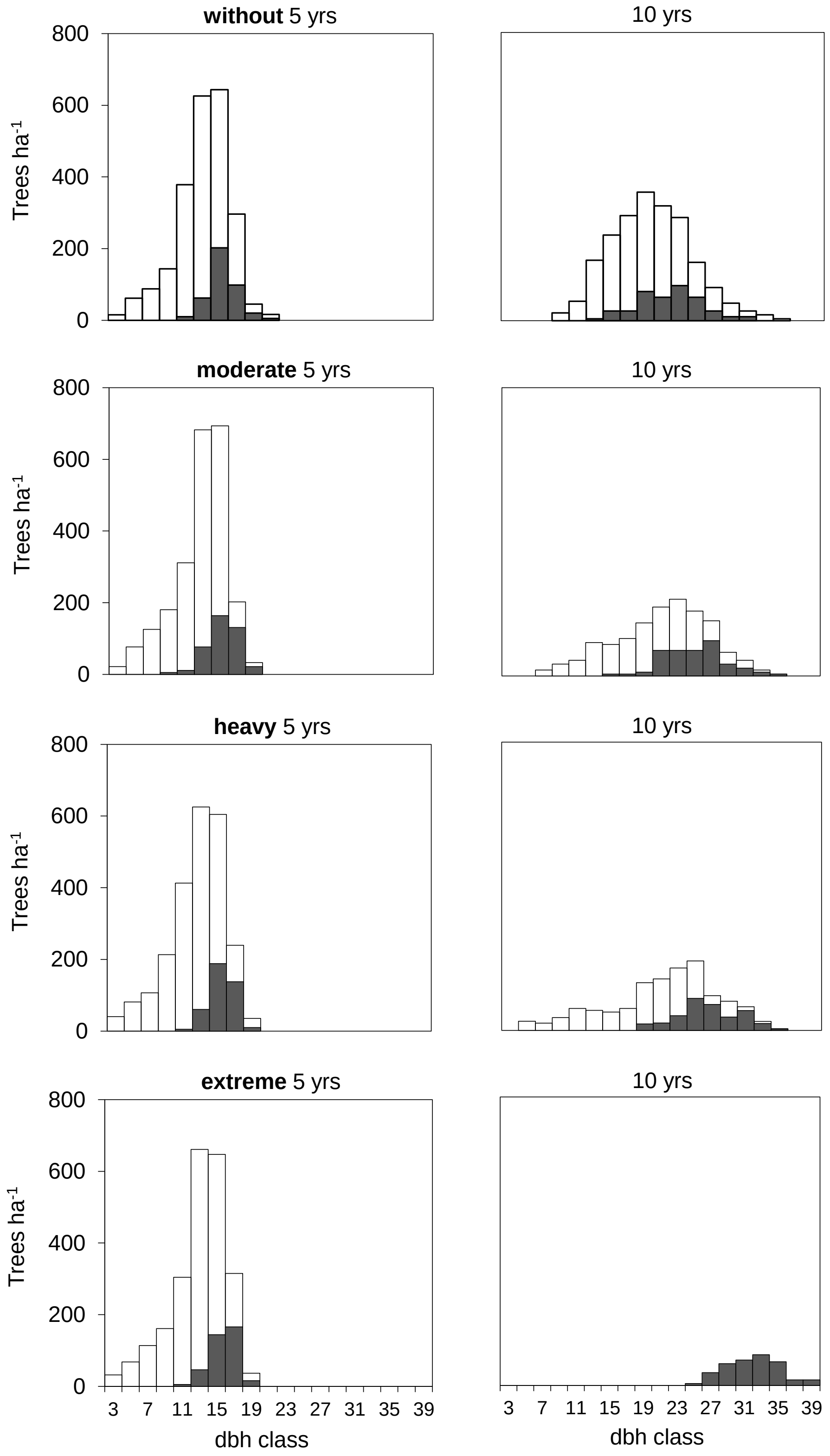


FIGURE 3.3-10: TREE FREQUENCY PER DIAMETER CLASS AT AGE 5 AND 10 YEARS OF THE DIFFERENT THINNING VARIANTS. SELECTED POTENTIAL CROP TREES ARE HIGHLIGHTED IN GREY. DIAMETER-CLASSES 2 CM WIDE, VALUE SHOWN ON 'X' AXIS ARE THE CENTRAL VALUES

SOURCE: The author (2014)

3.4 DISCUSSION

3.4.1 Tree mortality

At the beginning of the study (age 5 years), there was an average of 2,350 trees ha^{-1}, indicating some mortality had occurred since the original planting of 2,500 trees ha^{-1}. In relative terms, the mortality was 6 %.

Currently loblolly pine plantations in southern Brazil consider as acceptable a mortality up to 5 %. Replanting is recommended only beyond this value. Even then, it needs to be done within the first 2 months after planting, otherwise the replanting seedlings have no chance and will be suppressed by the surrounding ones.

In the stand 'without' thinning, tree mortality was critical (Figure 3.3-1). This stand reached age 30 years with ~¼ of the original stand density (less than 700 trees ha^{-1}). The reasons for mortality are the approach on the upper limits of stocking supported at the site capacity and the diminished levels of light received by the lower crown class individuals (MARTIN; JOKELA, 2004).

In the 90's (Figure 3.3-1, 9-18 years.), wood wasp (*Sirex noctilio* F.) attacked some of the suppressed trees, thus accelerating the natural mortality process, especially in the plots without thinning. Even so, the control area curve symbolizes the maximal tree number carrying capacity of loblolly pine as related to site class (a high productive one). On the other hand, not a single loss due to wood wasp was observed in the 'extreme' variant. According to Iede *et al.* (2008), the regulation of stand density through thinnings is, indeed, considered the best prophylaxis against wood wasp attacks. It preferentially attack tress under supressed condition, thus, by removing them of the stand and keeping only vigorous individuals, the attraction for the wasp is remarkably reduced.

The results found in this study are in agreement with the self-thinning rules reported by Yoda *et al.* (1964). The authors studied the mortality of herbaceous and woody plants in dense stands and concluded that numbers of plants in crowded stands tend to converge, since high-density stands thin before less dense stands, and open or lightly stocked stands may not thin at all.

Schneider *et al.* (2013) studied the self-thinning trends for loblolly pine plantations in southern Brazil. These authors reported that the mortality of stands with an initial density of 2,500 trees ha^{-1} started when mean stand diameter was 14 cm.

Comparatively, in the present study, substantial mortality began at age 8 years (Figure 3.3-1), when mean stand diameter was 17 cm. Nevertheless, some mortality was in fact observed earlier.

Hennessey *et al.* (2004) analysed loblolly pine stands in Oklahoma, United States, and reported a similar mortality rate for unthinned stands, declining from 2,100 trees ha^{-1} at age 10, to ~800 trees ha^{-1} at age 24. Significant mortality occurred as well only in unthinned treatments.

Although some studies reported that the mortality start mainly after stand basal area exceed 30-40 m² ha^{-1} (HENNESSEY *et al.,* 2004, JOKELA *et al.,* 2004, MARTIN; JOKELA, 2004) in the U.S., this was not verified in the present study. Basal area reached much higher values than those before significant tree mortality was observed.

However, in Hawaii, loblolly pine stands reach even higher site occupancy. Stands with an initial density of 2,990 trees ha^{-1} reached the age 34 years with ~1,500 trees ha^{-1} (HARMS *et al.,* 2000), which is more than twice as much verified in the present study. The same authors observed significant mortality only after age 20 years. According to them, the causes for this higher site occupancy were higher solar radiation intensities, in comparison to the south-eastern region in the U.S., which allowed greater retention of photosynthetically active leaf area that, in turn, facilitated enhanced survival and growth of trees of lower crown classes.

3.4.2 Diameter

Growth responses in diameter due to thinning were remarkable and consistent over time. At age 30 years, the stand ‘extremely’ thinned resulted in trees with a quadratic mean diameter (dg) over 70 % thicker than the control, without thinning. While the ‘moderate’ and ‘heavy’ ones showed a diameter gain of about 30 % (Table 3.3-1).

The analysis of top diameter development along time (Figure 3.3-2) showed that the ‘extreme’ variant produced not only bigger-sizes trees, but did it at earlier ages. While this treatment reached a top diameter of ~50 cm at age ~15 years, ‘moderate’ and heavy’ took at least 10 more years and the stand ‘without’ thinning did not reached this value at all. In fact, the stand ‘extremely’ thinned showed the highest top diameter values since age 10 years (Table 3.3-2).

According to Smith *et al.* (1997), with drastic thinning it is entirely possible to produce crop trees with twice the diameter that they would have attained in the same time without thinning.

The results found in the present study are in agreement with several available literature, which reported that the mean diameter of the stand is markedly influenced by stand density (MANN; LOHREY, 1974; HUSS, 1983; SHEPHERD, 1986; MOREIRA-WACHTEL, 2001; BURSCHEL; HUSS, 2003; CLARK *et al.,* 2004; BROCKLEY, 2005; DEL RIO *et al.,* 2008).

Stand density begins to influence mean diameter early in the life of the stand, certainly from the time of canopy closure and most probably 1 or 2 years earlier than this (SHEPHERD, 1986). Thus, because thinning reduces inter-tree competition in dense stands, the growth is redistributed on selected crop trees (BROCKLEY, 2005).

- Elesbão and Schneider (2011) evaluated a 17-years-old loblolly pine stand in southern Brazil, subjected to none, 1 or 2 thinnings. The first thinning started at age 11 years and reduced the basal area from 45 to 28 m² ha^{-1}. The stand where the 2nd thinning took place had another reduction to 28 m² ha^{-1} at age 15 years. Both thinned stands improved the mean diameter value similarly in ~37 % (or ~33 cm) over the value observed in the unthinned stand (24 cm).

- Baldwin *et al.* (2000) studied spacing and thinning treatments on 38-years-old loblolly pine stands in Louisiana, United States. Results showed greater mean diameters in low initial density and thinned stands. Values were inversely proportional to both initial planting density and thinning intensity. The largest diameter trees were produced by the widest spacing and the heaviest thinning combination – 37.5 cm, in the 3.7 x 3.7 m² spacing and with residual basal area after thinning of 14 m² ha^{-1}.

- Hennessey *et al.* (2004) reported also that the diameter distributions of 24-years-old loblolly pine was positively affected by thinnings. Futhermore, in the full-stocked stand only 33 % of the trees had sawtimber dimension (≥30 cm). However, treatments where basal area was reduced to 75 and 50 % in relation to the control one, without thinning, showed a remarkably higher proportion of sawtimber-dimension trees, over 90 %.

- Clason (1994), studying loblolly pine stands in Louisiana, U.S., found that competition between trees resulted in reduction of the diameter increment. Until age

6 years, no differences were detected between stands ranging from 2,500-40,000 trees ha^{-1}. Later on, all stands with initial density over than 2,500 trees ha^{-1} showed diameter increment reductions. Stands with initial stock of 500 trees ha^{-1} started showing reductions in diameter growth only at age 9 years. The author also concluded that late thinnings were not efficient in increasing or even keeping growth rate. Thinning at ages 21 and 26 on the stands with higher initial density (2,500-1,500 trees ha^{-1}) resulted in lower growth rates in comparison to the lower initial densities stands (500-250 trees ha^{-1}).

- Complementarily, Mann and Lohrey (1974) recommended for natural regenerated loblolly pine stands in southern U.S. that, in general, stands should have no more than ~1,400 trees ha^{-1} at age 3-4 years if maximal diameter growth is intended. According to the authors, this density would also allow no significant volume yield loss.
- Zhang *et al*. (1996) addressed the fact that diameter and crown ratio development are soon and significantly affected after planting for loblolly pine stands in the U.S.

However, because thinning removes smaller trees from the stand and thus, increases in mean diameter value is partially mathematical rather than silvicultural (ASSMANN 1970), a fairer comparison is done when only the 100 thickest trees are considered. Top diameter (d_{100}) showed the same trend but with lower differences between treatments. 'Extreme' thinning resulted in 40 % gain (20 cm) over the unthinned stand, while 'moderate' and 'heavy' improvement was similar and around 20 % (10 cm).

The similarity between 'moderate' and 'heavy' may be due to the fact that by removing the second competitor ('heavy'), it was not delivered so much additional growing space to the selected future-crop-tree in comparison to the removal of the first and main competitor. This possibility was also reported by HORNUNG (1989) for the same experiment. Later on, a 5th thinning applied in the stand under the 'moderate' regime was enough to equalize any eventual early disadvantage.

3.4.3 Height and crown length

The mean height of trees was affected by different thinning intensities. Nevertheless, only the 'extreme' variant showed a lower value (Table 3.3-3).

Top height (**=** the mean height of the 100 thickest trees ha^{-1}), was also slightly influenced by thinning. However, differences between treatment were more gradual and detected only between extremes.

Robert (2004) evaluated the same experiment at age 22 years and found no differences between treatments for average stand height. However, top height was different in the extremes, ~30 m on the unthinned area, and ~28.5 m on the 'extreme' one. Since then mean height reached 37 and 34 m, respectively.

These results corresponds to predominant idea that the development of the mean heights is not strongly influenced by the stand density. The top height development of trees is even less affected and differences can only be observed on very high or low stand densities (ASSMANN, 1970; SHEPHERD, 1986; SMITH *et al.,* 1997; BURSCHEL; HUSS, 2003; CLARK *et al.,* 2004; BROCKLEY, 2005).

- Schneider and Finger (1993) studied the mean and top height of *P. elliottii* in southern Brazil as affected by thinning intensities (25, 50 and 75 % of basal area removal). The authors concluded that thinning affected mean height, but not the top height.
- Elesbão and Schneider (2011) found no influences of thinning intensities on the height growth of loblolly pine stands in Southern Brazil, which differ from the present study to a certain extent.
- Hennessey *et al.* (2004) studying loblolly pine stands subjected to different thinning intensities in Oklahoma, United States, did not found significant differences among treatments.
- Baldwin *et al.* (2000) observed that spacing and thinning treatments affected mean height of 38-years-old loblolly pine trees in Louisiana, U.S. The authors detected also differences on the height of the dominants trees. Nevertheless, differences were inconsistent with respect to treatment levels.
- Differences in top height were found also in natural regenerated loblolly pine stands, however, with very high density levels (>20,000 trees ha^{-1}) (GRANO, 1969; HARMS; LANGDON, 1976). According to the studies, trees in unthinned stands were lower than the ones released from competition, which are contradictory to the findings of the present study.

In general and according to Zhan *et al.* (1996), the stand density may impact tree height growth, although the magnitude of the effects for height growth are relatively small compared to diameter growth.

Nevertheless, it is widely accepted that top height (h_{100}) is rarely or little affected by stand density. Thus, despite some inconsistency, also in the definition of top height (SHARMA *et al.,* 2002), the mean height of the 100 thickest trees ha^{-1} is commonly used to assess the site productivity**.** Comparing the top height measured at age 20 years (28-30 m) with the available site classification indexes for southern Brazil (MACHADO, 1980; SCOLFORO; MACHADO, 1988; SELLE *et al.,* 1994; TONINI *et al.,* 2002), the stands reached the highest or the second highest yield classes described (Index 29 m at age 20 years). Site index classification up to 30 years are not known, and reinforce the fact that loblolly pine stands older than 20 years are quite rare in Brazil.

Crown basis height is another important information, because it allows the evaluation of the crown length. Larson (1962, 1972) pointed out that all silvicultural practices to accelerate growth exert a direct effect on crown development, and only indirectly on the growth and quality of the wood. Thus, it is more realistic to interpret changes in terms of crown response.

The trees analysed in this study showed crown length ranging from 9-13 m at age 30 years. It means a live crown ratio range from 27-38 %. No statistical differences were detected between thinning variants. However, at age 30 years, this information is of little importance, as the rotation period was finalized or, at least, no more thinnings were intended.

On the other hand, the live crown ratio at earlier ages is a good indicator of the tree's ability to respond to cultural treatments (BLACKWELDER, 1983; SMITH *et al.,* 1997). For loblolly pine, it is recommended that the first thinning should be accomplished before live crown ratio falls below 35 % (MANN; LOHREY, 1974; BLACKWELDER, 1983).

- In fact thinnings in loblolly pine stands in Virginia, U.S., resulted in live crown recession and increased crown diameters due to increasing photosynthetic surface per tree (PETERSON *et al.,* 1997).

- Similarly, Baldwin *et al.* (2000) reported that crown length was significantly longer in thinned 38-years-old loblolly pine stands in Louisiana, U.S. According to the same authors, this was mainly due to a slower crown rise in the less dense stands, indicating increased and prolonged utilization of solar radiation available for photosynthesis in thinned stands.

- Hennessey *et al.* (2004) determined the crown length of loblolly pine trees at age 24 years. Values averaged 7-10 m, for remaining basal area of 100-25 %, respectively. The live crowns lengths mean live crown ratios of 31 % for the unthinned stands, and 45 % for the thinned one.
- However, Harms and Langdon (1976) studied the development of dense stands of loblolly pine in South Carolina, U.S., and found no differences in the height of the crown basis at age 14 years, even considering extremely high density levels (ranging from 2,500-40,000 trees ha^{-1}). According to the authors, the lack of significant differences indicates that crown closure was complete at the canopy base on all density levels.

Although no evidence is available for the present study, it is presumed that the pattern of longer crowns for thinned stands was even greater at earlier ages in this experiment, mainly in the ‘extreme’ variant, which was responsible for the observed high growth rates.

3.4.4 H:d-ratio

The relation between height and diameter is an index for the stability of the tree. Instable trees are slim, have small crowns and small root systems. Although flexible and pliable they tend to break or fall down at storms.

In fact, thinning variants showed significant differences of h:d-ratios. At age 30 years, however, differences were observed only between extremes (ranging from 97-58).

Unfortunately, no comparable data were found for the conditions of south Brazil. Hence the value used in Central Europe was considered. According to Burschel and Huss (2003), trees are stable when h:d-ratio is under 80. Furthermore, values over 100 are considered as very instable trees.

Mead (2013) reported a threshold of 70 for *P. radiata* in New Zealand, regarding the average value of the 200 largest trees ha^{-1}. According to the same author, when the h:d-ratio is less than 70, stands are relatively safe, although this rule is not absolute.

When considering the rules reported by Burschel and Huss (2003), stands ‘heavy’ and ‘extreme’ are very stable, while, after MEAD (2013), only the ‘extreme’ one can be so classified. Whether this values correspond to the studied conditions remains open.

According to Mann and Lohrey (1974), which study the effects of pre-commercial thinning in naturally regenerated loblolly pine stands in southern United States, the stand density reduction improves individual tree stability and reduces the long-term risk of catastrophic losses caused by fire, insects, disease, or adverse weather. Stands are somewhat more susceptible to these hazards immediately after thinning is made, especially if it is delayed. Nevertheless, the increased growth and vigour of individual trees and the improved access for inspection and management reduce the chances of losses during the rotation.

3.4.5 Basal area

Basal area is commonly regarded to classify the intensity of thinnings. In this study, thinning intensity in terms of remaining basal area at age 5 years were 80, 60 and 20 % for the treatments ‘moderate’, ‘heavy’ and ‘extreme’, respectively.

Basal area and volume are strongly correlated and, therefore, the first one is almost superfluous when accompanied by proper volume quantifications. However, when the objective are to understand the growth pattern of a species and to compare the values between different management practices or conditions, it turns into a suitable criterion of the growing space occupancy.

I this context, the fact that the stand ‘without’ thinning reached a maximum basal area of 71.7 m² ha^{-1} at age 22 years is quite impressive. Even more remarkable is that the same stand had already reached 69 m² ha^{-1} at age 13 years (Figure 3.3-4).

- Schneider *et al.* (2013), studying loblolly pine stands in southern Brazil (apart ~100 km from the present study) reported an estimated maximum value of 78 m² ha^{-1} at age 18 years.

These values are higher than the ones found in the literature in other parts of the world where loblolly pine is planted.

- Hennessey *et al.* (2004) related a maximum basal area for even-aged, unthinned, loblolly pine stands of 46 m² ha^{-1} at age 18 years and reported that the value was impressive for a plantation located on the north-western fringe of the species’ range, Oklahoma, United States. According to the same authors, after basal area have reached its peaks, it remained stable and even a little decline was observed in the following years.

Values between 36-48 m² ha^{-1} are reported as maximum occupancy in Southern U.S., according to site condition, including fertilizing and extremely high initial densities, up to 40,000 trees ha^{-1} (HARMS; LANGDON, 1976; BALDWIN *et al.,* 2000; JOKELA *et al.,* 2004; MARTIN; JOKELA, 2004)

- However, Harms *et al.* (2000) reported that loblolly pine plantations in Hawaii were able to reach basal area values of impressing ~100 m² ha^{-1} at age 34 years. According to HARMS *et al.* (1994), the green crown lengths of 25-years-old trees were 4-7 m longer than similar plantations in South Carolina, U.S., which resulted an associated crown leaf area 5 times greater in Hawaii. The differences in stockability was than attributed to the Hawaii site and climate conditions, which provided a long growing season.
- Martin and Jokela (2004) reported the same association between longer live crown lengths and higher basal area levels.
- Basal area values around 130 m² ha^{-1} were also reported by Woollons and Manley (2012) for 50 years old stands of *Pinus radiata* in New Zealand.
- According to Borders and Bailey (2001) the production potential of loblolly pine stands in the southern of U.S. may be as high as the ones verified beyond its natural distribution (for example, Brazil and South Africa). These authors reported, however, that intensified silvicultural practices (herbicide and fertilization) substantially increased stand yield at age 9 years, to comparable levels observed throughout other parts of the world.

The peak of current annual increment in basal area was observed at age 8 to 9 years for all treatments. The ‘moderate’ variant showed the highest value, 10 m² ha^{-1} $year^{-1}$, showing the growing space was being fully utilized. Similar maximum values were verified for the ‘heavy’ and ‘extreme’ ones (9.6 m² ha^{-1} $year^{-1}$), while the unthinned maximum value was only 7 m² ha^{-1} $year^{-1}$.

During the last 10 years of the analysed period (ages 20-30 years), the stand ‘without’ thinning showed no basal area growth. Instead, a negative development (-0.3 m² ha^{-1} $year^{-1}$). It means that during this 10-years period, tree diameter increase was only possible due to some other tree mortality. Even so, residual trees did not grew at the same rate that suppressed trees died.

At same period, the ‘moderate’ and ‘heavy’ thinned stands still grew ~2 m² ha^{-1} year^{-1}. Mean annual increment in basal area for the last 10-years period in the ‘extreme’ variant was 0.6 m² ha^{-1} year^{-1}, which, in comparison to the intermediate variants, shows that trees were not fully utilizing the available growing space. This pattern can be observer due to the levelling off trend of basal area growth during the last ~8 years (Figure 3.3-4), although still higher than the one observed in the unthinned stand.

Comparatively, Hennessey *et al.* (2004) concluded that thinned stands showed a growth rate in basal area higher than unthinned ones. These authors reported values in the magnitude of 3.0 m² ha^{-1} year^{-1}, remarkably lower than the ones observed in southern Brazil.

3.4.6 Volume

3.4.6.1 Individual volume

Although a higher individual tree volumes in the thinned stands were expected, the magnitude of the differences was impressive. Thinnings showed a remarkable influence on tree individual volume and led to the general relation of 1:2:3, meaning that the ‘moderate’ and ‘heavy’ thinnings were capable to produce trees twice as big as the control, while the ‘extreme’ one tripled it (Table 3.3-7).

When only the top 100 trees ha^{-1} were considered ($\mathbf{v_{100}}$), the differences were lower, but the trend remained and the trees on the ‘extreme’ variant were 2 times bigger than the dominant ones on the unthinned stands. These results contradict the idea that a stand does not need thinning, as trees will differentiate by themselves as a normal process.

Similar conclusions were obtained in previous studies.

- Baldwin *et al.* (2000), for loblolly pine stands in Louisiana, United States. These authors reported that the thinning treatments clearly affected total bole volume and biomass. Both increased dramatically from unthinned to thinning treatments.
- Although in completely different site conditions (56-years-old *Pinus sylvestris* in Sweden), Valinger *et al.* (2000) observed comparable trends. Stands were thinned

and nitrogen-fertilized. The growth response by thinning was larger than by fertilizing. Trees on thinned stands showed more than twice as much dry weight in comparison to unthinned stands.

- According to Peterson *et al.* (1997), from the physiological point of view, the increase in growth following thinnings and the final dimension of trees is the result of larger foliar biomass and higher physiological activity in the lower crowns of thinned stands.

3.4.6.2 Volume ha^{-1}

Although the stands 'without' thinning reached a high volume ha^{-1} production (~1,000 m³ ha^{-1} at age 30 years), this was not the maximum. The stands in the practice oriented variants showed the highest production – about 35 % above the one verified in the stand 'without' thinning. The 'extreme' and early thinned stand surprisingly reached the same volume production as verified in the unthinned stand.

The high mortality verified in the unthinned stand resulted in a great amount of wood loss. Individual tree volume was calculated one year previous to its death. Altogether, wood loss due mortality reached 430 m³ ha^{-1}, ⅓ of the whole volume production in this treatment, and ~70 % concentrated on the last decade (between ages 20-30 years).

When the amount of wood loss due to mortality was regarded, the total produced volume of the area 'without' thinning was just the same as the ones observed in 'moderate' and 'heavy'. As pointed out by Assmann (1970), the maximum volume production is obtained from unthinned and full-stocked stands. However, for practical purposes, the volume lost due to mortality could not be utilized, because the wood just rotted in the stand.

- Comparatively, 24-years-old and unthinned loblolly pine stands in Oklahoma, U.S., had a cumulative stem biomass lost due mortality of 61 ton ha^{-1} (31 % of the total stem biomass) (Hennessey *et al.,* 2004). The authors reported that the gross cumulative stem biomass production, which included live biomass, mortality losses and thinning removals, was greatest in the unthinned stand at age 24 years, which differ from the present study.
- For *P. sylvestris* stands located in Spain, del Rio *et al.* (2008) reported an average loss due to mortality of ~17 % within ages of 35-50 years.

Indeed, the apparently increase in productivity of thinned stands in relation to unthinned ones are essentially the use of mortality along time (BLACKWELDER 1983). According to Baker and Langdon (1991), thinning rarely increase volumetric increment in loblolly pine stands in the U.S. However, according to the same authors and Wenger (1957), light thinnings which harvest supressed trees, can increase the total production per are unit up to 20 % at age 50 years.

The volume harvest in the different thinning procedures in the present study was similar between treatments, being ~30 % of the total volume production. Although these values are strongly related to the type, intensity and when the thinnings are carried out, Daniel *et al.* (1979) also reported that thinned volumes rarely exceeds 25 to 35 %.

- Clason (1994) reported for loblolly pine in Louisiana, United States, that, by age 21 years, total merchantable volume (Ø > 7 cm inside bark) was the same (~209 m^3 ha^{-1}) for different initial densities, varying from 2,500-250 trees ha^{-1}, but sawtimber volume was inversely related to density level.
- Guiterman *et al.* (2011) studied thinned loblolly pine stands located in central Maine, U.S. Crown thinnings were applied to the stands in different intensities. Previous to thinning, crop trees were selected based on bole form and competitive dominance at a spacing of ~6 m (280 tree ha^{-1}) and then released on 3-4 sides be removing adjacent and competing trees until the recommended basal area was reached (20-35 m^2 ha^{-1}), depending on stand density, and thus, the medium intensity was established. The low-density thinning regime followed the same criteria for crop-tree selection, but crop trees were fully released by removing all non-crop trees. A 2nd thinning was implemented 10 years later removing codominant individuals that were competing with crop-trees in the medium treatment. In the low-density plots, crop trees showing little response to the initial treatment were removed if their crowns were touching adjacent, more desirable individuals. The authors concluded that
    - the volume growth at the stand level of the trees in the medium variant was 43 % higher than the low-density growth rate.
    - crop-tree sizes in the low-density stands were significantly larger than in the ‘medium’ stands because of the higher individual tree growth rates.

- despite 60% higher tree-level growth rates in the 'medium' treatment compared with the control, trees in the 'medium' treatment were barely larger than the ones in control.
- thus, thinning to a low density will diminish total stand yield. However, the gain in individual crop-tree growth may be worth the sacrifice for forest managers because of the high value of large white pine trees.

It is known that the maximum yield per area unit and the maximum tree individual growth are contradictory issues (SMITH *et al.,* 1997). In general, too many trees over-utilize site resources and too few under-utilize it (BALDWIN *et al.,* 2000). Hence, density management is typically a compromise between maximum production per unit area and individual-tree growth and size.

Indeed, the variant 'extreme' where very heavy and early thinnings were carried out, and from age 13 years onwards had only ~150 tree ha^{-1}, surprisingly resembled the volume production of the unthinned stand by the age 20 years, or maybe earlier (Figure 3.3-7).

Figure 3.3-8 followed an analysis presented by Assmann (1970). It was found that site occupancy of ~70 %, in terms of the maximum basal area, between ages 10-20 years was optimal and led to higher periodic increments in volume, up to ~50 % more than the ones verified in unthinned stands (Figure 3.3-8). The surplus in volume growth is even higher between ages 20-30 years, when a site occupancy of ~80 % is optimal, at which thinned stands are able to grow twice as much as unthinned ones. It is important to note that the thinnings applied to the stands in the present study were 'crown' oriented. Therefore, these remarkable growth responses were a result of favouring individual trees by removing direct competitors.

The results found in this study improve the understanding behind the capacity and optimum site occupancy for loblolly pine stands in southern Brazil. Variants 'moderate' and 'heavy' may represent the best practices for combining both, total production and individual growth.

In fact, when there is a compromise of full growing space utilization, several thinnings with light intensity along the rotation period are commonly the best option (LEWIS; FERGUSSON, 1993). The authors reported also that systematic thinnings should be avoided as they may reduce production along time, even if restrict to the first 2 interventions.

- Assmann (1970) pointed out that the maximum periodic increment in volume is obtained at 75 % of the maximum basal area. However, the surplus increment described by the author was ~10 % in comparison to the ones verified in the unthinned stand, much lower than the ones observed in the present study. According to the same author these exceptional growth reactions occur only in stands which have not yet reached the peak of their current volume increment. And if competing neighbour trees are removed early enough by intense thinnings, an acceleration of growth by individual trees will lead to an early culmination of the current volume increment. This, however, can be only temporary, because a stand which has undergone early and heavy thinning reaches not only its peak growth-rate but also the decline of its increment curve at an earlier date.
- Elesbão and Schneider (2011), studying 17-years-old loblolly pine stands in southern Brazil, found a reduction of ~15 % on the total volume produced on thinned stands when compared to full-stocked ones. Stands were thinned from below 1 or 2 times, at ages 11 and 15 years. It is important to note that thinnings from below did not sufficiently favour the crown development of the residual trees.
- Still about site occupancy, and from a physiological perspective, intensively thinned stands may profit from more water availability, by reducing interception, and thus, allowing higher nutrient uptake and growth (HENNESSEY *et al.,* 2004).

Noteworthy is that the site occupancy is strong dependent on the site quality, and it is difficult to define absolute optimal and critical values for stands of different sites and ages. Thus, a preliminary knowledge about site maximum carrying capacity is needed in order to optimally define management thresholds.

3.4.6.3 Mean annual increment

Mean annual increment (MAI) was highest in the 'moderate' and 'heavy' (~45 m^3 ha^{-1} $year^{-1}$) variants. Thinnings in this treatment were relatively light and frequent, 4-5 in total, which allowed satisfactory tree growth while harvesting big individuals which competed for growing space with other dominant ones (Table 3.3-10).

Surprisingly, MAI was similar between the extreme variants, 'without' and 'extreme' (34 m^3 ha^{-1} $year^{-1}$). While in the 'extreme' stand tree number were intensively and early reduced, in the unthinned stand, the high mortality rate was responsible for substantial loss on wood production.

Comparatively and according to ABRAF (2011), in the cold highlands of southern Brazil, loblolly pine growths better than any other tree. Annual increment are just under 50 m³ ha^{-1} in the best sites. In average, however, values around 37 m³ ha^{-1} ano^{-1} are described.

Still for the southern-Brazilian conditions, higher values were reported by Elesbão and Schneider (2011), which found a maximum MAI of 52 m³ ha^{-1} $year^{-1}$ at age 17 years, and by Mainardi *et al.* (1996), who observed a maximum of 57 m³ ha^{-1} $year^{-1}$ at age 16 years.

In the present study, current annual increments (CAI) of ~60 m³ ha^{-1} $year^{-1}$ were observed between ages 8-11 years.

For the growth conditions of southern United States, average MAI of 10-12 m³ ha^{-1} $year^{-1}$ are reported (HARMS; LANGDON, 1976; CLASON, 1994). However, in Hawai, MAI easily reaches 24 m³ ha^{-1} $year^{-1}$ (HARMS *et al.,* 1994).

Baldwin *et al.* (2000) reported that intensively thinned loblolly pine stands in South-eastern United States were not able to maintain the same yield production as observed in the lighter treatments, just as observed in the present study.

3.4.7 Accuracy of the crop trees selection

Since only vital trees are able to form big individuals, the main criterion of selecting a potential crop trees is vitality (BURSCHEL; HUSS, 2003). An optimal final crop tree should be straight, free of damages and with few and small branches. Vital trees, however, normally produce great crowns with thick branches. Thus, artificial pruning is a must for high value wood production.

Nevertheless, many forest owners and their staff tend to select the co-dominants or even intermediate individuals as these often seem to be better in ‘quality’. But later they do not grow sufficiently to meet the production goals. In fact, the growth responses as affected by the release of competition observed in this study was only possible because of the crown thinning approach. The remarkably growth responses verified in the present study strongly depend on the correct application of this method.

Burschel and Huss (2003) recommended to conifers that the selection of potential crop trees should be carried out when the stand height is around 12-18 m. According to the same authors, the praxis shows that after these height, very low biotic and abiotic risks remain to negatively affect the selected trees.

The low regression coefficients between age 5 and 20 years showed that many trees being dominant at the beginning of the experiment lost their leading rank in the following years (Table 3.3-11, Figure 3.3-9). The conclusion from these findings suggests to select the potential crop trees later, or to select more than the requested final number of crop trees.

The diameter is certainly a very important parameter when the potential crop trees are selected, but not the only one. Other aspects like height, stem form or even distribution within the stand are often regarded also. As it is very difficult to measure and evaluate them, they were not taken into account and this ran the risk of overestimating the role of the diameter as the only decisive information.

However, by correct selection and release from competition, it was demonstrated that early selection is feasible when the crown thinning approach is appropriately applied (Figure 3.3-10).

Furthermore, it should be pointed out that even the thinnest trees in the extreme thinned stands gained thicker stems than the leading dominants in the control – thus very impressively demonstrating the effective influence of early releases from competition and the possibility of favouring individuals that are not over-dominants. However, this flexibility on tree selection should not consider trees under co-dominated canopy classes. Moreover, it is important to keep in mind that big growing spaces should be delivered in order to favour trees.

Additionally, Hornung (1989), evaluating the same experiment when trees were 8 years old reported that already at this age, the selected crop trees in the unthinned stand were not able to maintain their dominant position. This fact showed the importance of releasing selected trees from competition and that pruning without a combined thinning program may be of high risk of not obtaining the expected growth rate on the selected and pruned individuals. On the other hand and according to the same author, trees on the ‘heavy’ variant have definitely established their dominant position 3 years after the removal of 2 direct competitors. Moreover, the author reported that low quality trees (i.a. fork) were in similar proportion in all treatments, ~10 %.

The selection of trees in the present study was realized by a height of 8-9 m (Table 3.3-4), which may be questionable.

However, by reducing the initial density (from 2,500 to 1,600 trees ha^{-1}, or even lower), which is already the current practice in southern Brazil, thinnings could be postponed in 2-3 years, allowing the selection of potential crop trees and their release from competition to age 7-8 years, when stand top height is 12-14 m (Table 3.3-4), just as suggested by Burschel and Huss (2003). Nevertheless, the problem of early selection remains because of the early pruning need. Hence, a higher number of trees have be pruned in order to allow an appropriate further selection of potential crop trees.

In fact, pruning should take place even earlier as the 5-years-old selection regarded in this study. Optimally at age 3-4 years in order to assure a knotty core of less than 12 cm in diameter, which is considered the best compromise between tree growth and the yield of industrial peeling process (SEITZ, 2000). According to the same author, the best pruning regime for loblolly pine in southern Brazil should be yearly from the 3rd to 7th year, lifting 1 to 1.5 m each year, and thus, combining reasonable growth and acceptable knotty core dimensions at the first ~6 m of the stem.

Since the potential crop trees are mainly selected in the dominant canopy class, it is important to consider the growth patterns of the dominant trees instead an average value for the whole stand. This is particularly true for pruning operations. For example, dominant trees were ~5 cm thicker (17 cm) and ~1 m higher (9 m) than the stand average at age 5 years, proving that a much earlier pruning was necessary to restrict knotty core zone to 12 cm, as pointed out by Seitz (2000).

3.5 CONCLUSIONS

Crown thinnings noticeable affect the growth of loblolly pine. While tree height is slightly affected by thinning intensity, tree diameter, and therefore tree individual volume is remarkably greater the more intense the thinning.

For the studied conditions, loblolly pine stands in a 30-years production period and subjected to:

- no thinning, result
    - the lowest diametric growth and a level off trend far lower than the values obtained on the thinned stands. Trees reached 30 years of age with a mean top diameter of 47 cm.
    - a great wood loss due mortality, ~⅓ of the total volume production.
    - the lowest average individual stability (h:d-ratio),

  - a peak in basal area growth at age 13 years (~70 m^2 ha^{-1}), without any substantial increase afterwards.
- intermediate crown thinnings (practice-oriented) deliver
  - trees with top diameter 20 % greater than the ones in unthinned stands,
  - top individual volume 40 % greater than trees in unthinned stands,
  - the highest total volume production (1,400 m^3 ha^{-1}), up to 40 % more than stands without thinning, as a result of an efficient site occupancy.
- early and extreme release of selected crop trees from competition result
  - trees with top diameter 40 % greater (67 cm) than unthinned stands,
  - top individual volume 90 % higher (5.3 m^3) than trees in unthinned stands, and 30 % greater than trees subjected to intermediate thinnings.
  - the same total volume production (1,000 m^3 ha^{-1}) as observed in stands without thinning.

Altogether, results show the impressive diameter growth response of young trees when released from competition due to crown thinnings. While intermediate thinnings result in the maximum volume production ha^{-1}, at the same time individual size is enhanced over unthinned stands, the highest diametric growth depends on extreme interventions. The maximum diameter growth is obtained, however, at the expense of the total volume production.

Although an early selection of potential crop trees might be risky, favouring them by removing direct competitors is an efficient way for maintaining their vitality. Nevertheless, it is recommended to start selecting at least 2 times the number of potential crop trees intended for the final cut.

4 RING WIDTH AT DIFFERENT HEIGHTS AS AFFECTED BY THINNING

4.1 INTRODUCTION

The growth of even-aged forest plantations changes with stand age, reaching a peak relatively soon in stand development followed by a decline (TSCHIEDER *et al.,* 2012). Increase in the growth rate after thinning are a consequence of higher levels of resource availability and higher levels of resource acquisition through an increase in leaf area of remaining trees (LONG *et al.,* 2004).

However, there are some contradictions about the response of trees to thinnings. While some authors reported that dominant trees did not respond to thinning (PUKKALA *et al.,* 1998), others found a remarkable increase in the growth rate following it (BRADFORD; PALIK, 2009; GUITERMAN *et al.,* 2011).

Reason for these contradictions are, for example, the time and type of thinning applied to the stand (BRADFORD; PALIK, 2009). Most of the previous studies which found little or no individual tree response to thinnings, did not regard crown thinnings. The remarkable growth rates described in Chapter 3 STAND DEVELOPMENT reinforce this.

Because dominant trees possess a higher efficiency in resource use even in full stocked stands (BINKLEY, 2004; TSCHIEDER *et al.,* 2012), they are little or no affected by removing intermediate or supressed trees, which is the common practice in weak to moderate thinnings from below.

Although there have been some thinning studies with loblolly pine stands in southern Brazil (MAINARDI *et al.,* 1996; SANQUETA *et al.,* 2000; SCOLFORO *et al.,* 2001; ELESBÃO *et al.,* 2011), in none of them crown thinnings were regarded. Moreover, knowledge about the radial development at different height is still lacking and are important to understand the effects of various growing space on diameter growth and volume production. Some of the cited studies were mathematical approaches, which although interesting, fail in express the real growth responses of trees.

Specific objectives were:

- Analysis of ring width of trees subjected to different crown thinnings and at various tree heights.

- Quantification of relative responses to thinnings in relation to the growth rate of trees in the stand without thinning.
- Evaluation of the growth rate per diameter class.

4.2 MATERIAL AND METHODS

Study site and design are described in detail in topics 2.1 and 2.2, Chapter 2 MATERIAL AND METHODS.

4.2.1 Data collection

The data used in this study were obtained from growth ring measurements. The evaluation of ring width is an important tool for assessing growth patterns of trees. For this purpose, cross sectional discs were sampled in the 4 thinning variants:

- From each plot, 10 trees (3 small-, 4 medium- and 3 big-sized) were selected to represent different diameter classes and thus growth rates, as described by Peltola *et al.* (2002).
- In each of the selected trees, 4 cross-sectional discs were taken at fixed and relative stem heights: 1.3 m, 25, 50 and 75 % of the commercial height.
- It was defined that commercial height was the one at which the diameter was 10 cm.
- For the relative height sampling, cross-sectional discs were taken in the possible nearest location, between two logs, in order to allow the stem to be sold by the enterprise where the study was carried out.
- A total of 80 trees and 320 discs were sampled.

Tree sampling regarded the whole diametric distribution within each plot. Mean diameter per diameter class and thinning variant, as well as the diameter range, are shown in Table 4.2-1. The quadratic mean diameter of each thinning variant is given for characterizing the stand.

From Table 4.2-1 it can be observed that diameter values substantially varied between thinning variants. Average small trees in the ‘extreme’ one are as thick as average big-sized ones in the stand ‘without’ thinning.

TABLE 4.2-1: MEAN QUADRATIC DIAMETER (D_G) OF THE DIFFERENT THINNING VARIANTS

THINNING VARIANT	d_g cm	DIAMETER CLASS cm **big**			**medium**			**small**		
		mean	max.	min.	mean	max.	min.	mean	max.	min.
without	35.6	52.6	61	48	35.1	41	30	24.2	27	20
moderate	45.8	60.4	68	56	45.8	49	42	33.2	37	26
heavy	48.8	62.2	71	57	48.0	52	45	37.1	39	32
extreme	61.9	69.1	76	66	58.6	64	52	51.0	59	43

Sampled trees were grouped in diameter classes.
max.: maximum;
min.: minimum.

SOURCE: The author (2014)

Relative stem heights were used instead of absolute ones in order to allow a fairer comparison between tree sizes. Commercial heights varied from 22-37 m. Medium commercial heights and their range are shown in Table 4.2.2.

TAB 4.2-2: SAMPLED HEIGHT WHERE CROSS-SECTIONAL DISCS WERE TAKEN PER RELATIVE POSITION AND THINNING VARIANTS.

THINNING VARIANT	SAMPLED HEIGHT m, in relation to commercial height (%) **25**			**50**			**75**		
	avg.	max.	min.	avg.	max.	min.	avg.	max.	min.
without	7.8	9	5	15.5	19	11	23.0	28	16
moderate	8.2	9	7	15.8	18	14	24.1	24	22
heavy	7.8	9	7	15.3	18	13	23.1	26	19
extreme	8.3	9	6	15.1	16	13	22.6	24	22

avg.: average;
max.: maximum;
min.: minimum diameter.

SOURCE: The author (2014)

Relative heights were, in average, 8, 15 and 23 m. However, because of the great variability between thinning variants, the relative position is shown in the following analysis.

The preparation of the cross-sectional disks comprised the following activities:

(1) Discs were dried and sanded with different sand paper grifts: 36, 60, 100 and 160.

(2) To obtain the growth sequences, 4 radii were marked on each of the disks by connecting the tree's pith with bark. The radii were traced with an angle of 90° from each other beginning 45° from the largest one (not measured).

(3) The discs were digitalized with a scale for image calibration, and the radii were measured with an accuracy of 0.01 millimetres by using the software 'Image Pro Plus', version 4.5.0.29 for Windows ®.

Some steps of the cross-sectional discs sampling are shown in Figure 4.2-1.

FIGURE 4.2-1: (A) CROSS-SECTIONAL DISCS SAMPLING; (B) BAND SANDING MACHINE AND (C) DISC READY FOR DIGITALIZATION.

SOURCE: The author (2014)

4.2.2 Data analysis

The data set consisted of year ring measurements over the period 1982-2011 (29 years). In total, ~37,000 measurements of ring width and age were collected. Data were stored in electronic spreadsheets (Microsoft Excel ®).

July was taken as the month at which the stand completed a full year. The respective rings were named according to the year in which its growth started: annual growth ring called '2010' was formed from August 2010 to July 2011.

The number of annual growth rings at the different heights varied between individuals and started from the year when the first ring was formed:

- 1.3 m: 29 rings (1982-2010).
- 25 %: 25 rings (1986-2010).
- 50 %: 21 rings (1990-2010).
- 75 %: 14 rings (1997-2010).

Ring width measurements were compared between thinning variants, thus growth rate as affected by thinning was assessed and quantified. The average growth rate was tabular and graphically evaluated.

Growth rings were judiciously fitted with the calendar year they were formed, thus, the effect of thinnings could be accurately determined.

The relative growth responses to thinning was the ratio between the ring width of a given height and thinning variant and the corresponding ring width of trees in the stand 'without' thinning. Procedure similar to the one regarded by Peltola *et al.* (2002).

To analyse the thinning response of trees in different diameter, sampled trees within each thinning variant were classified into three diameter classes (big-, medium- and small-sized) according to their diameter at age 30 years, as shown in Table 4.2-1.

The fact that one plot had been missed through storm led to its replacement by a surrounding stand (mentioned in Chapter 3 'STAND DEVELOPMENT'). Although the new plot could perfectly express the 'extreme' variant regarding trees ha^{-1} and individual tree size, the growth ring analysis showed differences between growth patterns. For example, an absence of a great response to the thinning at age 5 years, which was observed in all individuals of the other 'extreme' replication. Thus, only 3 individuals of these new plot were kept for expressing the 'extreme' variant. The trees that could be used were the ones nearest to the former plot, and were clearly released from competition very similarly to the other 'extreme' plot, as confirmed by the ring width development.

In total 73 trees were regarded in the analysis.

4.2.3 Statistical analyses

Statistical analyses were based on a fully randomized design, in which observations were pseudo-replicated. Trees were sampled within the plots of each thinning variant, i.e. trees were not totally independent observations. However, because of the homogeneity of the study area, a fully randomized approach was regarded. Previous analysis (Chapter 3) showed no significant differences between blocks for the great majority of variables. Moreover, LEVENE tests were performed and confirmed the variance homogeneity of the data.

The fully randomized approach was regarded because, as mentioned, one replication of the 'extreme' variant was lost, and trees in the new plot were mistakenly sampled. Finally, only 3 big individuals were suitable for the ring width analysis and a mean value of which would overestimated the growth rate of trees subjected to the 'extreme' variant. Thus, for a conservative approach and even with some method fragility, the fully randomized design was regarded acceptable.

In order to evaluate eventual bias of regarding a fully randomized design, ring width at 1.3 m were additionally analysed as a block design with two replicates. Despite of higher mean values for the trees in the 'extreme' variant, because of some small-sized tree losses, the significant levels were commonly lower, but still significant. Nevertheless, mean segregation through TUKEY's test and conclusions remained the same.

4.3 RESULTS

4.3.1 Ring width as affected by thinning

Data obtained from ring measurements allow a detailed evaluation of tree growth rate.

4.3.1.1 Diameter at breast height: 1.3 m

Ring width values at 1.3 m height are shown in Table 4.3-1.

All stands showed a similar growth rate previous to the establishment of the experiment – age 2-5 years. At age 3 years, the highest ring width value was observed in all stands, ~21 mm, which means a diameter growth rate of more than 4 cm under bark. After age 3 years, and before thinnings started, the stands showed a growth rate decrease, indicating competition between trees had already started (Table 4.3-1).

One year after thinnings were applied, the growth rate between treatments substantially differed. The removal of all competitor trees per potential crop tree, variant 'extreme', resulted in the highest growth rate. The practice oriented variants, where 1 and 2 competitor trees per potential crop tree were removed ('moderate' and ‘heavy’, respectively) showed a similar growth rate. However, the removal of only 1 competitor tree was not enough to distinguish the growth rate from the trees in the stand ‘without’ thinning.

From age 8-25 years, significant differences between thinning variants were detected. In general, the stand:

- ‘without’ thinning showed the lowest growth rate, with a decreasing trend with aging.
- trees under the ‘moderate’ management grew similarly to the ones in ‘heavy’ during the most of the 30-years period. Being also sometimes similar to the unthinned area (ages 6, 8, 10 and 25). On the second half of the rotation period trees in the ‘moderate’ variant resembled the growth rate of trees in the ‘extreme’ one (from age 17-25 years). This was because a 5th thinning procedure at age 15 years was carried out – the most intensive one under the thinnings applied on this treatment –.
- ‘heavily’ thinned showed a growth rate similar to the ‘moderate’. Both treatments oscillated in being similar to the other variants. The only age at which a significant difference between the growth rate on the ‘heavy’ and ‘moderate’ variant was 8 years. Probably as a result of the removal of 2 competitor trees instead 1 on the first thinning accomplished at age 5 years. Between ages 21-25 years, the growth rate measured on the ‘heavy’ variant was similar to the one in the ‘without’.
- ‘extremely’ thinned showed the highest growth rate during almost the whole period - immediately after thinning (age 6) and during the period from 9-16 years. At age 8 years, the ‘extreme’ variant grew only as much as the ‘heavy’. During most of the second half of the rotation period (age 17-25) the growth rate observed in the ‘extreme’ variant was similar to the ‘moderate’ or ‘heavy’.

From age 26-30, all treatments grew on a similar rate.

4.3.1.2 Height level: 25 %

Average ring width per thinning variant and age at 25 % height level (~8 m) is shown in Table 4.3-1. The growth pattern at 25 % of the commercial height was similar to the one observed at 1.3 m level. However, differences in ring width started later, being detectable from age 8 years onwards.

Until age 10 years, for example, trees in the ‘heavy’ variant grew just as much as in the one ‘without’ thinning. At 1.3 m level, trees under the ‘heavy’ management grew more than the ones in the ‘without’ already at age 6 years.

TABLE 4.3-1: RING WIDTH PER THINNING VARIANT AND YEAR AT 1.3 M AND 25 % OF THE COMMERCIAL HEIGHT

Means with the same letter do not significantly differ within the same age and height - test of TUKEY.

Years with bold number are the ones at which thinnings took place; parenthesis mean only some of the treatments were thinned - at age:
7 yrs – moderate and heavy,
15 yrs – moderate.

SOURCE: The author (2014)

	1.3 m					25 %				
AGE years	RING WIDTH mm				STATIST. SIGNIF.	RING WIDTH mm				STATIST. SIGNIF.
	without	moderate	heavy	extreme		without	moderate	heavy	extreme	
2	7.8	7.0	8.1	7.4	n.s.					
3	21.2	21.3	21.9	21.5	n.s.					
4	19.2	19.5	19.3	18.8	n.s.					
5	13.9	14.8	14.0	13.7	n.s.					
6	12.5 a	13.6 bc	15.8 b	20.6 c	* * *	13.6	16.2	15.0	15.4	n.s.
(7)	8.9	6.4	9.2	10.2	n.s.	16.2	15.2	15.8	13.7	n.s.
8	8.0 a	9.6 a	13.4 b	16.1 b	* * *	14.5 a	15.4 ab	16.4 ab	16.9 b	* *
9	6.7 a	10.1 b	12.2 b	17.5 c	* * *	12.6 a	13.9 a	14.7 a	17.8 b	* * *
10	5.6 a	8.2 ab	9.6 b	14.9 c	* * *	9.6 a	11.0 a	11.5 a	15.9 b	* * *
11	4.7 a	8.0 b	9.5 b	15.1 c	* * *	7.3 a	10.1 b	10.8 b	16.1 c	* * *
12	4.7 a	7.8 b	8.7 b	13.8 c	* * *	6.8 a	9.4 b	10.1 b	14.7 c	* * *
13	3.9 a	6.3 b	6.5 b	10.7 c	* * *	6.0 a	7.9 ab	8.6 b	13.1 c	* * *
14	3.5 a	6.3 b	6.9 b	11.0 c	* * *	5.3 a	7.9 b	8.4 b	12.8 c	* * *
(15)	3.3 a	5.7 b	6.3 b	9.7 c	* * *	4.4 a	6.7 b	7.6 b	11.0 c	* * *
16	3.0 a	5.2 b	5.7 b	7.6 c	* * *	4.1 a	6.1 b	6.8 b	9.1 c	* * *
17	2.8 a	5.4 b	5.4 b	6.9 b	* * *	3.6 a	5.9 b	5.9 b	7.7 c	* * *
18	2.8 a	5.8 b	5.9 b	7.6 b	* * *	3.3 a	6.0 bc	5.7 b	7.7 c	* * *
19	2.9 a	5.0 b	5.5 b	6.7 b	* * *	3.1 a	5.7 bc	5.1 b	7.1 c	* * *
20	3.0 a	5.6 bc	4.7 b	6.6 c	* * *	3.3 a	5.5 bc	5.0 b	6.8 c	* * *
21	2.8 a	5.2 b	4.2 ab	4.9 b	* *	3.2 a	5.0 bc	4.2 ab	5.7 c	* * *
22	2.5 a	4.5 b	3.6 ab	5.0 b	* * *	2.7 a	4.4 bc	3.8 ab	5.4 c	* * *
23	2.4 a	3.8 b	2.8 ab	3.6 ab	*	2.5 a	3.6 ab	3.1 a	4.3 b	* * *
24	2.4 a	3.8 b	3.0 ab	4.1 b	* *	2.4 a	3.6 bc	3.0 ab	4.3 c	* * *
25	1.9 a	2.8 ab	2.2 ab	3.1 b	* *	2.0 a	2.8 ab	2.2 a	3.3 b	* * *
26	2.2	2.6	2.3	2.9	n.s.	2.2	2.6	2.1	2.9	n.s.
27	2.4	2.5	2.1	2.5	n.s.	2.3	2.4	2.2	3.0	n.s.
28	2.7	2.7	2.5	3.0	n.s.	2.7	2.7	2.4	3.4	n.s.
29	2.4	2.3	2.4	2.9	n.s.	2.2	2.2	2.4	3.1	n.s.
30	2.4	2.3	2.7	3.3	n.s.	2.3	2.3	2.5	3.5	n.s.

TABLE 4.3-2: RING WIDTH PER THINNING VARIANT AND YEAR AT 50 AND 75 % OF THE COMMERCIAL HEIGHT

Means with the same letter do not significantly differ within the same age - test of TUKEY.

Years with bold number are the ones at which thinnings took place; parenthesis mean only some of the treatments were thinned - at age:
7 yrs – moderate and heavy,
15 yrs – moderate.

SOURCE: The author (2014)

AGE years	50 % RING WIDTH mm				STATIST. SIGNIF.	75 % RING WIDTH mm				STATIST. SIGNIF.
	without	moderate	heavy	extreme		without	moderate	heavy	extreme	
10	8.8	11.4	9.4	9.3	n.s.					
11	11.0	12.4	12.0	12.8	n.s.					
12	12.2	12.5	12.6	13.4	n.s.					
13	12.2 a	12.9 a	13.3 a	15.7 b	* *					
14	11.2 a	13.1 b	13.7 b	16.2 c	* * *					
(15)	8.9 a	11.2 b	11.8 b	14.9 c	* * *					
16	8.0 a	10.2 ab	10.8 bc	12.9 c	* * *					
17	6.5 a	9.7 b	9.8 b	13.2 c	* * *	9.2	9.1	10.2	7.9	n.s.
18	5.4 a	8.2 b	8.3 b	11.7 c	* * *	7.7 a	9.3 b	7.9 ab	9.1 ab	* *
19	4.8 a	7.2 b	7.4 b	10.6 c	* * *	7.4 a	8.6 ab	8.5 ab	9.5 b	* *
20	4.7 a	7.2 b	7.4 b	10.4 c	* * *	8.0 a	10.0 b	10.1 b	10.7 b	* *
21	4.1 a	6.0 b	6.4 b	8.7 c	* * *	7.7 a	10.4 b	10.0 b	11.8 b	* * *
22	3.6 a	5.6 b	5.7 b	8.3 c	* * *	6.9 a	9.8 b	9.5 b	11.9 c	* * *
23	3.2 a	4.2 b	4.3 b	6.3 c	* * *	6.1 a	8.3 b	8.1 b	10.9 c	* * *
24	3.0 a	4.3 b	4.1 ab	6.4 c	* * *	5.3 a	7.4 b	7.8 b	10.5 c	* * *
25	2.5 a	3.5 a	3.1 a	4.9 b	* * *	4.5 a	6.6 b	6.1 b	8.7 c	* * *
26	2.5 a	3.1 a	2.8 a	4.6 b	* * *	4.6 a	6.2 a	6.4 a	9.2 b	* * *
27	2.5 a	2.9 a	2.7 a	4.5 b	* * *	4.0 a	5.7 a	5.7 a	8.7 b	* * *
28	2.7 a	3.2 a	3.0 a	4.8 b	* *	3.9 a	5.5 a	5.6 a	7.8 b	* * *
29	2.4 a	2.7 a	2.8 a	4.3 b	* *	3.3 a	4.9 ab	5.3 bc	7.3 c	* * *
30	2.2 a	2.8 a	3.2 a	4.7 b	* *	3.3 a	4.8 ab	5.4 b	7.6 c	* * *

Trees in the stand ‘without’ thinning showed the lowest growth rate from ages 11-20.

Trees subjected to the ‘extreme’ variant, showed the highest growth constantly from age 9-17. Similarly to the 1.3 m level, trees in this treatment grew just as much as the trees in the practice oriented variants from age 17 years onwards. From age 26 years and on, no differences between treatments were found.

These results suggests that a positive influence of thinnings might take longer to be detectable at higher levels.

4.3.1.3 Height level: 50 %

Ring width per thinning variant and age at 50 % of the commercial height (~15 m) is shown in Table4.3-2.

At 50 % height level, differences between treatments in ring width were observed from age 13-30 years.

In general, it could be observed that the trees in:

- the ‘extreme’ variant showed the highest growth rate from age 13-30 years.
- the ‘moderate’ and ‘heavy’ variants grew similarly during almost the whole period and, from age 23 onwards, the same as the trees in the ‘without’ one.

These results suggested that positive influences on growth rate following thinnings take longer to be detectable than at trees basis and even then, a more intensive release from competition is needed to result in statistically higher growth rates. However, once a higher growth rate is established, it lasted longer than downwards in the stem.

4.3.1.4 Height level: 75 %

Ring width per thinning variant at 75 % height level (~23 m) is shown in Table4.3-2.

Differences in ring width between treatments were observed from age 18-30 years.

From age 18-21 years all thinned treatments grew in a similar rate. Only from age 22 years the trees in the ‘extreme’ variant showed the highest growth rate and, besides punctual similarity to the trees in the ‘heavy’, its superiority lasted until the end of the rotation.

Trees in the practice oriented variants resembled the growth rate of the stand ‘without’ thinning by the age 26 years.

In general, the pattern observed at the 50 % height level was confirmed. Trees took longer to react to the release from competition at higher levels, partially because they simply did not exist at the moment thinning took place. Nevertheless, along time the enhanced growth rate could be observed upwards in the stem, where thinnings effects persisted, at least, until age 30 years.

4.3.1.5 Graphical overview

The growth rate patterns of each thinning variant are better visualized in graphic form. The ring width of the treatments and at different height are presented in Figure 4.3-1.

In the stand ‘without’ thinning the growth rate at all height levels followed an expected pattern of reaching a peak and decreasing with aging, as a result of increasing competition. Therefore, the growth rate observed in this variant was taken as the basis for relative analysis of the responses to thinning.

The ‘extreme’ variant allowed the trees to grow on higher rates during most of the rotation length. The practice oriented variants, ‘moderate’ and ‘heavy’ showed similar growth rates.

The removal of 2 competitors per potential crop tree in the ‘heavy’ variant resulted in a punctual and slight growth reaction, restricted to age 8 years at the tree basis. During the last decade, the growth rate of the trees in the ‘heavy’ variant resembled the ones in the stand ‘without’ thinning, followed by the trees in the ‘moderate’ and, lastly by the ones in ‘extreme’. The 5th thinning procedure at age 15 years in the ‘moderate’ variant allowed trees to overtake the growth rate of the ‘heavy’ ones, which indicated stands under the ‘heavy’ regime required further density reductions (Figure 4.3-1).

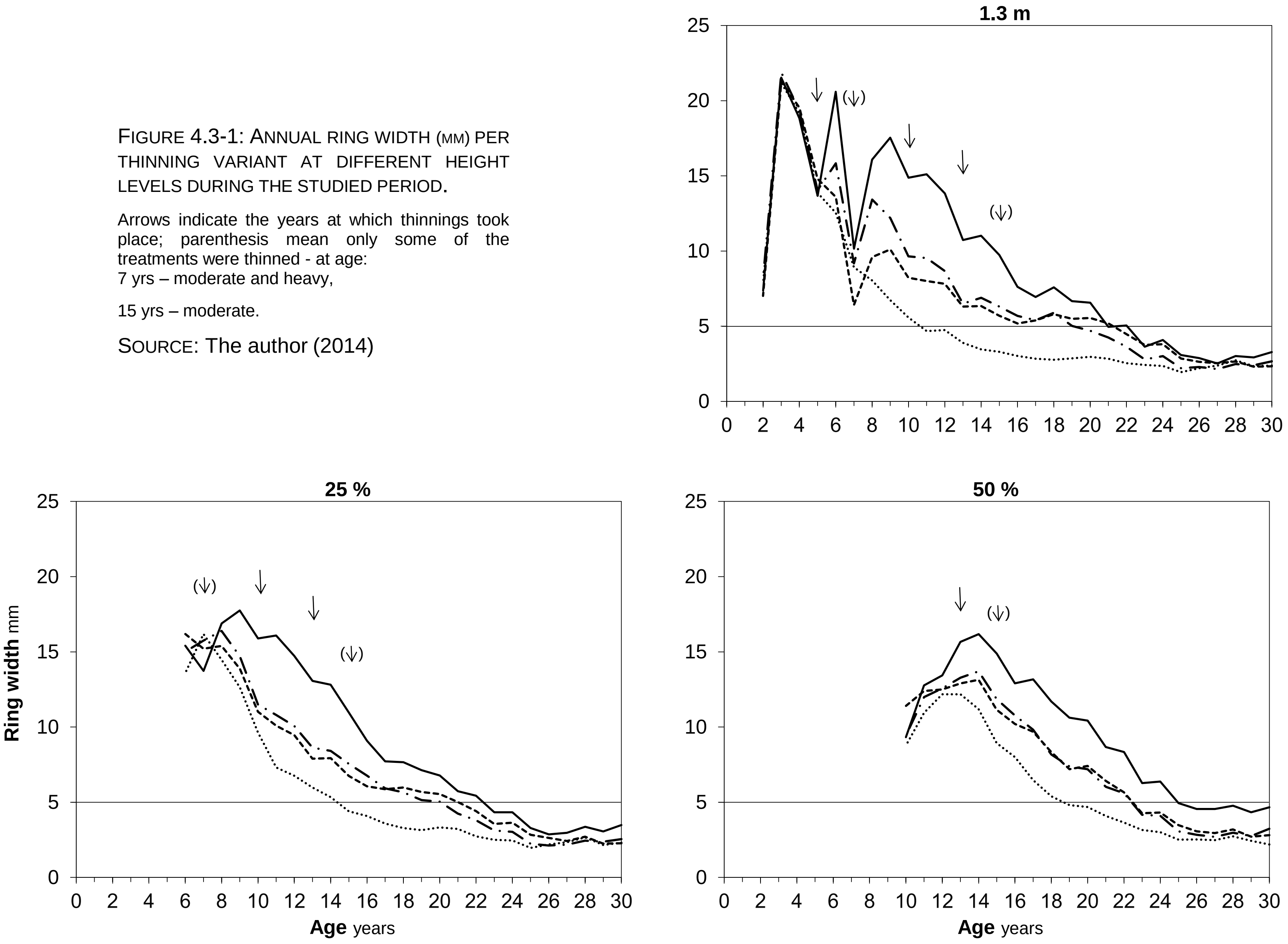
The decrease in the growth rate observed at age 7 years due to the pruning procedure could be clear observed. In fact, a sharply decrease could only be noted for the thinned stands. The reason is that the trees from which the cross-sectional discs were sampled on the thinned treatments were almost totally potential crop trees, the only ones pruned at age 7 years. On the other hand, trees in the area ‘without’ thinning were less than ⅓ ‘pct’s’. As discussed in Chapter 3 STAND DEVELOPMENT, many selected potential crop trees in the unthinned variant lost their dominant position

Figure 4.3-1: Annual ring width (mm) per thinning variant at different height levels during the studied period.

Arrows indicate the years at which thinnings took place; parenthesis mean only some of the treatments were thinned - at age:
7 yrs – moderate and heavy,

15 yrs – moderate.

Source: The author (2014)



or even died.

By analysing only the potential crop trees in the ‘without’ variant, the reduction on growth rate at age 7 years could also be detected.

The negative influences of pruning on the growth rate of the trees in the thinned variants was also detectable at 25 % of the commercial height, and was more evident in the ‘extreme variant.

These results indicated how adverse a wrong pruning procedure can be, negatively affecting the growth rate of selected trees which are rather expected to grow more than the stand average.

4.3.2 Response to thinning: relative values

4.3.2.1 First thinning (age 5 years)

The ring width values of the thinned pines were divided by the value measured in the stand ‘without’ thinning, and thus, expressing a percent thinning response. The values observed in the ‘without’ variant were set as 100 % for comparison purposes.

Results for the 1st thinning procedure at 0.2 m and 1.3 m (dbh) levels are shown in Figure 4.3-2.

FIGURE 4.3-2: GROWTH RESPON-SES (IN %) FOLLOWING THE 1ST THINNING PROCEDURE AT AGE 5 YEARS, AT THE HEIGHT LEVELS OF 0.2 AND 1.3 M

‘x' axis indicate the year in relation to the thinning:

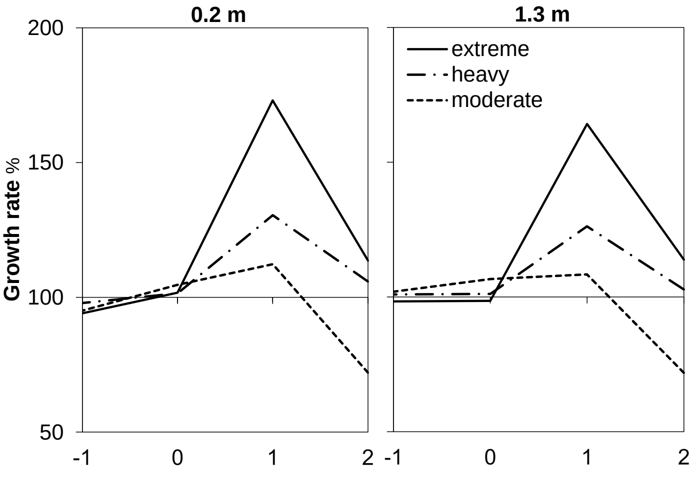
-1: one year previous to thinning

0: year at which thinning was carried out.

1 and **2**: years after thinning.

Values are relative to the one observed in the stand without thinning, 100 %.

SOURCE: The author (2014)



Results suggested that trees submitted to more intense thinning were more ‘resistant’ to the reduction of green crown. Trees which were totally released from competition (‘extreme’) may formed bigger crowns in the year that followed thinning, and thus resulting in a greater photossinteticaly active area after the pruning procedure.

For clarity purposes, the following figures kept the relative responses of the 0.2 m level out. Although always higher than the ones verified in the 1.3 m level, they are commonly residues from an industrial point of view and were considered superfluous for the following analysis.

4.3.2.2 Second thinning (age 7 years)

The relative responses for the 2nd thinning procedure, at age 7 years, are shown in the Figure 4.3-3.

For the 2nd thinning, it is important to note that the growth rate previous to thinning was still being influenced by the 1st intervention. Actually, as mentioned, the analyses regarding response to thinnings are, in fact, a cumulative influence considering the previous thinning procedures rather than isolated effects.

FIGURE 4.3-3: GROWTH RESPONSES (IN %) FOLLOWING THE 2ND THINNING PROCEDURE AT AGE 7 YEARS, FOR THE HEIGHT LEVELS DBH AND 25 % OF COMMERCIAL HEIGHT (~8 M)

The ‘extreme’ variant is shown in grey because it did not receive thinning at age 7 years.

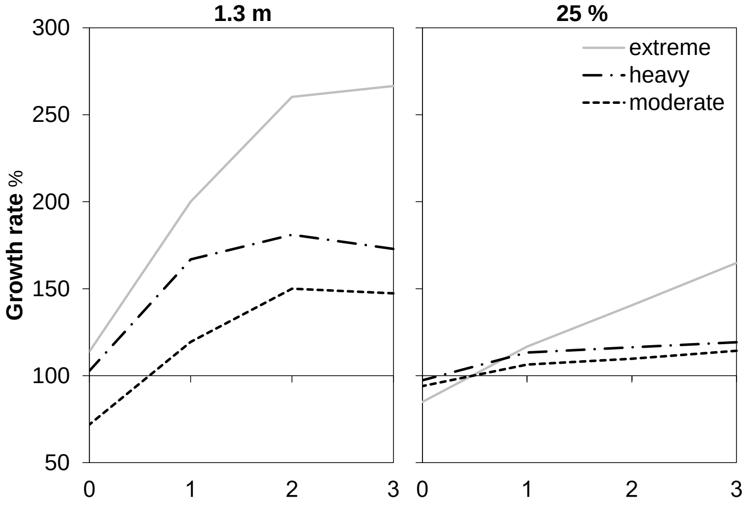
‘x' axis indicate the year in relation to the thinning:

0: year at which thinning was carried out.

1, 2 and 3: years after thinning.

Values are relative to the one observed in the stand without thinning, 100 %.

SOURCE: The author (2014)



The ‘**extreme**’ variant was shown to demonstrate that even without another thinning at age 7 years, the release from competition delivered by the 1st one was enough to keep a substantially higher growth rate in comparison to the others, reaching values 100 % greater than the practice oriented variants (‘heavy’ and ‘moderate’) and 150 % greater than the unthinned one.

The results clearly demonstrated that the growth response after thinning was concentrated at tree basis (1.3 m), where values over the control were much higher. However, a constant increase trend can be noted for the ‘extreme’ variant at 25 % level.

From Figure 4.3-3 it can also be observed that, at 1.3 m level and 3 years after the 2nd thinning, trees started showing a level off effect in the growth rate. On the other hand, as mentioned, at 25 % level the growth rate, although in a small scale, still increased prominently on the ‘extreme’ variant.

4.3.2.3 Third thinning (age 10 years)

The results obtained for the 3rd thinning are shown in Figure 4.3-4.

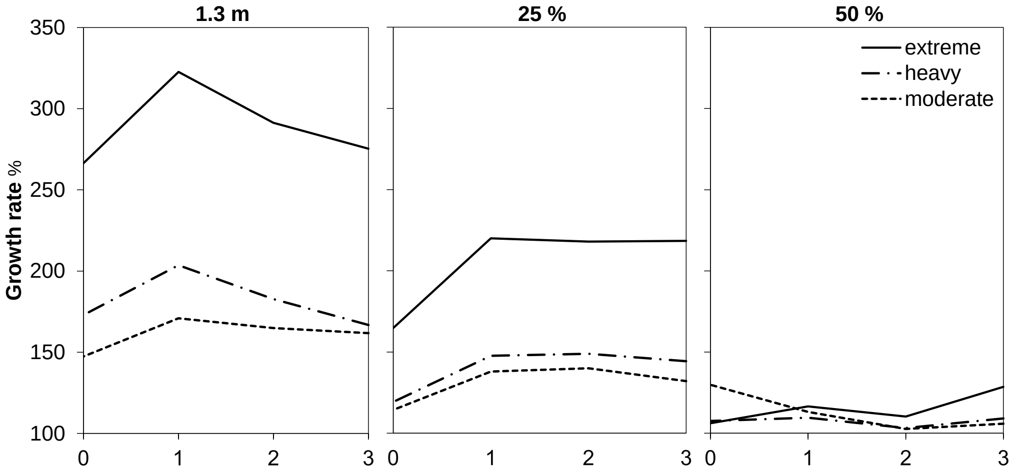


FIGURE 4.3-4: GROWTH RESPONSES (IN %) FOLLOWING THE 3RD THINNING PROCEDURE AT AGE 10 YEARS, FOR THE HEIGHT LEVELS 1.3 M, 25 AND 50 % OF COMMERCIAL HEIGHT

‘x' axis indicate the year in relation to the thinning:

0: year at which thinning was carried out.

1, 2 and 3: years after thinning.

Values are relative to the one observed in the stand without thinning, 100 %.

SOURCE: The author (2014)

From Figure 4.3-4 it can be seen once again how more intense were the responses to thinning at tree basis in relation to higher heights.

At 1.3 m level, trees in the ‘extreme’ variant reached growth rates 3 times higher than the ones observed in the stand ‘without’ thinning. While, at 25 % of the commercial height level (~8 m) the growth of the trees submitted to the ‘extreme’ treatment was only 2 times higher. Still, at 50 % level (~15 m) there was only a slightly increase (~20 % during the 3 years following thinning).

A similar pattern with lower magnitudes was verified for the practice oriented variants, ‘moderate’ and ‘heavy’. However, at 50 % height level, tree in the ‘moderate’ variant showed even a growth decrease after the 3rd thinning.

Another interesting aspect is that, at age 10 years, trees were certainly facing some competition in all thinned treatments, which is surprising especially for the ‘extreme’ variant with only 400 trees ha^{-1} before thinning.

Increases in the growth rate were observed immediately after the 3rd thinning. However, at the 1.3 m level, the positive effect of thinning on growth rate lasted only 1 year. 3 years after this thinning, trees were growing at a similar previous-to-thinning rate, which was already high because of the cumulative effect of the previous thinnings.

Although the responses at 25 % level were lower than the ones at 1.3 m, at 25 % thinning positive effects on growth rate lasted longer than on 1.3 m level. Trees reached the 3rd year after thinning with substantially higher grow rates in comparison to the previous-to-thinning one.

4.3.2.4 Fourth thinning (age 13 years)

The responses after the 4th thinning are shown in Figure 4.3-5.

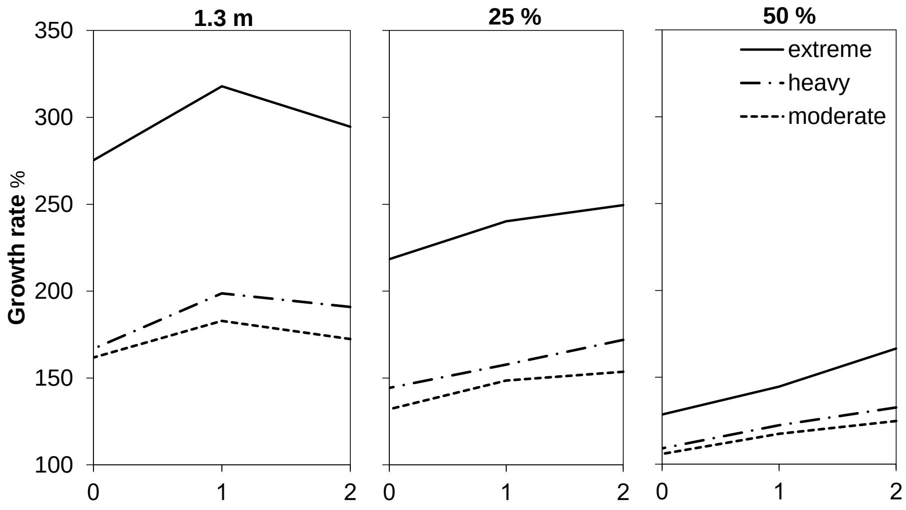


FIGURE 4.3-5: GROWTH RESPONSES (IN %) FOLLOWING THE 4ND THINNING PROCEDURE AT AGE 13 YEARS, FOR THE HEIGHT LEVELS DBH, 25 AND 50 %

‘x’ axis indicate the year in relation to the thinning:

0: year at which thinning was carried out.

1, **2** and **3**: years after thinning.

Values are relative to the one observed in the stand without thinning, 100 %.

SOURCE: The author (2014)

In Figure 4.3-5, very similar patterns in comparison to the Figure 4.3-4 (3rd thinning) can be seen. The response 1 year after the thinning was again clear, even on the 'extreme' variant, which kept the 3-fold superiority in relation to the unthinned area.

Growth responses at the 50 % level turned clearer and more expressive in comparison to the 3rd thinning at age 10 years. However, the higher the height level, the lower the relative response, just as previously verified.

The trend of a long-lasting effect upwards on the stem was reinforced.

4.3.2.5 Fifth thinning (age 15 years)

The results obtained for the 5th thinning at age 15 years are shown in Figure 4.3-6.

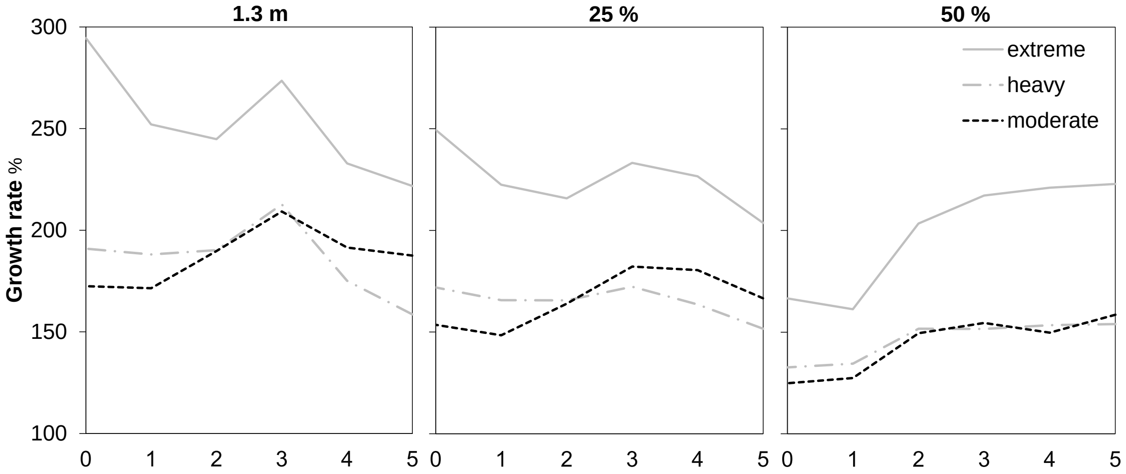


FIGURE 4.3-6: GROWTH RESPONSES (IN %) FOLLOWING THE 5ND THINNING PROCEDURE AT AGE 15 YEARS, FOR THE HEIGHT LEVELS DBH, 25 AND 50 %

The 'extreme' and 'heavy' variants are shown in grey because they did not receive thinning at age 15 years.

'x' axis indicate the year in relation to the thinning:

0: year at which thinning was carried out.

1, 2, 3, 4 and 5: years after thinning.

Values are relative to the one observed in the stand without thinning, 100 %.

SOURCE: The author (2014)

Because no thinning was done after age 15 years, the analysis of the 5th thinning could be extended: 5 years after thinning was evaluated, till age 20 years.

The 'moderate' variant was the only one on which a 5th thinning was carried out. On this treatment, differently from the previous thinning procedures, the growth rate increased only 2-3 years after thinning.

The positive effect of thinning lasted for:

- 3 years at dbh level,
- 3-4 years at 25 %, and
- at least 5 years at 50 %.

Following the 5th thinning, trees in the ‘moderate’ and after 3-4 years, trees on this variant overtook the growth rate of the trees in ‘heavy’ at 1.3 m and 25 % levels.

Treatment ‘extreme’ continued to grow at the proportional highest rate. A decreasing trend was observed for the ‘extreme’ and ‘heavy’ variants. Both treatments showed a peak at age 18 years more or less simultaneously to ‘moderate’, although no thinning procedures were carried out age 13 years. It is presumed that meteorological conditions might have favoured the growth of all trees, disregard of thinning intensity, which might have favoured the ‘moderate’ variant too.

In general, it could also be noted that the relative growth rate of the different height levels were on a more similar amplitude than on the previous thinnings.

4.3.2.6 Relative growth during the 21-30-years period

The growth rate of the trees during the period 21-30 years was strongly affected by the thinning intensities to which they were subjected at the first half of the rotation period. The relative growth rate of the trees in the last studied decade is shown in Figure 4.3-7.

From Figure 4.3-7 it can be seen that:

- At 1.3 m level, trees subjected to the ‘extreme’ thinnings kept a growth rate similar to the one observed in the ‘moderate’ variant, both ~50 % higher than the stand ‘heavy’, and this until age 25 years. At age 27-28 years, trees in the ‘extreme’ and ‘moderate’ resembled the growth rate of the control area, ‘without’ thinning, while the ones in ‘heavy’ grew even less. An increase on the growth rate was observed in the ‘extreme’ and ‘heavy’ variants at the end of the rotation period.
- At 25 % level, there was a clear segregation between thinning variants. Trees in the ‘extreme’ grew on a higher level the whole period, followed by the individuals in ‘moderate’. Tree growth in all thinned variants showed a general decreasing trend, more evident on the practice oriented ones.

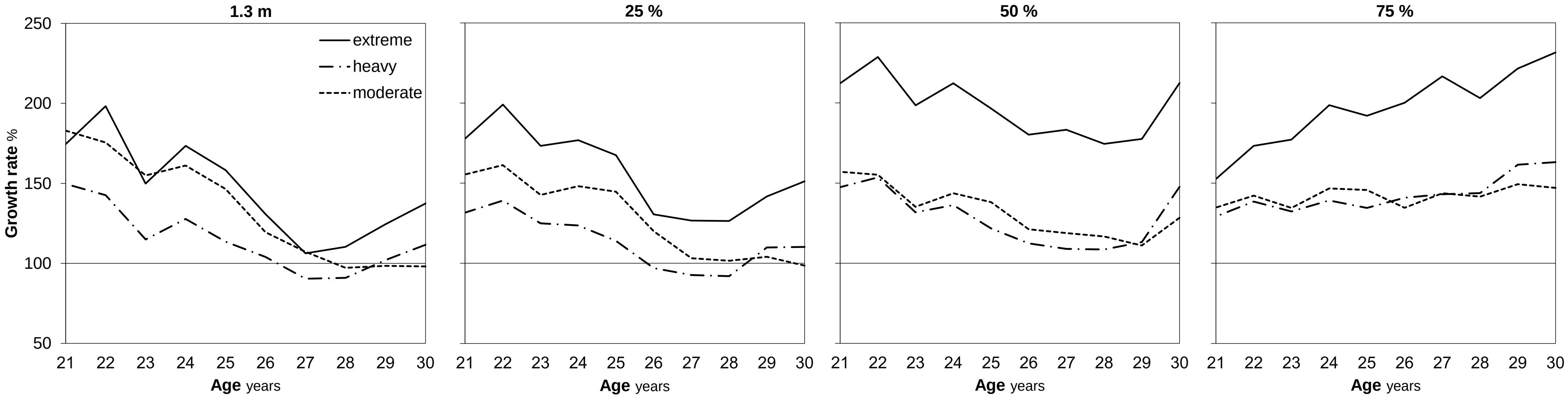


FIGURE 4.3-7: GROWTH RATE (%) DURING THE LAST DECADE OF THE ROTATION (AGES 21-30 YEARS), FOR THE HEIGHT LEVELS DBH, 25, 50 AND 75 % OF THE COMMERCIAL HEIGHT

Values are relative to the one observed in the stand without thinning, 100 %.

SOURCE: The author (2014)

- Differently to the pattern verified sooner in the rotation, during the period 21-30 years the growth rate at 50 % level was substantially higher than at tree basis in the ‘extreme’ variant.
- At 75 % level, which corresponded to ~23 m height, the trend of higher growth rate level with increasing height was reinforced, and this, for all thinned variants, although still more expressive for the ‘extreme’ one. Trees on the ‘extreme’ variant reached the age 30 years growing more than twice as much than the trees on the stand ‘without’ thinning. The same for the practice oriented treatments, in which trees reached age 30 years growing 50 % more than the ones in control.

Altogether the results indicate that the more tapered form achieved by the trees in the ‘extreme’ variant at the first half of the rotation decrease with time.

4.3.3 Response to thinning of different diameter classes

The evaluation of the growth responses to thinning showed that trees reacted most intensively at stem basis.

Therefore, the ‘diameter class’ analysis was focused at dbh level (1.3 m above ground).

In order to understand how different trees react to thinnings, individuals were classified according to their diameters at age 30 years in small-, medium- and big-sized classes. It is important to note that a big-sized tree in the ‘extreme’ variant (Ø 65-76 cm) had a substantially bigger diameter than a big- in the ‘without’ one (48-53 cm) and thus, comparisons between treatment need to be carefully taken.

However, considering one thinning variant was chosen and used in a loblolly pine stand, an analysis regarding diameter classes provides information for the silviculturist to known, for example:

- When trees differentiate into diameter classes during the rotation period.
- How trees that belongs to an specific diameter classes grow among the rotation.
- How is the response of trees in the different diameter classes to thinning.

The growth rate at 1.3 m level of the different diameter classes per thinning variant is shown in Figure4.3-8.

It was observed that trees in stands subjected to:

- ‘without’ and ‘heavy’ thinnings grew in a consistent growth pattern in relation to the different diameter classes: big-sized trees had the highest growth rate until the end of the rotation period (30 years).
- On the other hand, in the ‘moderate’ variant, big-sized trees resembled the growth rate verified in the medium-sized ones by the age 24 years.
- Because of the ‘extreme’ intensity of the thinning in this treatment, there was lower variability in the growth rate between diameter classes in comparison to the other variants, even than dbh values oscillated from 47-70 cm at age 30 years. The fact that trees of different diameter class grew similarly in the ‘extreme’ variant might be due to the presence of dominant individuals only.

Big-sized trees

Of more interest are the big-sized trees, which are the most valuable ones, since they are used on the production of high-value products. Moreover, between diameter classes, the ‘big-sized’ one is the most comparable among thinning variants. Although of different dimensions, only dominant trees were regarded.

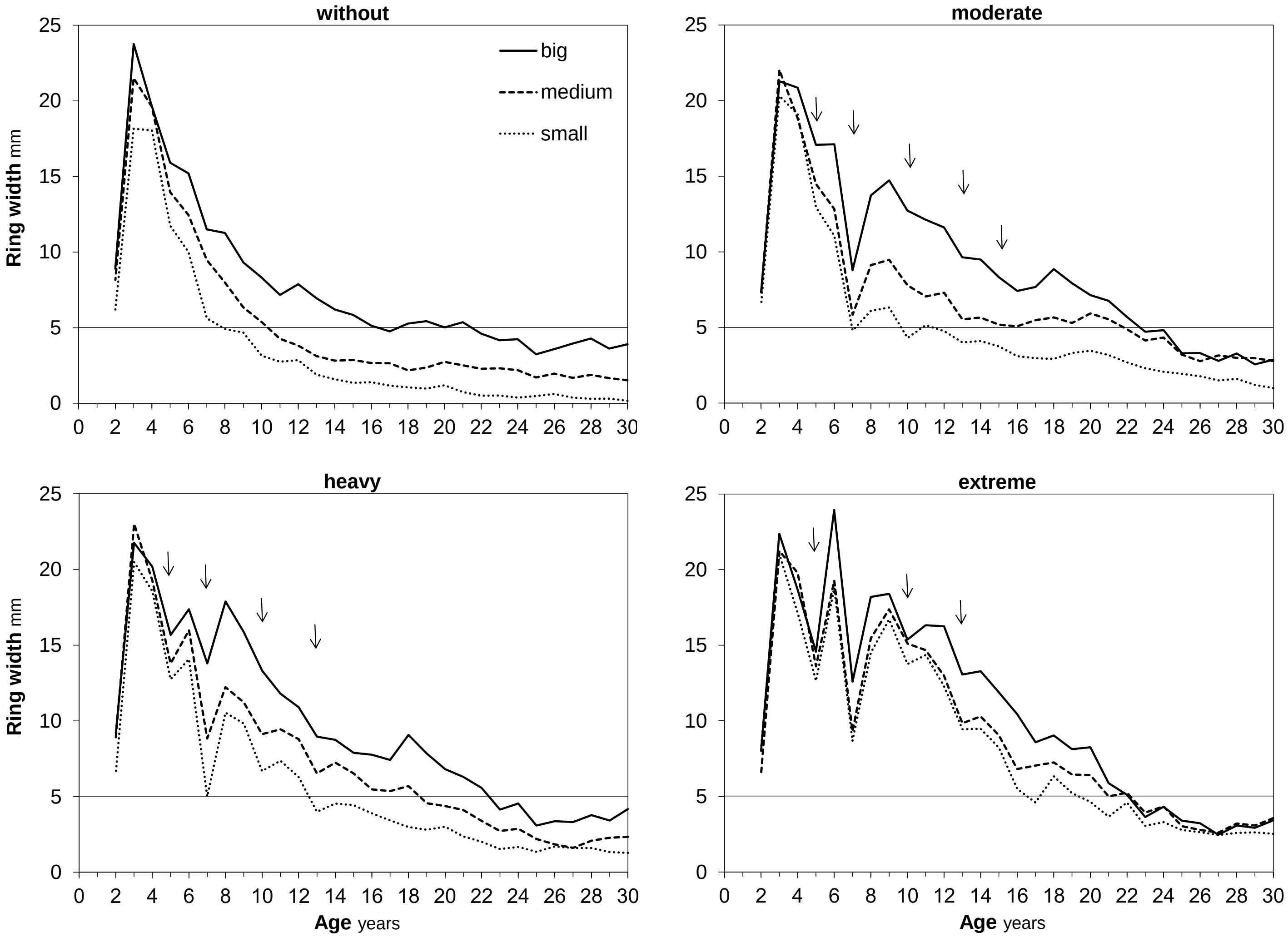
In general, big-sized trees:

- were already big-sized at early ages. In the area ‘without’ thinning, substantial differences were clear at age 4 years;
- grew similarly in all treatments, including a decrease in growth rate at age 7 years, when thinnings were carried out and remarkably affected their development;
- when released from the competition of 1 competitor tree (‘moderate’), only maintained the growth level previous to the 1st thinning, at age 5 years;
- when released from competition 2 competitor trees (‘heavy’), increased the growth rate in 10 %.
- when totally released from competition (‘extreme’), immediately increased the growth rate in 50 %.

FIGURE 4.3-8: ANNUAL RING WIDTH (MM) PER DIAMETER CLASS AND THINNING VARIANT AT 1.3 M LEVEL.

Arrows indicate the years at which thinnings took place.

SOURCE: The author (2014)



For comparison reasons, the growth development only of the big-sized trees in the different thinning variants are shown together in Figure 4.3-9

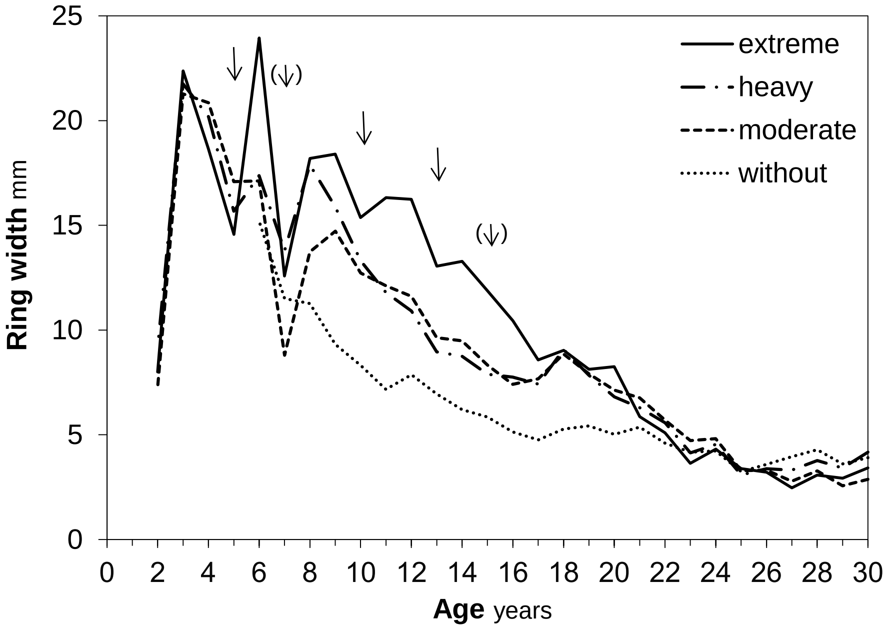


FIGURE 4.3-9: ANNUAL RING WIDTH (MM) OF THE BIG-SIZED TREES WITHIN EACH THINNING VARIANT AT 1.3 M LEVEL

Arrows indicate the years at which thinnings took place; parenthesis mean only some of the treatments were thinned - at age:
7 yrs – moderate and heavy,
15 yrs – moderate.

SOURCE: The author (2014)

From Figure 4.3-9 it can be seen that big sized trees showed a similar growth patter until age 5 years. Immediately after the experiment establishment, when trees were differently released from competition the growth rate between treatments remarkably differed, especially in the ‘extreme’ variant.

Even when only big-sized individual were regarded, there were a substantial difference between thinning variants. Big trees in the ‘extreme’ were higher than any other and reached a remarkable current increment of almost 5 cm in diameter at age 6 years.

The superiority on growth rate of the big-sized trees by removing 2 competitor trees per potential crop trees lasted only 2-3 years over the removal of 1 competitor. From age 9 years onwards, big-sized trees under the ‘heavy’ and ‘moderate’ conditions grew in a similar rate.

The growth rate of the big-sized trees in the thinned variants related to the growth of the trees in the unthinned stand (‘without’ = 100) is shown in Figure 4.3-10.

According to Figure 4.3-10 it can be concluded that big-sized trees subjected to thinning, regardless of intensity, showed a growth rate over the stand without thinning between ages 6-23 years. During this period the ‘extreme’ variant improved the current growth rate of the big-sized trees up to 2-times compared to the stand without thinning, and this during ~5 years. While the practice oriented variants, ‘moderate’ and ‘heavy’, increased the growth rate up to 50 %.

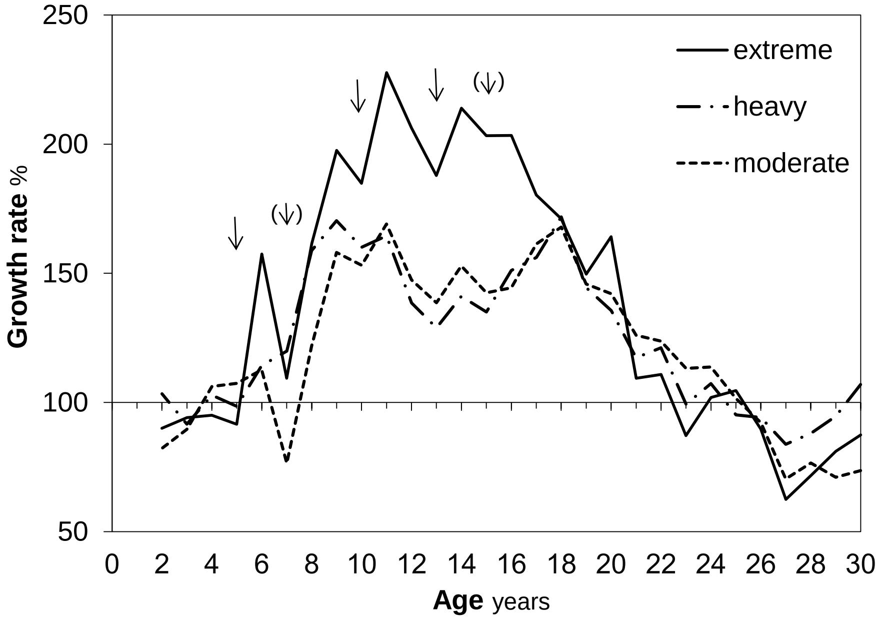


FIGURE 4.3-10: GROWTH RATE (%) OF THE BIG-SIZED TREES AT 1.3 M LEVEL PER THINNING VARIANT AND DURING THE 30 YEARS PERIOD.

Arrows indicate the years at which thinnings took place; parenthesis mean only some of the treatments were thinned - at age:
7 yrs – moderate and heavy,
15 yrs – moderate.

SOURCE: The author (2014)

Once more, the negative effect of pruning at age 7 years was clearly demonstrated for the ‘moderate’ and ‘extreme’ variants. However, for the ‘heavy’ one, it was verified that the trees were capable to maintain its growth rate in a constant level compared to the trees in the ‘without’ one. Nevertheless it still meant a growth reduction in absolute terms.

The greatest growth response to thinning was found on the ‘extreme’ variant at the 1st intervention, when trees were 5 years old.

Although trees in the ‘extreme’ variant did not face any apparent competition after the 1st thinning, when only 400 individuals ha^{-1} remained, there were substantial growth increases of the big-sized individuals after the thinning procedures at ages 10 and 13 years. The increase was clearer in relative terms, than in absolute, because trees in the stand ‘without’ thinning grew continuously slower until age ~25 years.

4.4 DISCUSSION

4.4.1 Growth rate as affected by thinnings

Tree growth rates previous to thinning (age 2-5 years) were similar between stands, which provided confidence in interpreting the growth-rate differences due to thinnings.

Maximum current growth was observed at age 3 years (21.5 mm, Table 4.3-1), reinforcing the pioneer and initial-fast-grown of loblolly pine trees. After this age, growth rate decreased, probably due to some level of competition between trees. The only exception was the ‘big-sized’ individuals in the ‘extreme’ variant, in which the maximum current growth was verified at age 6 years (23.9 mm, Figure 4.3-9), following the first thinning procedure.

Hence, the 2,500 trees ha^{-1} of initial density is not optimal for favouring individual tree growth. In fact, this density is no longer regarded in southern Brazil, where 1,600 tree ha^{-1} are now standard.

Increases in annual growth ring width following thinning at age 5 years showed that, already at this age, trees were growing under a certain level of competition, which was released after thinning. In fact, it is known that diameter and crown ratio development of loblolly pine trees are soon and significantly affected after planting (ZHANG *et al*., 1996).

The decline in stand growth rate near canopy closure is, according to Binkley (2004), driven by decreasing efficiency in using site resources by non-dominant individuals, lowering the overall stand growth.

At age 7 years, the growth rate of trees in all thinning variants sharply decreased, and no differences between them were detected. Although decreases in growth rate might occur after intense environment changes, such as the one caused by heavy thinnings and called ‘thinning shock’ (JACOBSON *et al.,* 2000; DEBELL *et al.,* 2002), this was not the case in the present study because trees positively reacted to thinnings already at the first year after them. The only plausible reason to this growth reduction is a pruning procedure, carried out at age 7 years, when all potential crop trees were pruned up to 6 m height (lift from 2.5-6.0 m). The average stand height at that age was ~11 m (Chapter 3, Table 3.3-4).

Although the remaining crown length was bigger than the minimum 3-4 m recommended by Seitz (2000) for loblolly pine in southern Brazil, the pruning procedure might do have affected diameter growth. The branches on the crown basis were favoured by thinnings, reaching big diameter and length, especially in the 'extreme' variant. By removing them, it is supposed that a proportionally great reduction in the photosynthetic area might followed. Moreover, reductions in diameter growth following pruning of green branches have been widely reported in the literature (SCHNEIDER *et al.,* 1999; COSTAS *et al.,* 2002; HOPPE; FREDDO, 2003; NEILSEN; PINKARD, 2003; PEREIRA; AHRENS, 2003).

Growth rate differences were detected immediately after thinning, being the higher the more competitors were removed – i.e. more growing space provided for each one of the selected potential crop trees. Responses to thinning were observed firstly at tree basis.

Earlier studies also verified a growth increase near the stem base immediately after thinning (MANN; LOHREY, 1974; SHEPHERD, 1986; VALINGER, 1992; SMITH *et al.,* 1997; TASISSA; BURKHART, 1997; PUKKALA *et al.,* 1998; PELTOLA *et al.,* 2002; BURSCHEL; HUSS, 2003; BROCKLEY, 2005; ANDRADE *et al.,* 2007; SCHNEIDER *et al.,* 2008; PEREZ-DE-LIS *et al.,* 2011; GOUDIABY *et al.,* 2012).

- Andrade *et al.* (2007) studied the growth at different heights of the stem of dominant and intermediate loblolly pine trees planted in southern Brazil and subjected to thinnings from below. The authors concluded that trees growing under high competition levels, as a result of growth and aging, dislocate their maxima growth rates upwards in the stem, to around ~50 % of the total height. As soon as the competition between trees is reduced, through thinnings for instance, the growth rate at tree basis became the highest again.
- Tassissa and Burkhard (1997) evaluated loblolly pine trees growing in a thinning trial in southeast United States. Stands were thinned at age 12-14 years, when basal area was reduced to 70 and 50 % of the previous value. Similar to the present study,

growth responses after thinning were substantial at tree basis, while, at greater stem heights, influences tended to last longer. The authors reported that

  - effects during the first 3-year period after thinning were detected only near the stem base. No differences between thinning intensities were detected.
  - during the period 4-9 years after thinning, differences between heavily and lightly thinned stands were significant over most of the stem.
  - During the last 3 years (9-12 years), while differences between thinned and unthinned stands remained significant, the difference between the growth rate of trees in the different thinning variants tended to be lower, with significant differences mainly occurring in the upper stem parts.

- Peltola *et al.* (2002) analysed the effects of the first thinning on the diameter growth distribution along the stems of *Pinus sylvestris* L. at heights of 1.3 (dbh), 4, 6 and 8 m. Stands were natural regenerated on a rather poor nutrient supply site. Thinnings were from below, and the remaining densities varied between 575-3,400 trees ha^{-1}. The authors observed that during the:
  - first 3 years after thinning an increase in the diameter growth was detected only at the tree basis (1.3 m).
  - period between 4-6 years after thinning, the diameter growth response to thinning was significant up to a height of 6 m on the stem, except in the lightly thinned plots, which did not differ from the unthinned ones.
  - period between 7-9 years after thinning, the mean diameter growth differed in all stands, except between the 2 sparsest variants at a height of 8 m. During this period, the diameter growth response to thinning was at its maximum at 1.3, 4 and 6 m, indicating there is a ~8 years period between thinning and the maximum response.

Different to the present study, Peltola *et al.* (2002) observed a reduction on tree growth following thinning at 8 m height. In the present study, instead, and also at 8 m height, trees did take 1-2 years longer to response to thinnings in comparison to 1.3 m level. However, once they started, the growth rate increased consistently, being the higher the more intense the thinning procedure. Nevertheless, this or a very similar pattern was verified at 50 and 75 % height level, 15 and 23 m, respectively. The first year at which growth ring were present at these height levels had a slight lower growth rate than trees in the stand ‘without’ thinning, being the lower the more intense the thinning. Still, the differences in absolute responses between thinning variants took also longer to be detected, which indicate, at least, that thinnings had no influences during the first following years.

- Another study of trees response after thinnings from below were reported by Perez-de-Lis *et al.* (2011). The authors studied even aged plantations of *Pinus canariensis* Sweet ex Spreng. In Tenerife Island, Spain. Stands were 35 years old when 20-30 % and 40 % basal area was removed, light and moderate variants, respectively. After 10 years, stands were similarly thinned once again. The results showed that only the most intense thinning treatment was able to induce an evident growth increase, which corroborate the lower effects of thinnings from below on individual trees growth of remained trees.
- Plauborg (2004) reported very limited enhancement of radial growth of *P. sylvestris* trees after thinning, planted in Denmark. Stands were thinned from below from an initial basal area of ~25 m^2 ha^{-1} to 85, 70 and 55 % of residual ones. According to the author, the reason why trees did not react was a weak competition between trees previous to thinning, so that tree growth was no being limited.
- Ruano *et al*. (2013) observed differences on the diameter of trees in thinned and unthinned stands only 5 years after thinning. The authors studied the effects of pre-commercial thinnings applied in 2 m height and naturally regenerated *Pinus halapenses* Mill. stands in Spain. Annual radial growth reached its peak by 20 mm, 3 years after thinning, while tree in unthinned stands reached the maximum of 5.6 mm.

It has been showed that tree growth following thinning was concentrated at tree basis. Beside this, the optimal growing condition in southern Brazil seemed to stimulate growth upwards in the stem in a more intensive way than the ones observed in several studies in Europe and North America. Nevertheless, releasing trees from competition resulted in more tapered stems. Which is in line with previous studies (SHEPHERD, 1986; BARBOUR, 1992; TASISSA; BURKHART, 1997, 1998a; ANDRADE *et al.,* 2007; PELTOLA *et al.,* 2002).

However, Arbaugh and Peterson (1993) observed that young *Pinus ponderosa* P. & C in United States significantly increased the wood production also in the upper bole after release from competition, which is in line with the results found in the present study.

One practical consequence of this is that traditional forest inventory, in which dbh (1.3 m) is measured in permanent plots tend to overestimate the volume increment after thinning when one single volume or taper function is used. In final analysis, not including thinning effects could lead to biases in tree volume predictions, just as addressed by Weiskittel *et al.* (2009). The authors reported that the current volume equation regarded in their study area, Maine, U.S., led to overestimations in volume of ~12 %, exactly by ignoring that thinning increase growth rate mainly at tree basis.

Differently, Guiterman *et al.* (2011) concluded that low densities management established due to heavy crown thinnings in *P. strobus* in the United States produced less tapered but logs than moderate thinnings did (first 5 m from tree basis).

Anyhow, further studies are needed in order to determine if annual volume increment is being over- or underestimated due to periodic measurement of permanent plots in the thinned loblolly pine plantations in southern Brazil.

4.4.2 Response to thinning: relative values

In the stands 'without' thinning, the diameter growth decreased as a function of aging at all height levels. Thus, the growth rate of trees in this variant was considered the normal development of the trees in an increasing competitive environment. The values measured in the thinned stands were than divided by the one observed in the 'without' at the same age and diameter class, thus, the relative growth increase as affected by thinning was assessed.

The 1st thinning procedure immediately increased the radial growth of the trees at 1.3 m level in about 160, 130 and 110 % in the 'extreme', 'heavy' and 'moderate' variants, respectively. Later on, following thinnings were applied to the stands. And the responses to thinning should regard this cumulative effect, rather than insolate ones. Further, expressive relative responses to thinning were observed on the trees subjected to the 'extreme' condition, over 300 % at ages 11 and 14 years, immediately after thinnings and even without an apparent competition between potential crop trees (Figure 4.3-4). The relative responses to thinning became higher at higher height levels with time, which was especially true for the 'extreme' variant.

- Peltola *et al.* (2002) reported lower relative responses to thinning, but similar trends for natural regenerated *P. sylvestris* stands in Finland. According to the authors, the highest relative thinning response was recorded in the diameter growth of trees subjected to the most heavily thinned plots and at 1.3 m level (155 %). On the other hand, no response to thinning was observed at 8 m height. Later on, however, and during the period 9-12 years after thinning, most of the differences between the thinned and unthinned plots remained significant, although the thinning response started to diminish, except at 6 and 8 m in the heavily thinned plots, where it still increased.

4.4.3 Response to thinning of different diameter classes

Crown thinning is focused only on the selected potential crop trees, being all others ignored. However, after several thinning procedures during the first half of the rotation period, intermediate and supressed trees were also removed. Hence, the growth responses of supressed or even intermediate trees could not be evaluated on the thinned stands. The following analysis are basically related to dominant trees.

It has been verified that the biggest trees at age 30 years were big individuals since early ages (3-5 years). However, some of the biggest trees at early ages lost their dominancy with stand aging.

Growth dominance is defined as the difference in relative growth between distinct tree sizes (TSCHIEDER *et al*., 2012). The same authors analysed the growth dominance of loblolly pine stands from 21 years of growth records obtained in a thinning experiment located in Missiones, Argentina. The initial density of the stands was ~1,750 trees ha^{-1}. Thinnings from below were applied since age 5 years, being repeated every 6 years, leaving a post-thinning residual basal area equivalent to 66 % of unthinned plots at the same age. The authors reported

- a continuously growth dominance increase with age, suggesting that larger trees accounted for an increasing proportion of the stand growth;
- the relative contribution of trees to stand growth would remain always proportional to tree size or would slightly increase in bigger trees.

Results observed in this study suggested that the maximum individual growth of dominant loblolly pine trees can only be achieved by very low stocking levels, and this from early ages:

(1) 400 trees ha^{-1} at age 5 years,

(2) 300 trees ha^{-1} at age 10 years,

(3) 200 trees ha^{-1} at age 13 years.

This stocking schedule, applied to the ‘extreme’ variant, was enough for delivering the same amount of wood as unthinned stands, at age 16 years or even earlier, which indicate the growing space was fully utilized.

Altogether, these results might help answering the questions proposed by Binkley *et al.* (2013):

- ‘how much space does a dominant tree need?’ and, complementarily
- ‘how many dominant, efficient trees can fit into a hectare?’

In general it could be concluded that big-sized trees reacted more to thinning and this in a long lasting way, both in absolute and relative terms, than medium and small-sized did. Moreover, the responses to thinning were higher the more growing space was delivered per potential crop tree. Similar results were also reported by:

- Makinen and Isomaki (2004) studied *P. sylvestris* stands, established mainly in early 1970 due to natural regeneration in Finland. The author evaluated the trees response to thinnings from below up to 42 % basal area removal. The results showed that the absolute effect of thinning on basal area increment was highest in the largest diameter classes, i.e. the smaller trees could not react in absolute terms to the increasing growing space as strongly as the larger ones which is in line with the present study. Another interesting conclusion of was that, in general, trees on lower site fertility could not utilise the free growing space as efficiently as the trees on higher site fertility. This is particularly important because the present study was conducted in a high productive site, which might also explain the remarkably response of trees to thinning.
- Goudiaby *et al.* (2012) studied the vertical growth of dominant *Pinus banksiana* Lamb. and *Picea mariana* (Mill.) B.S.P. trees after thinnings from below, in which relative basal area removal varied between 6-70 %. The authors reported that basal area removal had a significant positive effect on annual stem volume increment and

started 3-4 years after thinning for both species. Still, they observed that differences in growth pattern between control and thinned stands were still apparent 6 years after thinning, but limited to sections between 0-10 m in height.

- Pukkala *et al.* (1998) pointed out that dominant *P. sylvestris* trees with large crowns showed a minimal relative response to thinning from below. On the other hand, relatively greater response were observed in suppressed trees, which differ from the finding in the present study. However, the authors concluded that, in absolute terms, dominant trees increased their diameter growth more than did suppressed trees, and that the dominant trees showed a long lasting positive effect on growth rate after thinning, more than small-sized trees did.

Peltola *et al.* (2002), studying *P. sylvestris* in Finland, pointed out that largest trees had the highest diameter growth after thinning, and the growth was greater the more intense the thinning from below. Still, the absolute and relative thinning response over a 12-year post-thinning period was higher the more intensive the thinning was, regardless of tree size. However, it was observed that, in relative terms, the small trees on heavily or moderately thinned plots responded more rapidly and more strongly than the medium-sized or large trees over the whole stem, which is different from the observation made in the present study. It is important to note, however, that the thinning methods analysed by Peltola *et al.* (2002) were pre-commercial ones, which differ substantially from the crown thinnings applied in the present study.

Perez-de-Liz *et al.* (2011) also observed that co-dominant trees benefited most from thinning, followed by the dominant individuals. According to the authors, this behaviour can be explained by a lower effect of thinning from below on dominant crown classes.

Differently from the above cited studies, the results obtained in the present study showed that dominant trees not only grew better than other individuals, but were remarkably and positively affected by the crown thinnings. The increases observed in growth rate of dominant trees, even when no apparent competition was observed (Figure 4.3-10, age 10 and 13 yrs.) indicated that the maximum growth of individuals might be affected not only by a fully light availability.

Contradictions might be due to the completely differences environment conditions, which is certainly responsible for the huge distinction of growth scale.

Nevertheless, the distinct types of thinning may be the mainly reason for different conclusions about response to thinning of trees from different diameter classes.

Because dominant and co-dominant trees have the best growing conditions and physiologically more efficient crowns, they already show a higher individual growth rate than the suppressed and intermediate trees (TASISSA; BURKHART, 1997; PELTOLA *et al.,* 2002; BINKLEY *et al.,* 2013), being no or little favoured by thinnings from below.

In fact, Bradford *et al.* (2010) studying the influences of either thinnings from above or below in *Pinus resinosa* Ait. in Minnesota, U.S., concluded that the type of thinning affected trees of distinct diameter classes in a different way. The authors evaluated thinning intensities which varied from 7-35 m² ha^{-1} of residual basal area, while unthinned stands were ~50 m² ha^{-1}. Residual basal area were reached either by removing the dominant and co-dominant trees in order to favour residual trees within the same crown classes (from above), or by removing the smallest trees (from below). Similarly, and related to the same experiment, Bradford *et al.* (2009) reported that the thinning from above used in the experiment was operationally, if not conceptually, a crown thinning. The narrow range of diameters within the stand dictated that the thinning resulted in increased growing space for other dominant and co-dominant trees, rather than release of suppressed or intermediate trees, as would occur in a true thinning from above or dominant thinning. Thinnings started at age 45 years and were repeated in 10-years intervals. The authors

- found that the application of crown thinning is most effective at promoting the growth of dominant individuals at younger ages, whereas the other thinnings methods maintain similar levels of growth across size classes independent of age,
- concluded that these results have particular relevance to the effectiveness of crown thinning at promoting the growth of larger diameter tree over time. Nonetheless, the positive growth dominance created by thinnings was restricted to younger stands.

4.5 CONCLUSIONS

Responses in diameter growth after thinning are verified firstly at tree basis. Upwards in the stem, increases in the growth rate take longer to be observed and require thinnings of higher intensity. Nevertheless, once present, enhanced growth rates last longer than at tree basis. Thus, while there is an increase of tree tapers after thinning, it decreases with time.

When thinning is applied to 5-years-old stands with 32 m^2 ha^{-1} of basal area, no immediate increase in diameter growth of potential crop trees is to be expected by removing less than 2 competitors. Later on, and after at least 2 successive removals of 1 competitor, there is a substantial increase on the diameter growth rate of potential crop trees over the one observed in unthinned stands.

Following extreme thinnings, diameter growth increases are immediately detected – 60 % increase at 1.3 m over the growth rate of trees in unthinned stands. Trees subjected to the extreme regime show the highest diameter growth for, at least, 10 years after the first intervention. Growth rates increases >300 % over trees in stands without thinning are to be expected.

Big-sized trees response more to thinning than medium and small-sized individuals, and this in a long lasting way, both in absolute and relative terms.

5 WOOD QUALITY AS AFFECTED BY CROWN THINNINGS AND HARVEST AGE

5.1 INTRODUCTION

The worldwide trend of plantation forestry with short rotations ages led to concerns about the quality of wood that is produced in them (WALKER, 1993; LARSON, 2001; BARBOUR *et al.,* 2003; OLIVEIRA *et al.,* 2006; SCHNEIDER *et al.,* 2008). In Brazil, the rotation length of pine stands has been shortened due to remarkable increases in productivity obtained during the past decades.

The term ‘wood quality’ cannot be generalized and strongly depends on the particular end use of the wood (SMITH; BRIGGSM 1986). Several criteria can be measured in order to assess wood quality, of which **wood density** is considered the key-criterion for many species (MEGRAWM 1985; GUILLEY *et al.,* 1999; KOUBAA *et al.,* 2002; JYSKE *et al.,* 2008). It provides an index to which all end-uses can relate. It also affects the performance of sawtimber, the conversion for panel products and the yield and quality of pulp (WALKER, 1993).

Wood density is a result of the annual growth ring structure: ring width, early- and latewood distribution and the juvenile-mature wood proportion within a radial segment:

- **Ring width** is the parameter most frequently used to assess the stem growth rate. However, more than the growth rate, its formation patterns and uniformity are of interest when assessing wood quality.
- The patterns of **early-** and **latewood** distribution in the stem conform to the seasonal patterns of crown development (LARSON, 1962). The earlywood is formed when the new shoot is actively and vigorously elongating, and the transition to latewood occurs first near the base of the tree, farthest from the source of auxin supply, progressing upward as the season advances. It starts about the time when height growth stops (LARSON, 1964; LARSON, 1969; MEGRAW, 1985). Noteworthy is that this is a physiological process and it depends upon the vigour and growth conditions of the tree (LARSON, 1962). The proportion of latewood within a growth ring helps to define the type of the wood that was formed (HENNESSEY *et al.,* 2004).

- **Juvenile wood** is produced under strong influence of the uppermost part of the tree crown (LARSON, 1972; MEGRAW, 1985; SMITH; BRIGGS, 1986; ALTEYRAC *et al.,* 2006). Thus, with the term 'juvenile wood' the type of wood produced in young trees is described. Nevertheless, the same or a very similar type of wood is also produced in the rings nearest the pith at all heights in the stem (LARSON, 1969; ZOBEL; JETT, 1995).

Some of the characteristics (and quality) of the timber depend on the proportion of juvenile wood and on the size of the juvenile core within the log (GARTNER, 2005; ALTEYRAC *et al.,* 2006). This is because juvenile wood is, compared with mature wood, characterized by (ZOBEL, 1981; SMITH; BRIGGS, 1986; KRETSCHMANN; BENDTSEN, 1992; MACDONALD; HUBERTM 2002; BALLARIN; PALMA, 2003; MEAD, 2013):

- lower density: 15-30 %,
- shorter tracheids: increasing ~60 % until mature wood start to be formed,
- low strength and stiffness: ~50 % lower in the juvenile wood,
- low dimensional stability.

Intensively managed plantations deliver timber with a higher proportion of juvenile wood in comparison to that harvested from older, slow-growing natural stands (CLARK *et al.,* 2006). Although juvenile wood can be tolerated for some industrial processes and products (ZOBEL; SPRAGUE, 1998; GARTNER, 2005), its features are undesirable for solid end-uses (MACDONALD; HUBERT, 2002; BARBOUR *et al.,* 2003; ALTEYRAC *et al.,* 2006). Furthermore, industrial processes should consider avoiding the use of mixed juvenile and mature wood (ZOBEL; SPRAGUE, 1998).

Still, timber produced from young stems with a disproportionately large percentage of juvenile wood has a potentially dangerous structural application. This is because of the load which a beam can stand without failing, its modulus of rupture (MOR), which is commonly lower for juvenile wood (SENFT *et al.,* 1985; SMITH; BRIGGS, 1986; KRETSCHMANN; BENDTSEN, 1992). The general consensus is that juvenile wood is undesirable for products requiring stability or strength.

According to Megraw (1985), the question of whether fast growth rates cause lower density wood has probably stirred more debate than any other point regarding wood properties. However, the conclusion that management practices, which increase tree growth, resulted in timber of poor quality was a misunderstanding (LARSON, 1972).

The erroneous view that long persisted was that the strength of wood is directly controlled by the rate of growth (SMITH *et al.,* 1997). Moreover, and after Zobel (1981), maximizing volume growth is not necessarily incompatible with quality, and it is possible to improve both simultaneously by correct timing of silvicultural treatments. For example, if thinnings are applied after mature wood production started, the same type of wood will be laid down, even with growth rate increases.

With information on the growth and wood quality of specific silvicultural regimes, it is possible to produce suitable wood for the end uses according to their different needs (PELTOLA *et al.,* 2007; SCHNEIDER *et al.,* 2008).

In this study, the influences of thinning on ring width and wood density through X-ray densitometry profiles were analysed. The specific objectives were to

- investigate patterns of ring width,
- determine the radial variation in wood density (ring average density, latewood density and latewood proportion),
- estimate the beginning of mature wood production and thus, quantify its proportion on the different thinning regimes, and
- evaluate the influence of harvest age on wood density.

5.2 MATERIAL AND METHODS

Study site and design are described in detail in topics 2.1 and 2.2, Chapter 2 MATERIAL AND METHODS.

5.2.1 Data collection

Sampled trees were selected and categorized into tree diameter classes, regarding all diameter range and thus, representing different growth rates, namely: 4 small, 4 medium and 4 big-sized trees. In total, 12 trees were collected per thinning variant. Mean, maximum and minimum diameter of the respective diameter class and thinning variant are shown in Chapter 4 RING WIDTH, 4.2.1 Data collection.

Tree sampling aimed at comprising the whole diameter range within each one of the thinning variants, and thus providing a representative estimation of the wood density produced on them. Moreover, it was possible to analyse the trees grouped be diameter classes.

Altogether 48 trees and 96 radii were sampled. Wood samples were taken at 1.3 m (dbh), avoiding whorls and defects.

Anayses were carried out in the Wood Anatomy and Tree-Ring Laboratory, ESALQ, University of São Paulo, Piracicaba, Brasil, under the tuitition of Prof. Dr. Mário Tomazello F°.

5.2.2 Determination of wood density

Wood density was analysed with samples, 10 mm in height and 1.7 mm (± 0.02 mm) in width (a radial segment from pith to bark), cut out of the cross-sectional profiles using a twin-bladed circular saw (Figure 5.2-1).

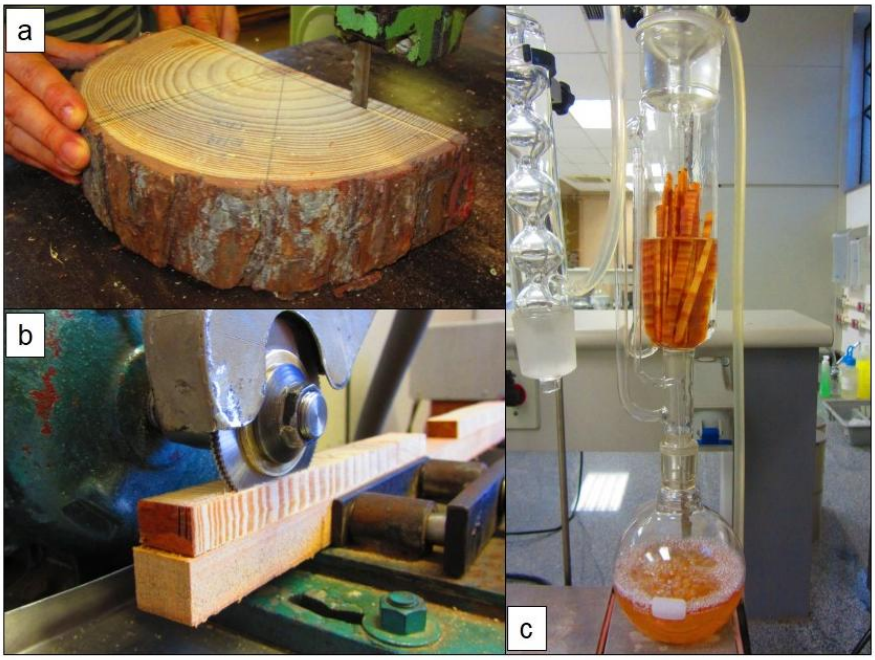


FIGURE 5.2-1: (a) WOOD SAMPLE FROM THE CROSS-SECTIONAL DISCS AND (b) THROUGH TWIN-BLADED CIRCULAR SAW. (c) SOXHLET APPARATUS USED ON THE RESIN EXTRACTION

SOURCE: The author (2014)

The next steps followed:

(1) Wood specimens kept for ≥24 hours at stable air humidity of 60 % and temperature of 20 °C = stabilised moisture of 12 %. Procedure described by Amaral and Tomazello (1998).

(2) Scanning of the wood strips using a direct X-ray microdensitometer (QTRS-01X, Quintek Measurement Systems), integrated with a computer analysis system.

(3) Wood density determination based on the relationship of X-ray attenuation. The mass attenuation coefficient is a material property and depends upon the energy of incident radiation (voltage from 10-50 kv, maximum current of 1.5 ma) and the material composition.

(4) Each annual ring density was the mean value of the 2 radii per tree.

(5) Density profiles were obtained from each sample with a linear resolution step of 0.004 mm.

(6) A fixed threshold density was adjusted to 0.550 g cm^{-3}, thus values above and below represented the late- and earlywood, allowing ring width delimitation.

Because wood samples were analysed with 12 % of humidity, measurement delivered apparent density values. For simplicity purposes, only the word ‘density’ is used from this point onwards.

The main analyses were carried out with not resin-extracted wood samples. However, an exploratory analysis with ⅓ of the samples was conducted considering resin extraction in ‘Soxhlet apparatus’: 8 h toluene 1:1, 8 h ethanol, 6 h lukewarm water (FERREIRA; TOMAZELLO, 2009). Afterwards, the steps described above were repeated and the apparent density once more obtained, now for resin-extracted samples.

X-ray images of wood samples were taken in equipment model MX-20, ‘Faxitron X-ray Corporation’ (USA).

As mentioned in chapter 3 STAND DEVELOPMENT, one plot where the ‘extreme’ regime was applied was lost due to storm and was replaced. As realized in chapter 4 RING WIDTH, 4 trees did not fully represented the extreme and early release from competition applied to the ‘extreme’ variant. Because of mistaken sampling, only 2 individuals of these new plot were used for assessing wood density of the ‘extreme’ variant, totalling 8 trees instead 12 in the other variants. In total 44 trees were regarded in the analysis.

5.2.3 Data analysis

Because the discs were taken at 1.3 m above ground (dbh), the annual growth rings corresponding to the 1st or even 2nd year of the trees’ life were not always present.

Moreover, although sometimes present, it was not possible to evaluate the whole growth ring because of losses during the specimens' preparation. Thus, density analysis started from the 3rd annual growth ring onwards.

In order to analyse the data and assure the absence of X-ray reading errors, density profiles were built and fitted with the image of the respective wood sample.

From the threshold of 0.550 g cm^{-3} annual growth rings were defined and its width determined. In average and at 1.3 m, the differences between ring width measurements through X-ray and digitalized cross-sectional discs (Chapter 4 RING WIDTH) was ±0.1 mm, or ±1.5 %. The results indicated both methods were accurate and led to similar results.

Graphical representations of mean ring density per thinning variant were used to analyse its development along time. The age of transition from juvenile to mature wood was determined by visual interpretation of these graphs by considering the moment at which density showed a level off trend. Additionally, it was also determined by evaluating the development of latewood density and proportion. Values $\geq$0.550 g cm^{-3} for density and $\geq$50 % for latewood proportion were utilized for this purpose. Similar threshold values were described by Clark *et al.* 2006.

Differences between thinning variants were evaluated with the following variables:

- ring width (mm),
- average, lowest and highest ring density (g cm^{-3}),
- wood density (ring values together),
- late-wood density (g cm^{-3}),
- latewood proportion (%),
- juvenile and mature wood proportions.

Aiming at comparing the wood density of different log assortments, sampled trees were classified in 3 diameter-class intervals, following log assortment classes defined in Chapter 6 LOG ASSORTMENTS: '30-39.9 cm', '40-49.9 cm', '50-59.9 cm' and > 60 cm'. The last one was compared only between the thinned variants, since there was only one tree over 60 cm in the stand 'without' thinning.

The wood density was averaged from the 3rd growth ring until age 10, 15, 20, 25 and 30 years, and thus, the influence of age (rotation length) on the density was evaluated, within and between thinning variants.

Statistical analyses were based on a fully randomized design, in which observations were pseudo-replicated. Trees were sampled within the plots of each thinning variant, i.e. trees were not totally independent observations. However, this approach was supported by the homogeneity of the study area, lack of block effect for the great majority of analysis in Chapter 3 Growth, and no substantial differences by disregarding the block design as described in Chapter 4 RING WIDTH (4.2.3). Moreover, LEVENE tests were performed and confirmed the variance homogeneity of the data set.

5.3 RESULTS

5.3.1 Resin content

Resin extraction before density analyses is not always necessary. In fact, when the whole radial segment is regarded, the potential ‘noise’ occasioned by resin can be considered marginal and does not substantially affect the conclusions, at least for loblolly pine (MEGRAW, 1985). However, because some resin impregnation was visually detected, and information about its amount in the wood of loblolly pine grown in southern Brazil was lacking, some profiles were evaluated both before and after resin extraction.

An enlarged radial profile with its respective density values are shown in Figure 5.3-1.

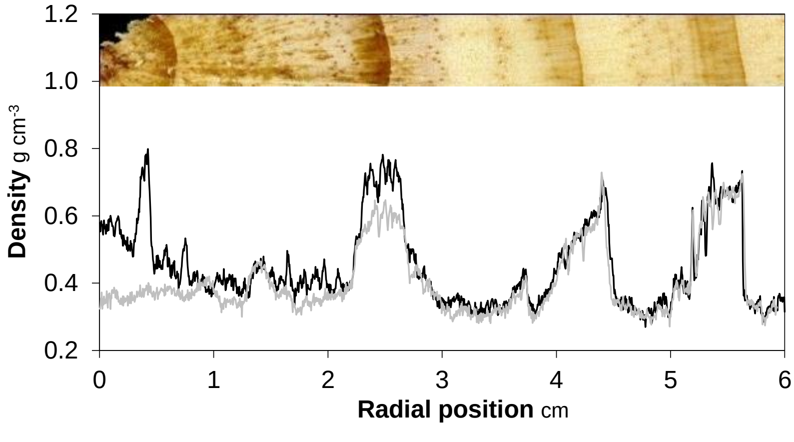


FIGURE 5.3-1: ENLARGED RADIAL SEGMENT SHOWING THE DENSITY PROFILE BE-FORE (BLACK LINE) AND AFTER (GREY LINE) RESIN EXTRACTION.

Image of not resin-extracted sample: pith at the left side, 4 growth rings are to be seen.

SOURCE: The author (2014)

From the Figure 5.3-1 it can be seen that the density profile after the resin extraction (grey line) showed a detectable lower level in comparison with the measurements before resin extraction (black line), especially near the pith. The digitalized image of the wood strip shown clearly the resin impregnation where the differences between measurements were higher.

It was also clear that from the 3rd growth ring onwards, almost no difference in the wood density between with and without resin could be visualized. There is not a perfect correspondence between density profiles (before and after extraction) because of slight variations in the path where density measurements were taken. The densities obtained with and without resin, as well as the relative difference between both are presented in Table 5.3-1.

TABLE 5.3-1: DENSITY (G CM^{-3}) OF THE WHOLE RADIUS SEGMENT (PITH TO BARK) AND OF THE INNER 5 CM PART FROM THE PITH, WITH AND WITHOUT RESIN.

THINNING VARIANT	**WITH**		**WITHOUT**			
	radius	5 cm	radius	%	5 cm	%
without	0.480	0.430	0.450	*-5.9*	0.360	*-14.9*
moderate	0.490	0.470	0.470	*-4.8*	0.380	*-18.1*
heavy	0.480	0.440	0.460	*-4.7*	0.380	*-14.1*
extreme	0.480	0.470	0.460	*-4.8*	0.390	*-16.9*
STATIST. SIGNIF.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

%: indicate the reduction of density after resin extraction.

SOURCE: The author (2014)

Resin extraction reduced the mean density of the whole radius segment similarly in all thinning variants (-5 %). It can be concluded that resin impregnated more close to the pith since higher reductions in density within the first 5 cm from the pith were detected (-16 %). Nevertheless, no differences between thinning variants could be detected indicating the resign impregnation had no relation to the thinning variants or growth rate.

Wood specimens were digitalized as X-ray images for detailed visualisation of density and resin canals (Figure 5.3-2).

From Figure 5.3-2 an inverted colour relationship in comparison to a normal image can be seen. The latewood is bright (denser) than the earlywood (less dense). Resin canals are clearly more numerous in the latewood. The greater number of resin canals in the latewood is in line with the image and density profile shown in the Figure 5.3-1, where the resin impregnation is more evident in this region, due to the colour and density reduction after extraction.

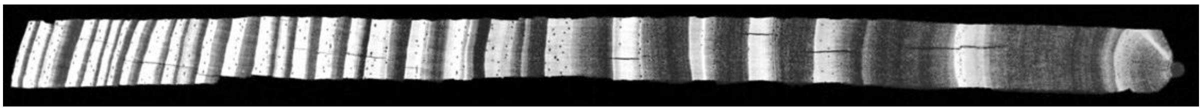


Figure 5.3-2: X-ray image of a resin-extracted wood specimen with clear resin canals - the denser the wood, the brighter the image.

Source: The author (2014)

5.3.2 Ring width

Radial density profiles of big-sized trees from the stands ‘without’ and ‘extreme’ are shown in Figure 5.3-2. From the figure it can be seen a density range within growth rings of ~0.3-1.0 g cm^{-3}. While there is gradual transition of increasing density from early- to latewood, the transition from late- to earlywood is abrupt.

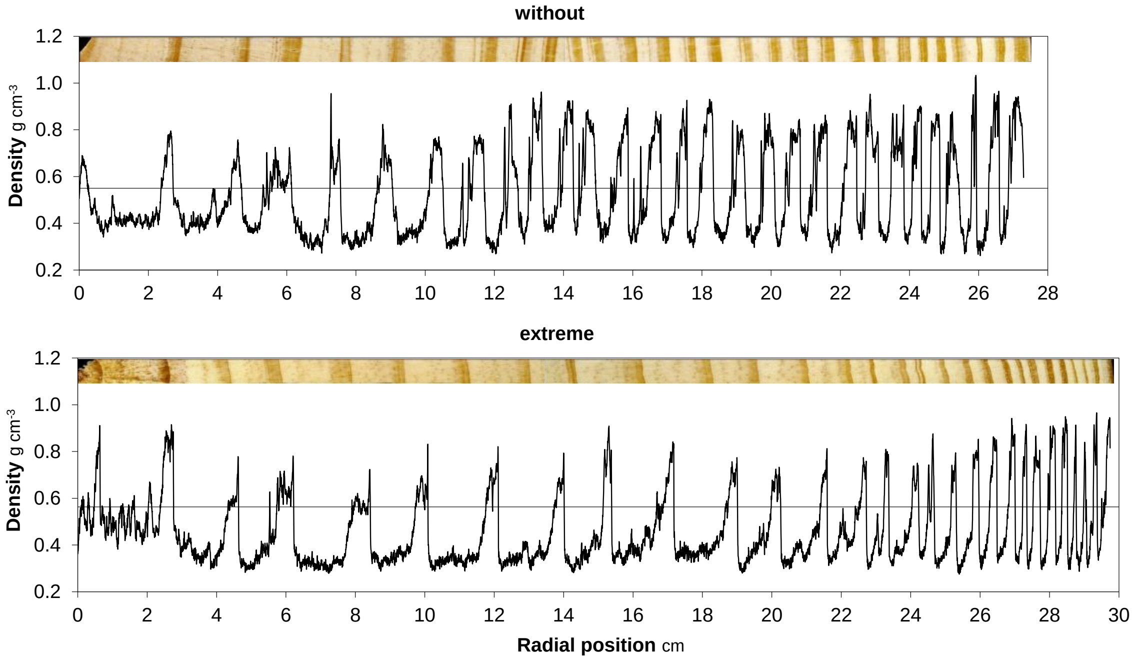


Figure 5.3-2: Density profile of 2 big-sized trees, pith to bark, from the ‘without’ (DBH = 61 cm) and ‘extreme’ (DBH = 67 cm) thinning variants. The line at 0.550 g cm^{-3} define early- and latewood threshold.

Source: The author (2014)

The line on 0.550 g cm^{-3} indicates early- and latewood thresholds (Figure 5.3-2). Although this threshold is not absolute, a value need to be defined in order to standardize the analyses. After some tests, the applied threshold valued was considered the most suitable one.

The ring width formed by the trees in the different thinning variants are shown in Table 5.3-2. From this table it can be verified that the ring width varied according to the thinning intensity. Trees in the 'extreme' variant produced, on average, the widest growth ring, followed by the practice oriented variants ('moderate' and 'heavy'), which produced ring with similar widths. Trees in the unthinned stand showed the lowest value.

However, no differences were detected for the maximum ring width. It means that trees in the stand 'without' thinning produced rings as wide as the ones in the 'extreme' variant. The widest rings were produced early in tree's life and are restricted to the core of the logs, close to the pith. Noteworthy is that the inner part of logs is commonly residue, because it encompasses the knotty core.

TABLE 5.3-2: MEAN AND MAXIMUM RING WIDTH REGARDING THE WHOLE ANALYSED PERIOD (AGE 3-30 YEARS) FOR THE DIFFERENT THINNING VARIANTS. MEAN RING WIDTH FORMED DURING THE MATURE PHASE (~15-30 YEARS) ARE ALSO GIVEN

THINNING VARIANT	**Ring width** mm mean		maximum	mature
without	5.7	a	21.7	2.5
moderate	7.1	b	21.9	4.1
heavy	7.5	b	22.3	3.8
extreme	9.4	c	22.7	5.0
STATIST. SIGNIF.	* * *		n.s.	n.s.

SOURCE: The author (2014)

From age 13-17 years onwards, trees started producing mature wood. Although the analysis of juvenile and mature wood is discussed in detail below, it could be verified that average ring width formed during the mature period was similar between thinning variants.

Altogether, results suggest that, although mean ring width is greater when the whole radius was regarded, the mature wood layer is composed by rings of similar widths between thinned treatments. Thus, no constrains are to be expected in applying the wood produced by the trees in the 'extreme' variant, even for demanding markets such as sliced veneers, where aesthetics play an important role and wide rings might be a constrain.

5.3.3 Ring density

In order to assess the quality of the wood produced in the different thinning variants, density values of individual growth rings were obtained. The ring density, determined by X-ray microdensitometry, is shown in Figure 5.3-3. Ring density values per year are shown in Appendix (Table 11.3-1).

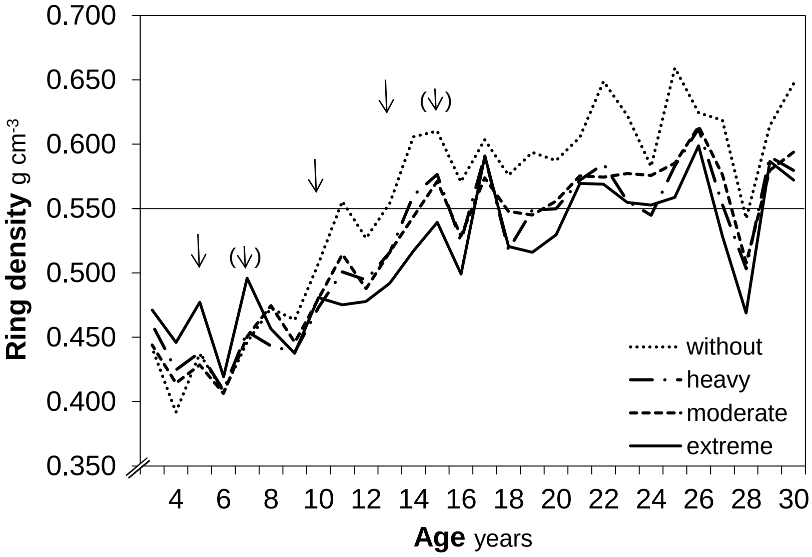


FIGURE 5.3-3: RING DENSITY FOR THE DIFFERENT THINNING VARIANTS ALONG YEARS

Arrows indicate the year at which thinnings took place; paren-theses mean only some of the treatments were thinned; at age:

7 yrs – moderate and heavy,
15 yrs – moderate.

SOURCE: The author (2014)

A consistent pattern of increasing ring density with aging was verified, characterized by a rapid progression that levelled off over 0.550 g cm^{-3} (Figure 5.3-3). The highest decrease in ring density was observed at age 28 years, far away from those ages at which thinnings took place and, therefore unrelated to them.

Statistic differences in ring density were detected at age 4 and 5 years, when trees in the 'extreme' showed the highest values. However, because no thinnings had been applied, no relation to the treatments could be assigned.

In general, a numerical superiority was observed in the ring density produced by the trees in the stand 'without' thinning. However, only occasional differences were detected among years, at ages 11, 14, 22 and 25 years, when the density of rings produced in the control, ‘without’ thinning, was similar to the practice oriented variants (‘moderate’ and ‘heavy’), but higher than the one of the ‘extreme’.

The density of the annual rings close to the pith had probably lower values, since it was observed that resin impregnation increased the density in ~16 % in the 5 cm region around the pith - growth rings formed at age 2-4 years at 1.3 m level (Fig 5.3-1, Table 5.3-1)

Mean ring density, standard deviation, minimum and maximum values regarding individual ring values, are shown in Table 5.3-3.

Table 5.3-3: Mean ring density (g cm^{-3}) and its standard deviation (Σ) in the different thinning variants, during the whole studied period (3-30 years). Minimum and maximum values are also presented

Thinning variant	mean	Σ		min.	max.
without	0.550	0.090	a	0.380	0.710
moderate	0.520	0.070	b	0.390	0.650
heavy	0.520	0.070	b	0.390	0.640
extreme	0.510	0.060	b	0.410	0.640
Statist. signific.	n.s.	* *		n.s.	n.s.

min. = growth ring with the lowest average density,
max. = growth ring with the highest average density.

Source: The author (2014)

Although punctual differences were detected, no differences between thinning variants were detected for mean, minimum and maximum densities regarding growth ring values among the 30-years period (Table 5.3-3).

The standard deviation of density indicated the rings formed in the thinning variants were more homogenous than the ones produced in the stand ‘without’ thinning.

Another approach is the analysis of the mean density of logs of different diameter classes (Table 5.3.4), according to the classes defined in Chapter 6 LOG ASSORTMENTS. Not all diameter classes have been produced by all treatments, for example ‘>60 cm’ in the stand ‘without’ thinning.

When the density of the trees was analysed in different diameter classes, the only class with significant differences between thinning variants was the ‘50-59.9 cm’, where the logs produced on the ‘extreme’ variant averaged denser wood than the ones produced in the ‘heavy’. However, the density of the logs produced in the ‘without’ and ‘moderate’ variants were similar to both, ‘extreme’ and ‘heavy’, which indicate no clear trend related to thinning intensity and no implication for the praxis.

Table 5.3-4: Mean density (g cm^3) of different diameter classes (cm) regarding the whole radius segment

Thinning variant	Diameter class					Statist. signific.
	>60	50-59.9		40-49.9	30-39.9	
without	-	0.500	a b	0.550	0.540	n.s.
moderate	0.490	0.520	a b	0.500	0.540	n.s.
heavy	0.500	0.490	a	0.550	0.520	n.s.
extreme	0.500	0.530	b	-	-	n.s.
Statist. signific.	n.s.	*		n.s.	n..s	

Lacking values are due to the absent of the respective diameter class in the thinning variant.

Source: The author (2014)

Within thinning variants, no differences were detected either, indicating the big-sized logs were formed with wood of similar density of small-sized ones.

5.3.4 Juvenile and mature wood

The transition from juvenile to mature wood occurs gradually. It is accepted that mature wood is being formed when ring density, latewood density and percent latewood stop showing increasing values.

A first approach is related to the mean ring density (Figure 5.3-3). According to it, transition from juvenile to mature wood happened between the 10-18th growth ring for all treatments, firstly for the trees in the stand ‘without’ thinning and lastly for the ones in the ‘extreme’, levelling of around 0.550 g cm^{-3}.

The latewood density and percentage per growth ring are shown in Figure 5.3-4 and 5.3.5, respectively. Both are important to support conclusions about the transition age from juvenile to mature wood.

Conclusions about the transition age obtained through latewood density (Figure 5.3-4) were similar to the ones from the mean ring density (Fig 5.3-3). Latewood density of trees in the stand ‘without’ thinning levelled off by the ages 10-12 years, although thinned treatments apparently took 3-6 more years to reach the 0.750 g cm^{-3} density level. More important than the value 0.750 g cm^{-3} is the level off pattern.

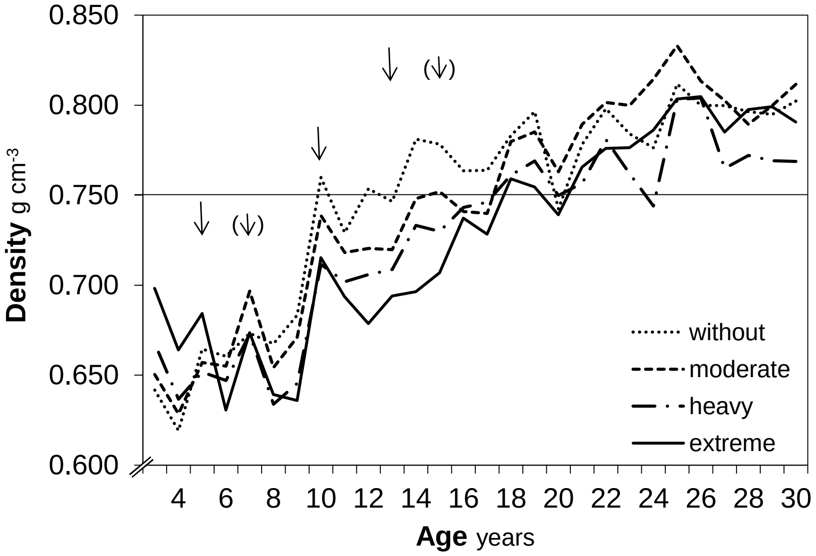


FIGURE 5.3-4: LATEWOOD DENSITY FORMED BY TREES IN THE DIFFERENT THINNING VARI-ANTS ALONG TIME.

Arrows indicate the year at which thinnings took place; parentheses mean only some of the treatments were thinned; at age:

7 yrs – moderate and heavy
15 yrs – moderate.

SOURCE: The author (2014)

Significant differences in latewood density between thinning variants were detected for ages 12, 14 and 15 years, when the latewood produced by the trees in the ‘extreme’ variant was lower than the one produced in the stand ‘without’ thinning. In all cases when differences were detected, the practice oriented variants showed similar values to the ones verified in the ‘without’.

From Figure 5.3.5 a level off trend of ~50 % in the latewood percent of rings can be verified. It occurred earlier in the stand ‘without’ thinning, followed by ‘heavy’, moderate and, finally, ‘extreme’. While the 50 % level was reached by the growth rings formed in the stand ‘without’ thinning at age 13 years, trees in the ‘extreme’ one reached this value only at 17 years. Again, it was observed that the mature wood started to be produced later in the ‘extreme’ variant.

A sharply decrease on latewood percent at age 28 years for all treatments was observed. As mentioned, it occurred 13 years after the last thinning and, therefore, it was not related to them. The explanation is a drought period observed in March and

April in this year, which affected the formation of latewood. Nevertheless, and because this was not the objective of the present analysis, no further analysis were carried out.

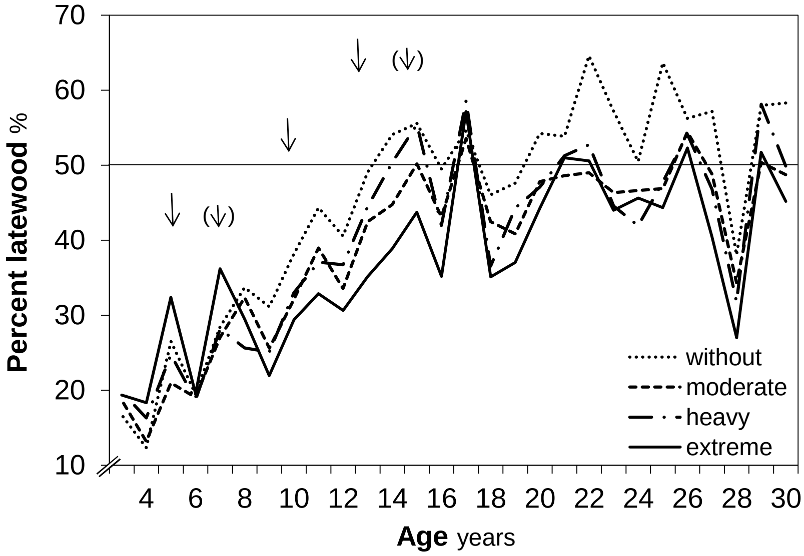


FIGURE 5.3-5: LATEWOOD PERCENT OF RINGS FORMED IN THE DIFFERENT THINNING VARIANTS ALONG TIME

Arrows indicate the year at which thinnings took place; parentheses mean only some of the treatments were thinned; at age:

7 yrs – moderate and heavy
15 yrs – moderate).

SOURCE: The author (2014)

In general, results suggested that the early and ‘extreme’ release from competition resulted in a longer period of juvenile wood production. While the stand ‘without’ thinning and the practice oriented ones started producing mature wood at about the same age, 10-13 years, the stand with ‘extreme’ thinnings started only at age 16-17 years onwards. Therefore, conservatively and for practical reasons, it was defined that treatments started producing mature wood from age

- 13 years for the trees in the ‘without’, ‘moderate’ and ‘heavy’,
- 17 years for trees in the ‘extreme’ one.

Thus, juvenile and mature wood densities were quantified. Results are shown in Table 5.3-5.

From Table 5.3-5 it can be seen that both the juvenile and mature wood were similar between treatments. However, within treatments, mature wood was denser than juvenile wood, which reinforce the difference between these 2 types of wood, and indicate the previous analyses and segregation was successful.

After defining the age that mature wood started to be produced, it was also possible to determine its dimension. Average width and proportion of juvenile wood, as well as mature wood, for the different treatments are shown in Table 5.3-6.

TABLE 5.3-5: MEAN DENSITY (G CM^{-3}) OF JUVENILE AND MATURE WOOD OF THE DIFFERENT THINNING VARIANTS

THINNING INTENSITY	DENSITY		STATIST. SIGNIFIC.
	juvenile	**mature**	
without	0.460 A	0.610 B	* * *
moderate	0.460 A	0.560 B	* * *
heavy	0.450 A	0.560 B	* * *
extreme	0.480 A	0.550 B	* * *
STATIST. SIGNIFIC.	n.s.	n.s.	

Means with the same capital letter do not significantly differ **within treatment**.

SOURCE: The author (2014)

TABLE 5.3-6: ABSOLUTE AND RELATIVE DIMENSION OF JUVENILE WOOD AND ABSOLUTE DIAMETER GROWTH OF MATURE WOOD PER THINNING VARIANT

THINNING INTENSITY	**JUVENILE WOOD**		**MATURE WOOD**
	width cm	proportion %	cm
without	21 a	*71* b	9 a
moderate	24 a	*61* a	16 b
heavy	27 a	*66* ab	15 b
extreme	41 b	*77* b	13 ab
STATIST. SIGNIFIC.	* * *	* *	* *

Juvenile width is 2 times the radius = juvenile core.

SOURCE: The author (2014)

From Table 5.3-6 it can be observed that the juvenile wood core produced in ‘extreme’ variant was highest, 2-times bigger than the one in the ‘without’, while the practice oriented variants resembled the value obtained in the stand ‘without’ thinning. Nevertheless, by comparing the proportion in relation to tree diameter at age 30 years, the ‘moderate’ variant showed the lowest value, similar to the one verified in the ‘heavy’. In relative terms, trees in the stand ‘without’ thinning produced a juvenile wood core just as big as the ‘extreme’ ones did.

Although a smaller juvenile core in absolute terms was produced in the unthinned variant, the growth rate in this treatment was lower during the second half of the rotation, which resulted in the smallest mature wood layer added over the juvenile core. Because the production of mature wood started later in the ‘extreme’ variant (from age 17 years onwards) trees in this treatment added just as much mature wood as the individuals in the ‘without’ did, although also similar to the practice oriented variants, ‘moderate’ and ‘heavy’.

5.3.5 Wood density according to harvest age

In order to evaluate the influence of the age at which harvest is carried out on the wood quality, mean wood density of the first 10, 15, 20, 25 and 30 annual growth rings were determined and compared within and between thinning variants (Table 5.3-7). The first 10-years period regarded growth rings from age 3-10 years.

The analysis of the harvest age between thinning variants reinforced the conclusion that the wood quality delivered by the different regimes was only punctually affected. Between treatments, no differences in the mean density of the wood produced at the same harvest age were detected.

Table 5.3-7: Mean density (g cm^{-3}) according to harvest age (years) for the thinning variants

Thinning variant	**Harvest age** years					Statist. Signific.
	10	15	20	25	30	
without	0.450 A	0.490 AB	0.520 BC	0.540 BC	0.550 C	* * *
moderate	0.440 A	0.480 AB	0.500 C	0.510 C	0.520 C	* * *
heavy	0.440 A	0.480 AB	0.500 BC	0.510 BC	0.520 C	* * *
extreme	0.460 A	0.480 A	0.490 AB	0.510 B	0.510 B	* *
Statist. Signific.	n.s.	n.s.	n.s.	n.s.	n.s.	

Means with the same capital letter do not significantly differ **within treatment**.

Source: The author (2014)

However, within treatments, harvest age was determinant for obtaining higher density wood. In general, the greater the harvest age the denser the wood.

Nevertheless, by harvesting trees at age 20 years, a similar mean wood density with age 30 years is obtained.

5.4 DISCUSSION

5.4.1 Resin content

Resin extraction led to a reduction of 5 % in the density of a whole radius, from pith to. The impregnation of resin was higher close to pith (5 cm), where the extraction led to a 16 % reduction in the wood density (Table 5.3-1).

Similar results were reported by Einspahr *et al.* (1964), who analysed 30-years-old loblolly pine trees and found ~7 % of extractives.

Beside density reductions, no differences between treatments were detected, which confirmed the statement of Megraw (1985) for loblolly pine. The author pointed out that while there are certainly individual tree differences in extractive content, it makes little difference in comparative cross-sectional results whether all the samples in a study are extracted or not if a number of trees are averaged. This is particularly true if trees are less than 40 years of age.

Resin impregnation around pith is an important issue since not rarely complains arise from rotary peeling industries. During rotary peeling process the logs are laterally fixed by two clamps in the pith region. Slipping of logs was frequently associated with a visual greater resin impregnation.

Although more studies are needed and the understanding of why there are logs with higher resin impregnation which difficult the rotary peeling process, it was concluded that the resign impregnation had no relation to thinning regimes or higher growth rates.

5.4.2 Growth rings characterization

Growth rings delimitation was done by means of threshold (CLARK *et al.,* 2006; ANTONY *et al.,* 2012). Values between 0.400 and 0.550 g cm^{-3} can be found in literature, depending on the species (KOUBAA *et al.,* 2002). For loblolly pine grown in North Carolina, United States, Antony *et al.* (2012) reported that 0.480 g cm^{-3} is a suitable value.

For the analysed trees, however, it was concluded that 0.550 g cm^{-3} was optimal and accurately delimitated the boundary of early- to late- and late- to earlywood formation. The used value proved to be appropriate since ring measurements through images with a 0.01 mm accuracy led to very similar results.

Under high competition between trees, which was the case in the ‘without’ variant, 4 suppressed trees did not formed up to 9 annual rings at 1.3 m height. According to Larson (1962), in extreme cases of suppression, trees may not growth at stem base, whereas entire rings are produced within the crown. Surprisingly, for 2 trees in the ‘heavy’ variant, where competition was reduced through thinnings, up to 2 annual rings were lacking in two individuals. Beside this, there was no problem during the ring-by-ring analysis since chronologies were easily fitted.

5.4.3 Ring width

Growth rate patters as affected by thinnings were extensively discussed in Chapter 4 RING WIDTH. Regarding the wood quality, however, an analysis of annual ring width is an interesting issue since it is considered as a grade index in market.

According to Castillo *et al.* (2000), in the United States, the ring width of timber for structural uses should be no wider than 6 mm. A similar criterion was reported by Krahmer (1986), but with a maximum width of 4 mm per ring.

Although growth ring width alone is not necessarily related to wood strength. However, wide rings are often associated with low proportion of latewood. After Dickens and Moorhead (2005) this 6 and 4 mm rules make only sense when related to the amount of latewood:

- 6 mm rings with ≥⅓ of latewood per ring, or
- 4 mm rings with ≥½ of latewood.

Still according to Dickens and Moorhead (2005), there are wood products, generally the most valuable ones, in which the ring width is regarded because of aesthetic reasons. According to Koch (1972) wide rings may affect attractiveness, paint retention, gluing characteristics and machinability of wood products.

In fact, the most important wood characteristic related to its strength seems to be density, instead rings width (BIBLIS *et al.,* 2004; KNOWLES *et al.,* 2006).

Biblis *et al.* (2004) studied thinned and unthinned 40-years-old loblolly pine stands planted in Alabama, United States. The authors concluded that the most important wood characteristic in predicting wood strength was wood density (45 %), followed by percent latewood (30 %) and lastly ring width (25 %).

In the present study, mean ring widths varied between 6-9 mm, in the treatments ‘without’ and ‘extreme’, respectively. However, ring width reached maximum values of 22 mm, similar for all thinning variants. Nevertheless, it is important to note that wide growth rings were formed during the first 3-6 years of trees life. The mean ring width of the mature wood production phase was 4-5 mm in all thinned stands, which would allow high quality end-uses according to the rules cited above, whenever strength or decorative purposes are needed.

Another important issue is the ring width homogeneity. According to Larson (1969), the more erratic the growth conditions, the greater the non-uniformity of the wood. Failure to thin a stand that has reached full-stocking, or radical thinning of a dense stand, can both produce non-uniform wood by varying abruptly the growth rate and thus, the ring width. Additionally, Smith *et al*. (1997) pointed out that it is desirable to avoid abrupt changes in the rate of diameter growth, such as those that can occur when trees are released from competition by long-delayed thinning. According to the same authors, pronounced increases in growth rate indicate that the competition release might better have been done earlier.

In relation to the ring width, it was verified that the ‘moderate’ variant showed the lowest standard deviation (5 mm), indicating that the trees subjected to this thinning regime grew homogeneously, similar to the growth rate of the trees in the ‘without’ and ‘heavy’ variants. A greater heterogeneity was observed in the growth rate of trees in the ‘extreme’ variant. However, although statistically different, it was only 1 mm higher, which could be questionable from the practical perspective.

5.4.4 Ring density

By regarding growth ring individual values, the mean density during the 30-years-period was ~0.530 g cm^{-3}, similar between treatments and comparable to previous studies with loblolly pine:

- Einspahr *et al.* (1964) reported values of 0.499.
- Lower values, 0.366 g cm^{-3}, for 13-years-old trees, were found by Higa *et al*. (1973),

- while higher values were measured by Ballarin and Palma (2003), 0.605 g cm^{-3} for 37-years-old trees, indicating average density of a tree is a characteristic driven by age.

Discussion about the density of wood produced under different management regimes is an old (MEGRAW 1985) and contradictory theme (ZOBEL; SPRAGUE, 1998).

In the present study, density reductions occurred following thinnings at age 5 and 7 years (Figure 5.3-3). Treatments ‘extreme’, ‘heavy’ and ‘moderate’ showed a reduction of, respectively, 13, 7 and 5 % in wood density confined to the first subsequent annual ring after the 1st thinning. Although it might show a trend of decreasing density with increasing thinning intensity, a decrease of 7 % in density at the same year on the trees in the stand ‘without’ thinning indicated that other factors might have acted, for example, weather conditions. According to Megraw (1985), combinations of soil, moisture, temperature, and sunlight interactions can likewise be expected to occasionally produce combinations that influence wood density.

Punctual statistical differences between the wood density produced in the thinning variants were observed. The growth ring density formed in trees subjected to the ‘extreme’ variant was sometimes lower than the one in the stand ‘without’ thinning. However, no long-term implications were verified. Moreover, the rings formed in the practice oriented variants did not differ from the ones formed in the ‘without’.

In fact, no differences between the wood density produced under all tested conditions were detected when mean (over the whole radius), minimum and maximum ring densities were compared (Table 5.3-3). The punctual lower densities verified in the ‘extreme’ variant might have been caused due to a greater crown vigour of the trees, which were totally released from competition and, therefore, formed wider and longer crowns. According to Megraw (1985) extreme crown vigour may influence wood density downward slightly by prolonging earlywood or intermediate cell production.

Noteworthy is that the standard deviation of the wood density produced in the thinned variants was significantly lower than in the stand ‘without’ thinning, indicating that a more homogenous wood was produced due to thinnings (Table 5.3-3).

Previous studies found contradictory results about the influence of thinnings on wood density:

- While some studies show no effects on wood density of widely spaced stands (MEGRAW, 1985; ZHANG *et al.,* 1996; TASISSA; BURKHART, 1998b; PELTOLA *et al.,* 2007; VINCENT *et al.,* 2011; BLAZIER *et al.,* 2013),
- others reported lower (BARBOUR *et al.,*1994; KOUBAA *et al.,* 2000; KANG *et al.,* 2004),
- or even higher densities (ZHANG *et al.,* 1996; PELTOLA *et al.,* 2007; GULLER *et al.,* 2012) in unthinned stands.

This contradiction was deeply discussed by Megraw (1985). The author reported that some misunderstanding happened, as wood from different cambial ages has been compared. This was also recently reported by Ivković *et al.* (2013).

Results presented in this study were similar to previous (MEGRAW, 1985; PELTOLA *et al.,* 2007; VINCENT *et al.,* 2011; BLAZIER *et al.,* 2013). It was found that ring density was not significantly reduced following thinning, and can be expected to be undetectable when mean values over an entire cross section are evaluated some years later. This is because effects of silvicultural treatments have an ordinarily short-term effect in wood density (MORA *et al.,* 2007).

Similar results to the present study were also reported by:

- Megraw (1985), studying loblolly pine stands in Louisiana, U.S.. The effect of thinning to a widely varied stand density levels was evaluated. Stand densities after thinning at age 9 years were 2.500, 1.500, 750, 500 and 250 tree ha^{-1}. Wood density was evaluated from cross-sectional discs every 5 m in height starting at tree basis. No significant difference in wood density was found at any height at age 22 years (13 years after thinning) for any of the stocking levels down to and including 500 tree ha^{-1}. However, the most intense thinning (250 trees ha^{-1}) resulted in a 7 % reduction at both tree basis and 5 m height. The author also reported no effects from the other treatments in the years immediately following thinning were discernible when averaged over the entire cross section (MEGRAW, 1985).
- Vincent *et al.* (2011) found that the variability in average ring density along the stem within the same tree was greater than that induced by thinning. This implies that increased growth rate of loblolly pine trees is not necessarily linked with decreased mechanical properties of wood.
- Blazier *et al.* (2013), who evaluated loblolly pine stands in Louisiana, U.S., established with ~3,000 trees ha^{-1}. At age 4 years, stands were pre-commercially

thinned, which reduced the stand density to different levels: 2,500-250 trees ha^{-1}. Between age 21-41 years, thinning procedures were superimposed to the stands, reducing the stand density to ~60 trees ha^{-1} after up to 5 procedures and regarding different schedules. At age 49 years, trees were fell and the wood density analysed. According to the authors, key wood properties were relatively little affected by thinnings, indicating forest managers have great flexibility in stand density management from a wood quality perspective.

According to Megraw (1985), wood density and growth rate are independent traits for coniferous trees of comparable environment, considering equal age and height level. Additionally, Senft *et al.* (1985) pointed out that there is overwhelming evidence that wood density and growth rate are not always correlated.

In fact, if conifers are encouraged to grow more rapidly by thinnings, they produce a greater volume of the same kind of wood that might have been laid down without any intervention (SHEPHERD, 1986; SMITH *et al.,* 1997). Consequently, a mature tree, will continue to form high-quality wood in spite of a relative increase in the growth rate following a heavy thinning (LARSON, 1969).

According to Tasissa and Burkhart (1997), wide growth rings show a proportional increase of early- and latewood, and thus, no differences in wood density after thinnings can be detected.

Indeed, differences in wood density of conifers are more likely related to site quality (climate and soil), where the wood produced in better sites was denser, even though the trees grew faster (MEGRAW, 1985; JOKELA *et al.,* 2004).

- Malan (2007) studying *P. patula* grown in South Africa, reported a clear enhancement of growth rate by the manipulation of the growing space by thinning, but no adverse effect on wood density, or any negative implication related to the wood properties were verified. In fact, the advantages of fast growth by far outweighed slower growing trees. Higher growth rates imply not only higher volume production, but improved wood density uniformity across the radius without compromising the suitability of the wood for structural purposes to any serious level.
- According to Clark *et al.* (2006), a lower competition level between trees provides more moisture for the trees and, when water is a limiting factor in late summer, it favours the latewood formation. For loblolly pine, increasing soil water availability

via irrigation increased wood density and latewood percentage by 0.036 g cm^{-3} and 7 %, respectively (GONZALEZ-BENECKE *et al.,* 2010).

The analysis of the wood density of logs of different diameter classes suggested that they were relatively homogenous regardless of thinning variant and diameter class. The only class where differences were detected was the '50-59.9 cm'. However, differences were small and without any clear relation to the thinning variants.

5.4.5 Juvenile and mature wood

Because of the gradual transition from juvenile to mature wood, it is difficult to define it as a specific year (MACDONALD; HUBERT 2002; ALTEYRAC *et al.,* 2006; CLARK *et al.,* 2006; MEAD, 2013). However, by evaluating in conjunt some characteristics such as ring density, latewood density and latewood percent, and after the increasing trend along the years levelled of, it is possible to identify the moment from which mature wood is being formed. Furthermore, and from the practical perspective, the characterization of the transition is needed to understand the effects of silvicultural treatments on wood quality (MORA *et al.,* 2007).

According to Kretschmann and Bendtsen (1992), the segregation of juvenile and mature wood was found to be the most important criterion related to wood strength. The authors concluded this studying loblolly pine plantation in North Carolina, United States.

The transition between juvenile to mature wood occurs commonly between 5-20 years, (SHEPHERD, 1986; ZOBEL; SPRAGUE, 1998; CASTILLO *et al.,* 2000; BALLARIN; PALMA, 2003; CLARK *et al.,* 2006; MORA *et al.,* 2007; GULLER *et al.,* 2012; MEAD, 2013; PALERMO *et al.,* 2013).

A graphical analysis of the ring density development along years showed that the transition from juvenile to mature wood occurred in the period between the 10-17th year in the pines of the experiment (Figure 5.3-3). Similar results to the ones found in the present study are widely reported for loblolly pine. The transition from juvenile to mature wood has been found to occur between ages 11-13th (ZOBEL. 1981; KRAMER, 1986; TASISSA; BURKHART, 1998a; HENNESSEY *et al.,* 2004; PAULESKI, 2010).

According to Alteyrac *et al.* (2006), the use of the latewood density is another suitable criterion to determine the boundary between juvenile and mature wood. When the latewood density was regarded, the level of trend (around 0.750 g cm^{-3}) was observed (Figure 5.3-4):

- at age 10 years for the trees the stand ‘without’ thinning,
- at age 15 years for the trees in ‘moderate,
- at age 17 years, for ‘heavy’, and trees in ‘extreme,
- at age 18 for ‘extreme’

When the latewood proportion of loblolly pine comprises more than 50 % of the growth ring, it is assumed that mature wood is being produced (HENNESSEY *et al.,* 2004). With this criterion, trees in the ‘without’ variant started forming mature wood at age 13 years, while it took 1, 2 and 4 more years for the ‘moderate’, ‘heavy’ and ‘extreme’ variants, respectively (Figure 5.3-5).

According to Larson (1972), the latewood proportion develops as a function of age, but the slope of the curve and the age at which it culminates, can be altered by growth conditions.

Altogether, findings suggest that thinning had a postponement effect in producing mature wood, however, a clear effect was verified only in ‘extreme’ variant.

- Koubaa *et al.* (2005) also reported that silvicultural practices might influence the transition age from juvenile to mature wood.
- Tasissa and Burkhart (1998a) and Alteyrac *et al.* (2006) studied the influences of thinning on the transition age from juvenile to mature wood in loblolly pine grown in the United States. The authors concluded that there were no consistent trends relating thinning to the transition age of juvenile-mature wood. Reports were different from the findings of the present study. Clear trends in the cited studies might have not been observed due to the absence of extreme thinning regimes, as was the case in the present analysis.

Finally, it could be concluded that trees started producing mature wood

- at age 13 years in the ‘without’, ‘moderate’ and ‘heavy’ variants,
- at age 17 years in the ‘extreme’ one,

The difference between juvenile and mature wood density within the thinning variants substantiated the segregation between both (Table 5.3-5). The density of juvenile wood was substantially lower, around 20 % in comparison to the mature wood.

However, no differences were detected of the same wood type among thinning variants, suggesting a similar wood was produced, even though starting at different ages. By regarding other combinations of age from which mature wood started to be produced, statistical differences were not so clear.

Considering the above cited transition ages, the diameter of the juvenile wood was widest in the ‘extreme’ variant, while similar between trees of the other treatments. (Table 5.3-5). By regarding the proportion of juvenile wood in relation to tree diameter, it was verified that the ‘moderate’ regime was optimal for restricting the size of juvenile core. The ‘heavy’ variant showed a juvenile core similar to the ‘moderate’, but as big as the ones observed in the ‘extreme’ and ‘without’.

The similarity of the juvenile core formed by trees in the ‘heavy’ regime with the one verified in the ‘without’ and ‘extreme’ occurred due to a decrease in growth rate after age 13 years (mature wood formation period), since no more thinning were carried out, as was the case for treatment ‘moderate’, which overtook ‘heavy’ growth rate in the period between ages 16-25 years (Chapter 4 RING WIDTH).

- Zobel and Sprague (1998) concluded also that pine plantations with low initial density resulted larger juvenile cores. However, the juvenile cores were proportionally smaller in comparison to the total tree volume.
- Differently, results found by Harding (1990) indicated that volumes of mature wood are approximately the same in widely and closely spaced plantations and, therefore, the size advantage in the widely spaced trees consists primarily of juvenile wood. Which is in line with the result obtained for the ‘extreme’ variant.
- Noteworthy is that the lower proportion of juvenile wood obtained in moderately thinned stands might not be true for harvesting trees at earlier ages (GAPARE *et al.,* 2006), as can be supposed by the lower wood density obtained by harvest trees at ages earlier than 20 years (Table 5.3-7).

Results found in the present study indicate that, regardless of some differences between thinning variants, the proportion of juvenile wood was remarkable high, ranging from 61-77 %, even for an unusual old harvest age (30 years) for Brazilian standards of loblolly pine management.

- According to Macdoonald and Hubert (2002), early harvest ages are inevitable linked to a greater proportion of juvenile wood and reduced density.

- Senft *et al.* (1985) found a juvenile wood core proportion of 31-55 % of loblolly pine trees with ~30 years, when tree diameters ranged from 24-31 cm. According to the same authors, if strength of wood is required, the harvest age have to be postponed to increase amounts of mature wood.

Regarding the same harvest age, and comparing the mean wood density obtained from different thinning variants, no differences could be detected between treatments (Table 5.3-7). This means that at the same harvest age, thinning had no effect on mean wood density. However, within a single thinning variant, harvest age was determinant for producing higher density wood. In general, it could be noted that the same average wood density obtained at age 30 years was already reached at age 20 years for all treatments.

5.5 CONCLUSIONS

It was found that:

- The maximum ring width was similiar between thinning variants (~22 mm). Ring width during the mature wood formation is similar between thinning variants (4-5 mm). Although wider than the ones verified in the stand without thinning, observed values are suitable for high valuable appearance end-uses.
- Ring density shows a consistent general pattern of increasing values with aging, regardless of thinning intensity. However, it is punctual and negatively affected by ‘extreme’ thinnings.
- No influence of thinnings on the wood density was detected when averaged for the whole radial segment. Instead, thinnings result in a more homogenous density profile.
- The transition from juvenile to mature wood occurs between ages 13-17 years. Extreme and early thinnings (i.e. post-thinning stand density of 400 stems ha^{-1} at age 5 years) delays the production of mature wood in ~4 years when compared to unthinned stands or practice-oriented thinnings.
- The diameter of the juvenile wood core is similar between practice oriented thinning regimes and unthinned ones, while greater under ‘extreme’ thinning regimes. Trees in thinned stands produce more mature wood than unthinned stands. In order obtain

the optimum proportion of juvenile/mature wood, heavy thinnings within the first ~13 years should be avoided. Later on, thinnings can be intensified.

- At the same harvest age thinning has no effect on wood density. However, harvest age itself is determinant for obtaining wood of higher density. The same wood density produced at age 30 years, can be obtained at age 20 in all studied thinning variants.

Altogether results indicated that due to crown thinning it is not only possible to produce bigger-sized trees, but also

- more homogeneous growth rate,
- more homogeneous wood density,
- proportionally less juvenile wood and with a wider mature wood layer.

Even though the extreme variant led to the postponement of mature wood production, from the practical perspective, and considering the requirements of the pine timber market in southern Brazil, there are no constrains related to wood quality by applied extreme regimes to loblolly pine stands.

6 PRODUCTION OF LOG ASSORTMENTS AS AFFECTED BY THINNING INTENSITY AND HARVEST AGE

6.1 INTRODUCTION

Beyond the total volume production per area unit, the amount of logs classified by their diameter is even better suited for evaluating the effects of thinnings on timber production.

Log assortment classification currently used by the pine based industry in Brazil is essentially based on diameter. Whether logs are pruned or not is also regarded by specific markets.

In general, logs are commercialized in relatively short lengths. The most common dimensions and industrial uses in southern Brazil are shown in Table 6.1-1.

TABLE 6.1-1: COMMON DIMENSIONS AND INDUSTRIAL USES OF PINE LOG ASSORTMENTS IN SOUTHERN BRAZIL

Nr.	**length** m	**SED** cm	**Pruning**	**Use**
1	1.5-3.1	>10	unpruned	pulp and paper
2	1.9	18-35	unpruned	small-sized sawtimber (i.a. fancy)
3	2.4-2.6	>30	unpruned	rotary peeled veneer
4	3.1	>25	un- or pruned	sawtimber (concrete building forms)
5	2.2	>35	pruned	sliced veneer (i.a. clear wood products)

SED: small-end diameter

SOURCE: The author (2014)

Although mass production (pulp and paper and reconstituted boards industry) still plays an important role in Brazil, the market of pine logs have developed and high-quality demanding markets are being supplying. An example is the sliced veneer industry with high quality requirements and to which pruned logs is a must. It is important to note, however, that high-quality markets are regarded as ‘niche’ ones, where the amount of timber processed every year is, in comparison to the other, relatively small.

With the recently economic growth of the country, there have been an increasing demand for the ‘house building sector’. Differently than it could be supposed, the main use of pine wood in this sector is related to sawtimber for concrete building forms. Thus, there are almost no requirements related to quality (i.a. pruning), but relatively big-sized assortments are preferred since it is aimed at producing sawtimber 30 cm wide.

The objective was to analyse the performance of the different crown thinning regimes in producing log assortments classified according to their small-end diameter. Specific objectives were:

- To quantify the amount of unpruned and pruned log assortments
- To evaluate the production of log assortments regarding harvest ages from16-30 years.
- To separately evaluate the production of log assortments >30 cm.

6.2 MATERIAL AND METHODS

Study site and design are described in detail in topics 2.1 and 2.2, Chapter 2 MATERIAL AND METHODS.

6.2.1 Data collection

The data collection and taper models given in Chapter 3 STAND DEVELOPMENT were the basis for the calculations presented in this chapter.

As no inventory was carried out between ages 23-29 years, the growth rate during this period was obtained through growth rings measurements at 1.3 m height, as described in Chapter 4 RING WIDTH. Because cross-sectional discs were sampled comprising the whole diameter range of each plot, it was possible to estimate the radial increment separately for small, medium and big-sized individuals.

Trees which died during the 7 years period without inventory had their radial growth estimated with the small-sized group rate, regardless of diameter size. The mortality rate regarded small-sized individuals, regarding a linear trend from year 23 to 30.

6.2.2 Data analysis

The amount of timber produced in the different thinning variants were assessed regarding production periods from 16-30 years. For simplicity reasons, quantifications were done only for even ages (16, 18, 20, and so on).

The assortment classes were classified according to the pruning status and in 10 cm wide groups, from 10 to >60 cm. Logs under 10 cm were considered non-commercial. Log length was set as 2.5 m.

Because stump height was ~0.2 m above ground, the first 2.5 m log was evaluated according to the diameter at 2.7 m above ground, the second at 5.2 m and so on.

Pruned logs were exclusively the 1st and the 2nd ones, as the 5.7 m pruned segment comprised only 2 logs of 2.5 m length.

The volume of timber harvested via thinnings was added to the standing volume at the respective harvest age, thus resulting the total volume produced.

Paired data of volume and harvest age were used for fitting quadratic regression curves. Thus, the development of volume production was obtained, allowing the assessment of general patterns related to them.

The volume calculation in the ‘extreme’ variant for ages 26 and 28 years were higher than the value obtained due to field measurements at age 30 years. This inconsistency was due to the loss of one replication of this treatment, mentioned in Chapter 3. Thus, because data from age 24-28 were obtained through annual rings analysis while the 30-years-value were assessed by measuring a new established plot, differences were faced. Nevertheless, and because the growth ring approach worked satisfactorily for the other treatments, these inaccuracy was considered acceptable. Moreover, the main conclusions from these data were assessed through regression analysis, and so general patterns of development instead punctual values.

6.3 RESULTS

6.3.1 Volume per assortment at age 30 years

The volumes obtained in the different thinning variants at age 30 years are shown in Tab 6.3-1.

TABLE 6.3-1: VOLUME OF LOGS PER DIAMETER CLASS, UNPRUNED AND PRUNED, PRODUCED AT THE DIFFERENT THINNINGS, AND AT AGE 30 YEARS

	Diameter class	WITHOUT		MODERATE year								HEAVY year							EXTREME year					
	cm	Total$_1$	%$_1$	5	7	10	13	15	30	Total$_1$	%$_1$	5	7	10	13	30	Total$_1$	%$_1$	5	10	13	30	Total$_1$	%$_1$
unpruned	10 - 19.9	145	*14*	29	46	36	58	51	52	272	*19*	46	29	46	67	44	231	*17*	93	10	13	13	129	*13*
	20 - 29.9	352	*34*			5	18	37	195	254	*18*			3	31	161	195	*14*		11	28	44	83	*8*
	30 - 39.9	157	*15*					5	290	294	*20*				4	311	315	*23*			36	114	150	*15*
	40 - 49.9	31	*3*						122	122	*8*					154	154	*11*			7	188	195	*19*
	50 - 59.9								18	18	*1*					23	23	*2*				125	125	*12*
	> 60																					8	8	*1*
	Sub-total$_1$	685	*66*	29	46	41	76	93	676	961	*66*	46	29	48	102	692	918	*67*	93	21	84	492	690	*68*
pruned	20 - 29.9	101	*10*		1	28	33	47	14	123	*9*		3	30	63	4	101	*8*		24	3	-	27	*3*
	30 - 39.9	165	*17*				5	16	109	130	*10*				14	74	88	*6*		7	29	11	47	*5*
	40 - 49.9	54	*5*						141	141	*11*					168	168	*13*			24	34	58	*6*
	50 - 59.9	15	*2*						46	46	*3*					67	67	*5*				115	115	*11*
	> 60								11	11	*1*					19	19	*1*				75	75	*7*
	Sub-total$_2$	335	*34*		1	28	38	64	320	452	*34*		3	30	77	333	443	*33*		31	56	235	322	*32*
	Total$_2$	**1,020**	*100*	29	47	69	114	156	996	**1,412**	*100*	46	33	79	179	1,025	**1,362**	*100*	93	52	140	727	**1,012**	*100*

Total volume of logs (in m³) per diameter class produced in the 30-years period (Total$_1$). Sub-totals for the unpruned (Sub-total$_1$) and pruned (Sub-total$_2$) assortments. Total volume per intervention (Total$_2$). Proportion of log assortment in relation to the total volume produced (%$_1$).Log classified according to the small-end diameter (in cm), with constant lengths of 2.5 m.
5, 7, 10, 13, 15, 30 = year at which thinning or final cut took place.

SOURCE: The author (2014)

From Table 6.3-1 can be seen that:

- the production of unpruned logs on the different thinning variants was mainly distributed on 3 diameter classes. While the stand ‘without’ thinning comprised the first 3 classes (10-39.9 cm), the production obtained in the ‘extreme’ variant was distributed in the range from 30-59.9 cm. The ‘moderate’ and ‘heavy’ variants had the greatest amount of wood was in the diameter class of ‘30 - 39.9 cm’, although the production in these treatments was well distributed between the first 4 assortment classes.
- the total production of pruned logs at age 30 years varied from 320-450 m^3 ha^{-1}, in the ‘extreme’ and ‘moderate’, respectively. However, in relative terms, similar values between treatments were observed, about 30 %. When regarding pruned logs >40 cm, it was verified that the stand ‘without’ thinning produced only ~70 m^3 ha^{-1}, while a production of ~200 m^3 ha^{-1} in the ‘moderate’ and ~250 m^3 ha^{-1} in the ‘heavy’ and ‘extreme’ variants was observed.

6.3.2 Volume production according to harvest age

In the first analysis (6.3.1), the volume of different log assortments was given for thinnings and a harvest age of 30 years. However, of more interest is the development of log assortments along time. Therefore, harvest ages from 16-30 years were analysed.

Volume per log assortment of the different treatments and regarding harvest ages varying from 16-30 years are tabular shown in Table 6.3-2 and 6.3-3. The volume obtained when harvesting the stands at age 30 years and shown in Table 6.3-1 is once more presented together with the other harvesting ages for comparison reason.

From Table 6.3-2 it can be seen that the volume of logs ‘10-19.9 cm’ in the stand ‘without’ thinning decrease with increasing harvest age. While at age 16 years ~320 m^3 ha^{-1} of this log assortment is harvest, at age 30 years, only ~150 m^3 ha^{-1} were produced. These is obviously consequence of diameter growth of trees, but also the result of the great mortality rate, discussed in Chapter 3 STAND DEVELOPMENT. Although slight decreases in the volume production are to be seen in other diameter classes and thinning variants, none of them are as sharply as is the case in the ‘without’.

In general and for all thinning variants, a consistent increasing volume within diameter classes together with increasing proportion of bigger-sized log assortments can be observed (Table 6.3.2, 6.3-3).

For a better visualisation and understanding of trends, single entry regression models were fitted (independent variable = age), and so curves of the volume production development were drawn. At first, only the standing volume at the respective age was regarded, shown in Figure 6.3-1.

When regarding only the standing volumes, treatment ‘without’ thinning showed the highest production level during all 16-30 years period. The ‘extreme’ variant, otherwise, showed the lowest production level. Both ‘without’ and ‘extreme’ seemed to level off the volume production by the last years of evaluation (Figure 6.3-1).

At age 30 years, stands ‘moderately’ and ‘heavily’ thinned have reached a similar standing volume level to the one observed in the stand ‘without’ thinning. Noteworthy is that the practice oriented variants did not show a level off pattern in the volume production curve. Whereas curves drawn for the extreme variants showed a more clear slowing production, indicating differences in the standing volume of practice oriented variants and extreme ones might improve even with time (Figure 6.3-1). By describing differences between thinning variants, information from ANOVA and TUKEY analyses are regarded, even though not shown in text. Tests and their significant levels are presented in Appendix.

TABLE 6.3-2: STANDING VOLUME (IN M³) PER LOG ASSORTMENT, UNPRUNED AND PRUNED, WHEN HARVESTED AT THE RESPECTIVE AGES, GIVEN FOR AGES 16-30 YEARS, IN 2 YEARS INTERVALS, FOR THE 'WITHOUT' AND 'MODERATE' VARIANTS.

Diameter class cm		**WITHOUT** year								**MODERATE** year							
		16	18	20	22	24	26	28	30	16	18	20	22	24	26	28	30
unpruned	10 - 19.9	318	304	283	247	250	212	168	145	72	70	66	63	63	58	55	52
	20 - 29.9	127	179	230	286	321	362	367	352	140	177	192	204	205	202	194	195
	30 - 39.9	10	23	37	53	75	93	111	157	31	66	112	171	210	252	261	290
	40 - 49.9				4	8	13	23	31		8	18	32	59	70	91	122
	50 - 59.9														6	6	18
	> 60																
	Sub-total$_1$	454	506	550	590	654	680	669	686	243	321	387	470	536	588	607	676
pruned	20 - 29.9	185	191	194	192	192	180	150	101	88	62	54	37	29	24	20	14
	30 - 39.9	31	60	77	97	114	130	149	165	71	113	125	137	142	124	107	109
	40 - 49.9		5	14	26	29	38	43	54	12	26	45	76	80	114	141	141
	50 - 59.9						8	8	15			8	17	36	38	39	46
	> 60																11
	Sub-total$_2$	216	256	284	316	335	355	350	336	170	202	232	267	287	300	308	320
	Total	**670**	**762**	**834**	**906**	**989**	**1,035**	**1,019**	**1,022**	**414**	**522**	**619**	**737**	**824**	**888**	**916**	**996**

Total volume (Total). Volume for the unpruned (Sub-total$_1$) and pruned (Sub-total$_2$) log assortments. Log assortments classified according to the small-end diameter (in cm), with constant length of 2.5 m.

16, 18, 20...: year at which harvest took place.

Table 6.3-3: Standing volume (in m^3) per log assortment, unpruned and pruned, when harvested at the respective ages, given for ages 16-30 years, in 2 years intervals, for 'heavy' and 'extreme' variants

	Assortments cm	**HEAVY** year								**EXTREME** year							
		16	18	20	22	24	26	28	30	16	18	20	22	24	26	28	30
unpruned	10 - 19.9	54	50	46	49	45	48	48	44	17	19	14	18	13	21	20	13
	20 - 29.9	145	168	175	167	168	173	167	161	55	51	48	48	47	42	37	44
	30 - 39.9	49	105	152	201	237	252	259	311	121	135	129	118	123	115	116	114
	40 - 49.9			18	45	65	88	108	154	31	75	116	172	191	221	230	188
	50 - 59.9						6	11	23		11	23	45	66	82	92	125
	> 60														8	23	8
	Sub-total$_1$	248	323	391	462	515	567	594	692	225	291	329	400	441	489	518	492
pruned	20 - 29.9	58	30	18	8	7	7	7	4								
	30 - 39.9	104	126	136	140	118	106	110	74	44	17	6	3				11
	40 - 49.9	9	46	73	98	117	124	116	168	85	112	110	82	66	52	29	34
	50 - 59.9				15	29	53	60	67	19	44	62	100	123	138	156	115
	> 60								19			20	35	53	52	68	75
	Sub-total$_2$	171	202	227	260	271	290	292	333	147	173	199	221	242	242	254	235
	Total	**419**	**524**	**618**	**723**	**786**	**857**	**886**	**1,025**	**372**	**464**	**528**	**621**	**682**	**732**	**772**	**727**

Total volume (Total). Volume for the unpruned (Sub-total$_1$) and pruned (Sub-total$_2$) assortments. Assortments classified according to the small end diameter of each log (cm), with constant length of 2.5 m

16, 18, 20...: year at which harvest took place.

Source: The author (2014)

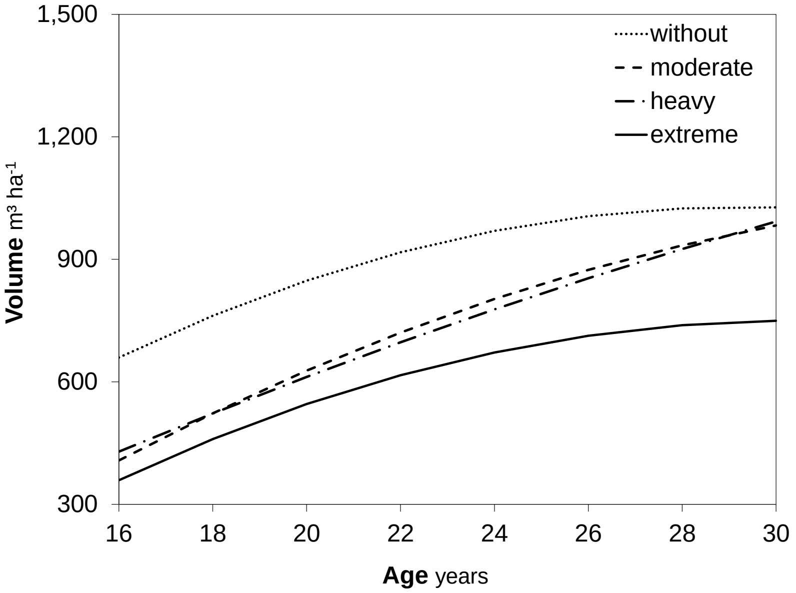


FIGURE 6.3-1: DEVELOPMENT OF STANDING VOLUME (V_{STAND}) OBTAINED THROUGH THE EQUATIONS 1-4, EXCLUDING THINNINGS. HARVEST AGES FROM 16-30 YEARS, FOR THE DIFFERENT THINNING VARIANTS. EQUATIONS ARE GIVEN IN TABLE 6.3-4

SOURCE: The author (2014)

The total volume production, including thinnings, and for the different treatments is shown in Figure 6.3-2. The curve drawn for the ‘without’ variant is the same one shown in Figure 6.3-1. For comparison reasons, the scale of ‘y’ axis was kept identical to Figure 6.3-1.

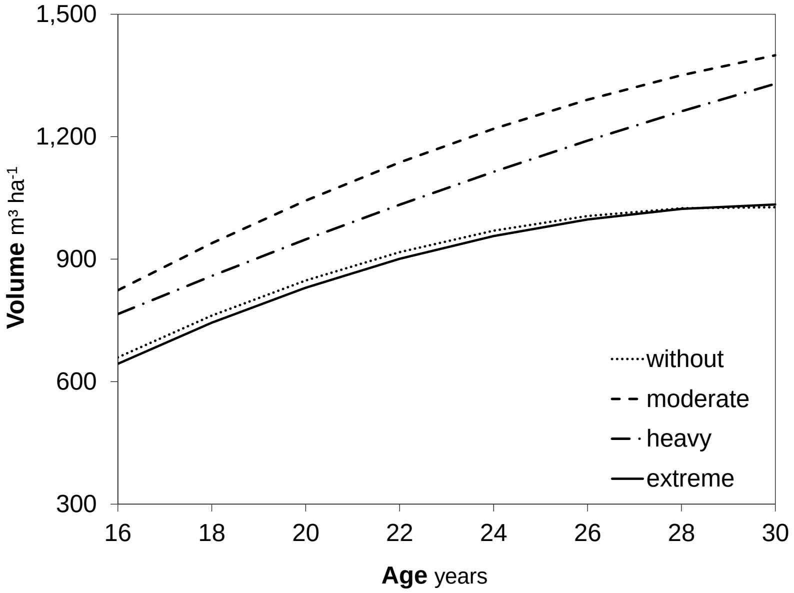


FIGURE 6.3-2: DEVELOPMENT OF TOTAL VOLUME (V_{TOTAL}) OBTA-INED THROUGH THE EQUATIONS 5-7, INCLUDING THINNINGS. HARVEST AGES FROM 16-30 YEARS, FOR THE DIFFERENT THINNING VARIANTS. EQUATIONS ARE GIVEN IN TABLE 6.3-4.

SOURCE: The author (2014)

When thinned volumes were included to the standing one, and thus total produced volume was assessed, the treatment under the 'extreme' regime showed a total production similar to the stand 'without' thinning, and this already at age 16.

The stands with 'moderate' and 'heavy' thinning intensities were both superior in comparison to the extreme ones. Both kept these higher level along the whole analysed period, resulting in greater amount of timber production. Nevertheless, there was no statistical difference between the total volume produced in the 'heavy' variant and the ones verified in the 'without' and 'extreme' ones from age 18-22 years. A clear segregation in two groups, where 'moderate' and 'heavy' were similar to each other and higher than the 'without' and 'extreme' was observed only at age 30 years.

Equations fitted for volume development analysis are given in Table 6.3-4.

TABLE 6.3-4: EQUATIONS FITTED FOR VOLUME DEVE-LOPMENT ANALYSIS SHOWN IN FIGURE 6.3-1 AND 6.3-2.

Nr.	THINNING VARIANT	**EQUATION**	R²
1	without	$v_{stand.} = -762.6 + 122.2\ (A) - 2.1\ (A)^2$	0.92
2	moderate	$v_{stand.} = -915.5 + 104.8\ (A) - 1.4\ (A)^2$	0.88
3	heavy	$v_{stand.} = -478.5 + 65.4\ (A) - 0.5\ (A)^2$	0.99
4	extreme	$v_{stand.} = -986.9 + 114.1\ (A) - 1.9\ (A)^2$	0.84
5	moderate	$v_{total.} = -499.5 + 104.8\ (A) - 1.4\ (A)^2$	0.88
6	heavy	$v_{total.} = -142.0 + 65.5\ (A) - 0.5\ (A)^2$	0.98
7	extreme	$v_{total.} = -701.7 + 114.0\ (A) - 1.9\ (A)^2$	0.94

Single entry = age (A).

SOURCE: The author (2014)

6.3.3 Logs >30 cm

The production of log >30 cm, unpruned and pruned, were analysed separately. The volume of unpruned logs >30 cm and obtained via thinnings were included, although their relative contribution to total production was quite small: 1, 3 and 13 % for the the treatments 'heavy', 'moderate' and 'extreme', respectively.

The development of timber production of unpruned logs >30 cm was plotted according to harvest age on Figure 6.3-3.

From Figure 6.3-3 it can be verified that trees in the stand 'without' thinning showed the lowest production level. The difference between the stand 'without' thinning and other thinned stands increased with time. However, variants 'moderate' and 'without' had similar volume production until age 20 years.

The ‘extreme’ variant resulted in the higher production level of unpruned logs >30 cm. A numerical superiority was observed during the whole study period (16-30 years), however statistically similar to the practice oriented variants from age 26 onwards (Figure 6.3-3). From age 22-24 years onwards, there was a clear segregation when the production of unpruned log assortments >30 cm in ‘extreme’ was highest and in ‘without’ lowest. The practice oriented variants were similar to each other and intermediate.

The volume development of pruned logs >30 cm produced at different harvest ages is presented in Figure 6.3-4. The ‘y’ axis scale used in Figure 6.3-3 was kept for comparison purposes.

The lowest production of pruned logs >30 cm was observed in stand ‘without’ thinning (Figure 6.3-4). Its production was negligible until age 20-22 years, and even later always less than 50 % of the amount verified in the thinned stands.

On the other hand, the ‘extreme’ variant delivered the greatest production of pruned logs >30 cm. Until age 18 years, stands subjected to the ‘heavy’ variant produced a similar volume of the same type of logs in comparison to the one verified in the ‘extreme’. From age 20 years onwards, no differences between thinned stands were detected.

Equations fitted for the volume development analysis regarding pruned logs >30 cm are given in Table 6.3-4.

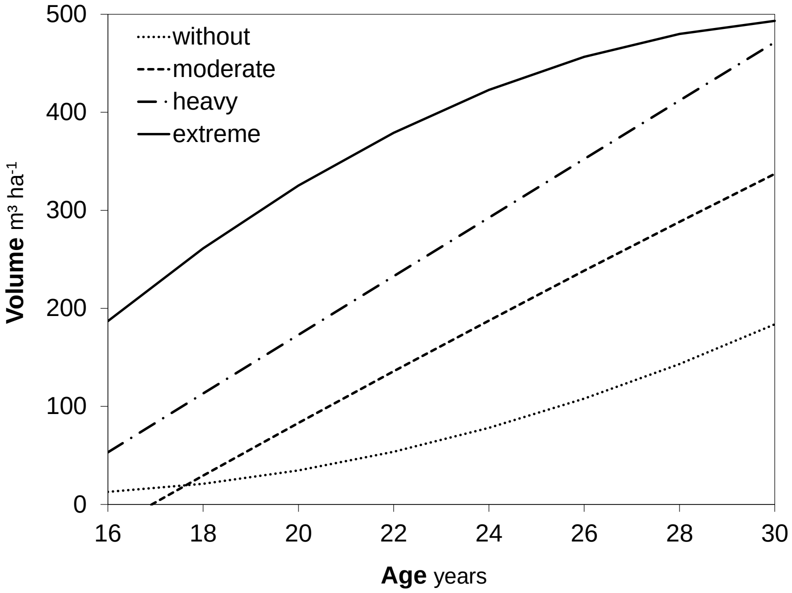


FIGURE 6.3-3: VOLUME DEVE-LOPMENT OF UNPRUNED LOGS >30 CM ($V_{UNPR. >30}$), OBTAINED THROUGH THE EQUATIONS 8-11 FROM AGE 16-30 YEARS AND FOR THE DIFFERENT THINNING VARIANTS. EQUATIONS ARE GIVEN IN TABLE 6.3-5.
SOURCE: The author (2014)

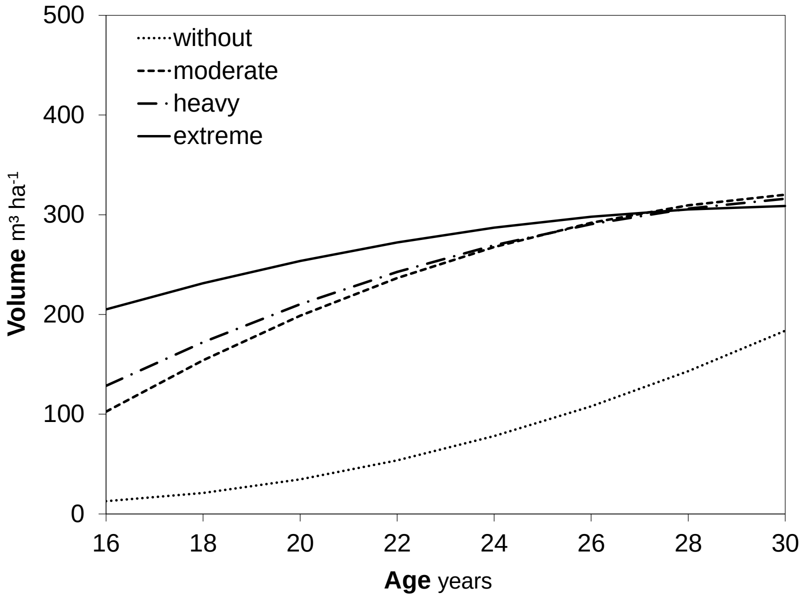


Figure 6.3-4: Volume deve-lopment of pruned logs >30 cm ($V_{pruned>30}$), obta-ined through the equations 12-15, from age 16-30 years and for the different thinning variants. Equations are given in Table 6.3-5.

Source: The author (2014)

Table 6.3-5: Equations fitted for volume deve-lopment analysis shown in Figure 6.3-3 and 6.3-4

Nr.	Thinning variant	**Equation**	R²
8	without	$V_{unpr.\ >30} = 141.1 - 18.8\ (A) + 0.7\ (A)^2$	0.99
9	moderate	$V_{unpr.\ >30} = -496.6 + 31.4\ (A) - 0.1\ (A)^2$	0.94
10	heavy	$V_{unpr.\ >30} = -428.8 + 30.2\ (A) - 0.01\ (A)^2$	0.98
11	extreme	$V_{unpr.\ >30} = -771.7 + 80.2\ (A) - 1.3\ (A)^2$	0.94
12	without	$V_{pruned\ >30} = -198.3 + 14.8\ (A) - 0.02\ (A)^2$	0.98
13	moderate	$V_{pruned\ >30} = -553.6 + 54.6\ (A) - 0.8\ (A)^2$	0.91
14	heavy	$V_{pruned\ >30} = -423.7 + 45.8\ (A) - 0.7\ (A)^2$	0.97
15	extreme	$V_{pruned\ >30} = -140.3 + 29.2\ (A) - 0.5\ (A)^2$	0.92

Single entry = age (A).

Source: The author (2014)

6.4 DISCUSSION

6.4.1 Volume of logs at age 30 years

Thinnings improved the growth of the potential crop trees and resulted in a greater amount of bigger logs. This effect is widely described in this and previous chapters.

Similar results of increasing diameter growth following thinnings are widely reported (HUSS, 1983; MOREIRA-WACHTEL, 2001; CLARK *et al.,* 2004; BROCKLEY, 2005; DEL RIO *et al.,* 2008).

Thinnings, moreover, did not reduce the total volume production, but even increased it as long as their intensity was not extreme.

Instead discussing the production of logs at age 30 years alone, it was done together with other harvest ages, as followed.

6.4.2 Log production over time

In Brazil, pines are currently managed mainly without thinnings and with harvest ages of 15-20 years (MAINARDI *et al.,* 1996; SCOLFORO *et al.,* 2001; CUBBAGE *et al.,* 2010). There is even a trend of decreasing harvest age. Although this practices might be suitable for mass production, a remarkable potential was observed for producing big-sized logs when thinnings are conducted and harvest ages are delayed.

It was verified that final harvest accounted for, at least, 70 % of the total wood production for the thinned stands at age 30 years. For the unthinned one, the final harvest was, obviously, 100 %. Although less than 30 % of the produced volume was harvest via thinnings, and normally delivering small-sized logs, it might be of importance if 'extreme' thinnings are early applied to the stand. For example, ~50 m^3 ha^{-1} of logs >30 cm were harvested already at age 13 years, when a 3rd thinning was carried out in the 'extreme' variant (Table 6.3-1).

The growth responses of pine trees early and 'extremely' released from competition resulted to an impressive volume production. This stand, even with only ~150 individuals ha^{-1} and already at age 16 years, resembled the volume production of the stand 'without' thinning, where the density was 1,300 trees ha^{-1} (Table 6.3-2 and -3).

- Results obtained in the present study were in line with the ones reported by Huss (1983), who studied the growth reactions of *Pinus sylvestris* trees to crown thinnings of different intensities in Germany. Accorded to the author, the goal of producing big size timber can be properly reached by applying early and heavy crown thinnings, with the clear objective of favouring selected potential crop trees. The author also reported that there was no significant negative effect on stem quality due to heavy thinnings. Instead the production of bigger and more valuable basal logs were obtained.

- However, Elesbão and Schneider (2011) studied the influences of 1 and 2 thinnings from below in loblolly pine stands in Southern Brazil. The authors found no differences on the diametric distribution as affected by thinnings at age 17 years. The contradiction observed by the authors might be related to the applied thinning method.

Thinnings from below, especially of low intensity, differently from crown thinnings, are not oriented to favour the individual growth of selected trees. Moreover, it may result in no additional growing space for the remaining trees. Hence, it is not surprising that thinnings ‘from below’ are not as efficient as ‘crown’ ones in improving tree dimensions.

- Similar to the present study, Scolforo *et al.* (2001) evaluated different management schedules in southern Brazil varying initial density, thinning and pruning procedures. Although it was a substantially economic study and used simulations instead field measurements, the authors reported that 3 thinnings and harvest age at 21 years resulted in better results than less or no thinnings, mainly due to the higher productions of big-sized assortments. However, the results were dependent of site class. To thin stands in poor sites was not recommended because remaining trees did not grew enough to compensate the reduction in total volume production.
- According to Hennessey *et al.* (2004), to thin loblolly pine stands in the United States increased the amount of logs >30 cm to 90 % of the total volume produced, while it was only 33 % in a unthinned stand. However, the authors reported a total volume reduction in thinned stands, which is contrary to the observed in the present study.
- Clark *et al.* (2004) summarized and re-evaluated at age 57 years a ‘sawn log study’ with loblolly pine in Arkansas, U.S. The study hypothesis was that it was possible to produce sawtimber-size trees in 30 years with intensive management:
  - thinnings between ages 9-19 years, so that at age 19 only 100 crop trees ha^{-1} remained,
  - pruning starting at age 9 years, being replicated every 3 years, so that at age 24 years, trees were pruned up to 10 m high,
  - understory growth was controlled every 2 years.

  - other stands were thinned from below to a residual basal area of 20 m² ha^{-1}, starting at age 12 and being replicated every 3 years until age 30 years, when stand density was ~300 trees ha^{-1}.

  The authors reported that diameter at breast height was 37 % greater in the intensively managed stand in comparison to the ones thinned from below (58 over 41 cm). In relation to the timber production, intensively managed butt logs yield 10 % more amount of the highest quality class, which resulted ~23 % more value for both, 1st and 2nd but logs. The authors also concluded that the pruning strategy should be intensified, since the one carried out resulted a knotty core up to 25 cm.

- Results obtained in previous studies of the same experiment cited above suggested the hypotheses of producing sawtimber in 30 years period was correct. Indeed, Burton and Shoulders (1974) reported that already at age 21 years, the intensive treatment produced the greatest sawtimber volume.
- Lewis and Fergusson (1993) pointed out that, if log size or quality are not relevant, thinnings might be not recommended, as the maximum growing potential of site would not be fully utilized. However, results found in the present study showed it is possible to increase the total production per area unit by applying ‘moderate’ and ‘heavy’ thinnings. In the ‘moderate’ one, there was an additional production of ~350 m³ ha-1 at age 30 years and in comparison to the stand ‘without’ thinning. It is important to note that a similar amount of wood was lost due to mortality in the unthinned stand.
- According to Bravo and Diaz-Balteiro (2004), besides the larger dimensions of logs, the lengthening of rotation would be also justified to obtain a greater percentage of high-quality wood. Results obtained in Chapter 5 WOOD QUALITY are in line with this argument.

6.4.3 Log >30 cm

When big-sized logs are the management goals, unthinned stands take longer to produce reasonable amounts of such assortments and could be considered inefficient for this purpose. At least until age 20 years, this treatment has a negligible production of unpruned logs >30 cm (Fig 6.3-3). Moreover, it reached the age of 30 years with 50 % of the production of logs >30 cm verified in the ‘moderate’, and ~30 % of the one in the ‘extreme’ and ‘heavy’ variants.

At age 30 years, the proportion of logs with the small-end diameter >30 cm was highest in the ‘extreme’ variant, totalising ~75 % of whole volume production. On the other extreme, the stand ‘without’ thinning had only ~45 %. The practiced-oriented variants showed intermediate values, ~55 %.

Although the ‘moderate’ variant produced a great amount of total wood, when only the unpruned logs >30 cm were regarded, it was only more efficient than the stand ‘without’ thinning, and this after age 22 years.

In general, it was verified that treatments ‘moderate’ and ‘heavy’ are capable to efficiently produce pruned logs >30 cm with harvest ages higher than 18 and 20 years. However, the ‘extreme’ variant delivered a similar amount of >30 cm pruned logs ~5 years earlier in the than the practiced oriented did.

Regarding only pruned logs >40 cm, differences between thinning variants were even greater. At age 30 years, the ‘extreme’ variant produced more than 3 times (225 m^3, 24 % of total production) the amount observed in the stand ‘without’ thinning (60 m^3, 7 %). The ‘heavy’ variant was as efficient as the ‘extreme’ one. The treatment ‘moderate’ delivered a lower production than the other thinned ones, however, still 3 times higher (190 m^3) than the unthinned one.

6.5 CONCLUSIONS

For the studied conditions, loblolly pine stands subjected to

- No thinning results in a great wood loss due to mortality and is not efficient in producing big-sized logs. Until age 20 years, only small amounts of unpruned and pruned logs >30 cm are produced (~150 m^3 ha^{-1} each). At age 30 years, unthinned stands deliver less than ½ of the volume of pruned >30 cm logs obtained in the ‘heavy’ and ‘extreme’ variants.
- ‘Moderate’ and ‘heavy' thinnings result in the highest total volume production, up to 35 % more than unthinned stands at age 30 years. However, when unpruned logs >30 cm are regarded, ‘moderate’ thinnings are only as efficient as unthinned stands until age ~20 years.

- Early and extremely release of selected potential crop trees from competition (‘extreme’ variant) produce the same amount of wood than unthinned stands within production periods varying from 16 (~700 m^3 ha^{-1}) to 30 years (~1,000 m^3 ha^{-1}). It is also more efficient in producing big-sized assortments (deliver more and earlier) – it provides the same amount of pruned logs >30 cm 5 years earlier than practice oriented variants. In a 30 years long production period, ~500 and ~300 m^3 ha^{-1} of unpruned and pruned logs >30 cm, respectively, are to be expected.

In general, it can be concluded that substantial productions of log assortments >30 cm are possible within production periods <20 years only if early and extreme thinnings are applied to the stands. By concentrating the growth in 400 potential crop trees ha^{-1} there is no volume ha^{-1} loss in relation to the production obtained in unthinned stands. However, if production periods are >25 years, intermediate thinnings deliver reasonable amounts of logs >30 cm together with a surplus of timber production.

Notwithstanding, the production of logs >50 or even >60 cm are only feasible if extreme crown thinnings are regarded.

7 INDUSTRIAL YIELD OF LOGS FOR SAWTIMBER AND VENEER PRODUCTION: AN ANALYSIS INCLUDING BIG-SIZED LOG DIAMETERS

7.1 INTRODUCTION

Pines have not been widely pruned and thinned in southern Brazil, and the logs obtained at the standard harvest ages of 15-20 years are of relative small diameters. The main goal of this management schedule is to maximize the production of volume aiming at supplying raw material for the paper and board industries. However, log producers which are not linked to industrial plants can diversify their production, for supplying different market niches, including those in which high quality timber is demanded. According to Mancini (2011), the risks inherent to the forest activity are reduced through multi-product regimes. Moreover, they might increase profitability, since the market will always valorise high quality timber.

Stands managed for multiple-use products supply logs for a wide range of wood based industries:

- Sawtimber is currently used in several low-requirements applications. However, there are high quality ones, in which loblolly pine timber could be outstandingly utilized.
- Veneer products, such as plywood and laminated veneers, have been developed as an alternative to solid products (TENORIO *et al.,* 2011). According to Pfriem and Buchelt (2011), lamination is the most efficient way of using wood, either through rotary peeling or slicing techniques.

Of particular importance for recovery rate and quality of veneer production are log diameter and internal knottiness, as the grading rules existing worldwide confirm. Methods that predict veneer yields obtained from trees and tree components are an essential assessment (LYNCH; CLUTTER, 1998).

The sliced lamination technique is preferable for the production of high quality veneers sheets, commonly used for decorative purposes. This is the case for sliced veneers produced with pines in southern Brazil (ABIMCI, 2004). The market, however, is restricted, with comparatively low volume demanding. According to Polzl (2002), in 2001, ~35,000 m³ of sliced veneers were produced in the state of Paraná, Brazil, 2 %

of the solid wood production of that year. Pine veneer accounted for 16 % of the whole amount.

However, the low volume is compensated by the high value obtained by the sliced veneers (GROSSHENNING, 1971; FUCHS, 1982; BUCHELT; WAGENFÜHR, 2007).

Furthermore, the strategy of producing high quality logs could be interesting for both wood producer and the wood industry (CARINO; BIBLIS, 2000, 2009; COWN, 2005). Managing stands with multiple-products goals allows delivering a great variability of logs, which can be optimally used in different industries. However, reliable data about the industrial processing of logs obtained from fast growing pine stands are still missing in Brazil.

Analyses were carried out by monitoring standard industrial processes. The specific objectives were to analyse the performance of logs assorted by diameter classes on the yield, quality and economic performance of

- sawing process,
- rotary peeled veneer,
- sliced veneering.

An overview of the different products obtained from the monitored industrial processes are shown in Figure 7.1-1.

FIGURE 7.1-1: PRODUCTS OBTAINED FROM THE EVALUATED INDUSTRIAL PROCESSES. SAWTIMBER OF DIFFERENT DIMENSIONS (LEFT); ROTARY PEELED VENEER TOTALLY FREE OF DEFECTS (UP RIGHT); AND SLICED VENEER SHEETS (DOWN RIGHT)

SOURCE: The author (2014)

Industrial analysis are shown below, starting with the sawing process.

7.2 SAWMILL

7.2.1 Material and methods

7.2.1.1 Data collection

In total, 37 logs were harvested, identified and transported (~13 t) to a medium-sized sawmill, with an average consumption of ~3,000 tons month^{-1}. The conversion ratio of m^3 ton^{-1} for the transported logs was 1.01.

The small-end diameter (SED) of the logs varied between 20-57 cm, corresponding to 0.1-0.8 m^3 per log. All logs were unpruned, obtained from the higher stem parts (3rd-10th log).

For the financial evaluation, commercial values per log assortment provided by the enterprise Florestal Gateados were regarded (personal communications, 2011). Values in U.S. Dollar (US$), converted from Real (R$) at an exchange rate of R$ 2.04 = US$ 1.00 (Brazilian Central Bank, Mai 2013). However, for the yield analysis, logs were reclassified in 5 cm wide diameter classes, as shown in Table 7.2-1. The class '>50 cm' hold logs up to 57 cm.

Although a slight difference between ton and m^3 exists, it was considered 1:1, where the prices per ton where regarded for obtaining logs price per m^3. For illustrative purposes, the prices per m^3 obtained after dividing average logs value by the volume of logs within the same diameter class are also shown in Table 7.2-1.

TABLE 7.2-1: DIAMETER CLASSES, NUMBER OF LOGS, MEAN LOG VOLUME AND PRICES PER LOG AND M³.

Original diameter classes and prices provided by Florestal Gateados (2011):

- 18-24.9 cm: 33 US$ ton^{-1},
- 25-34.9 cm: 45 US$ ton^{-1},
- >35 cm: 61 US$ ton^{-1}.

SOURCE: The author (2014)

Diameter class cm	Logs	V_{log} m^3	Value US$ log^{-1}
20-24.9	4	0.11	4
25-29.9	6	0.20	9
30-34.9	9	0.25	12
35-39.9	7	0.33	21
40-44.9	4	0.42	29
45-49.9	3	0.52	33
>50	4	0.68	44

The sawing process was carried out in a conventional way, representative to southern Brazil, similar to the one described by Manhiça (2010):

- Band saw, cut 3 mm width (manufactured by ‘Schiffer’, model STE 125),
- Horizontal band saw with 2 heads, cut 3.5 mm width (manufactured by ‘Vantec’, model SFH2-800).
- Squaring of blocks by 2 circular saws, parallel to each other (‘Vantec’, SFH7/1);
- Finally, boards obtained through a multiple circular saw, with 6 saws and cut width of 3.5 mm (manufactured by ‘Mendes’).

Logs were randomly processed. Previous to sawing, the operator visually analysed the log and decided for the best cutting schema.

The pieces resulted from the sawing process were identified, counted and measured, which allowed the assessment of individual log yield. As it was aimed at evaluating a standard process, no quality classification of the boards was carried out, hence these practice is not currently done by the sawmill. According to the sawmill owner, there is no respective demand on the market. Noteworthy is that only unpruned logs are sought after by the market, which are applied for low requirement uses: building forms, fence, inside parts of furniture.

7.2.1.2 Data analysis

The concept of volume yield described by Rocha (2000) was regarded, where the yield is the relation between the volume of the products and the log total volume over bark.

A frequent terminology used by the timber industry is the amount of logs in m³, necessary for producing 1 m³ of sawtimber, named ‘conversion factor’.

The products obtained in the sawn process are described in Table 7.2-2 in order of increasing value. The piece dimensions are the ones regarded for commercialization. The real dimensions of the sawtimber are greater, 9 % in average. This additional volume is left to compensate losses during further processing steps, like planning and drying.

The commercial value of each product was provided by several sawmills in the region, thus reflecting mean data.

TABLE 7.2-2: WIDTH, THICKNESS AND LENGTH OF THE BOARDS, THEIR VOLUMES AND MARKET VALUES.

Pieces with constant length of 3 m.

SOURCE: The author (2014)

Product	width	thickness	volume	value
	mm	mm	m^3	US$ m^{-3}
1	100	25	0.008	137
2	150	25	0.011	137
3	200	25	0.015	137
4	250	25	0.019	137
5	100	50	0.015	147
6	150	50	0.023	147
7	300	50	0.045	167

From the Table 7.2-2 it can be seen that prices are equal when thickness is 25 mm, regardless of board width. Increases in price are verified when board thickness increase to 50 mm and, finally, when width reaches 300 mm.

The economic benefit of each log and, therefore, for a specific diameter class was assessed throughout the difference between the log individual price in US$, named purchase value, and the gross revenue, obtained by selling all the products originated from the same log. No further production costs were regarded.

7.2.1.3 Statistical analysis

Statistical analyses were done considering a fully randomized sampling design. Significance levels and mean tests followed the standard method already described in Chapter 3 MATERIAL AND METHOD.

Standard regression techniques were used. Firstly, regression models for predicting yield depending on log dimension were fitted. The variables used for modelling were tested in a correlation analysis and then included in the regression analysis. Only terms with significant F-values ≤0.05 were regarded. The coefficient of determination (R^2), standard error (S_{yx}) and residual analysis were used as criteria for selecting the best fitted models.

The same approach was used for rotary peeling and sliced veneering and, therefore, are not described in the respective sub-chapters.

7.2.2 Results

7.2.2.1 Yield and conversion factor

The yield of sawtimber volume in relation to the log volume over bark and according to the small end diameter (SED) is shown in Figure 7.2-1.

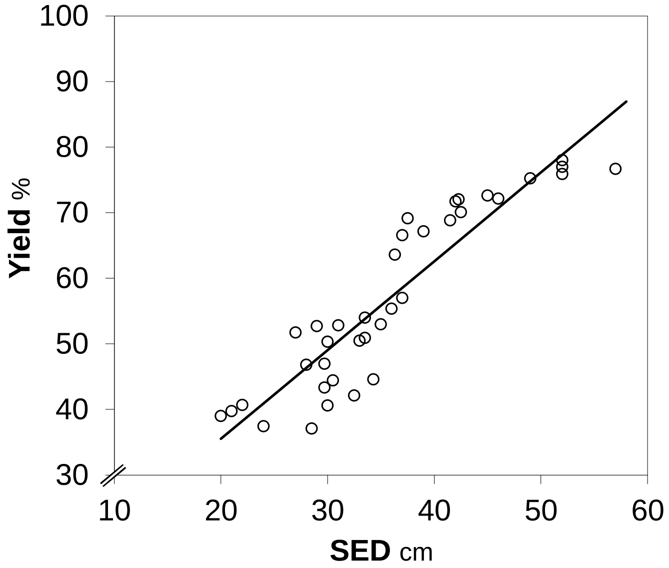


FIGURE 7.2-1: SAWTIMBER YIELD (CIRCLES, %) ACCORDING TO LOG DIAMETER AT SMALLER END (SED). THE EQUATION OF THE LINEAR TREND IS SHOWN BELOW

Yield= 8.431+1.354 (SED) $R^2 = 0.84$ $S_{yx} = 9.6$ %

SOURCE: The author (2014)

From Figure 7.2-1 it can be seen that log's yield varied between 37-78 %, within the analysed diameter amplitude, with a linear trend of increasing yield by increasing small-end diameter. Great differences of yield were observed within similar diameter class, obviously as a result of log taper and tortuosity.

The mean yield and the conversion factor per diameter class are shown in Table 7.2-3.

It has been verified that the **yield** statistically differed between diameter classes. Log assortments with small-end diameter of ≥35 cm had a significant higher yield than the smaller ones. A second differentiation was observed for the assortments >45 cm.

In relation to the **conversion factor**, significant differences were also detected, showing a pattern similar to the one observed for yield. However, and although the amount of m^3 needed to obtain 1 m^3 of sawn product keeps decreasing with increased SED of logs, there was no difference between assortments bigger than 35 cm, which were superior in comparison to the others.

TABLE 7.2-3: YIELD AND CONVERSION FACTOR DEPENDING ON DIAMETER CLASS OF LOG.

SOURCE: The author (2014)

Diameter class cm	**YIELD** %	**CONVERSION** $m^3\ m^{-3}$
20-24.9	39.2 a	2.55 a
25-29.9	46.4 a	2.18 ab
30-34.9	47.8 a	2.11 b
35-39.9	61.7 b	1.64 c
40-44.9	70.7 bc	1.42 c
45-49.9	73.3 c	1.36 c
>50	76.9 c	1.30 c
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7.2.2.2 Economic aspects

The purchase costs and the gross revenues per log are shown in Figure 7.2-2.

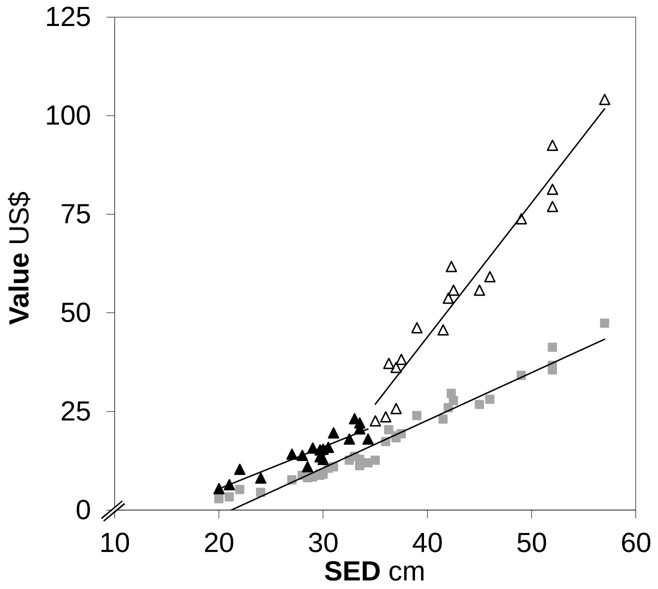


FIGURE 7.2-2: COSTS (SQUARE) AND GROSS REVENUE FOR THE LOG ASSORTMENTS UNTIL 34.9 CM (BLACK TRIANGLE) AND >35 CM (WHITE TRIANGLE), PER LOG, ACCORDING TO THE SMALL END DIAMETER (SED). LINEAR TRENDS ARE SHOWN BELOW

Cost= -25.667+1.211 (SED)	$R^2 = 0.96$
$Revenue_{20\text{-}34.9}$= -15.771+1.059 (SED)	$R^2 = 0.83$
$Revenue_{>35}$= -92.353+3.406 (SED)	$R^2 = 0.94$

SOURCE: The author (2014)

It could be observed that costs and revenues per log increased in linear form with increasing log SED. However, the gross revenue obtained from the logs >35 cm showed a more sloped pattern than the ones ≤34.9 cm. Thus, two different regression lines were fitted.

Aiming a better understanding of the economic aspects related to the different assortment classes, the individual economic benefit was assessed: gross revenue minus log cost, divided by log cost. No further production costs were regarded. The values per log are shown in Figure 7.2-3.

From Figure 7.2-3 it can be verified that logs with SED <25 cm had a relative economic benefit higher than the intermediate assortments and similar to the bigger-sized ones. These intermediate assortments (25-34.9 cm), resulted in the lowest economic benefits, but showed also a great amplitude of values, varying between 25-70 %. The logs >35 cm shifted again to the 80 % level and higher.

Statistical analyses proved the explained differentiation between stems of the assortment classes. The economic benefit provided by the assortments '20-24.9 cm' and '>45 cm' were similar and higher. The classes between 25-34.9 cm were similar and lowest. Finally, the classes between 35-44.9 cm were similar to each other and with the adjacent assortment class (Figure 7.2-3).

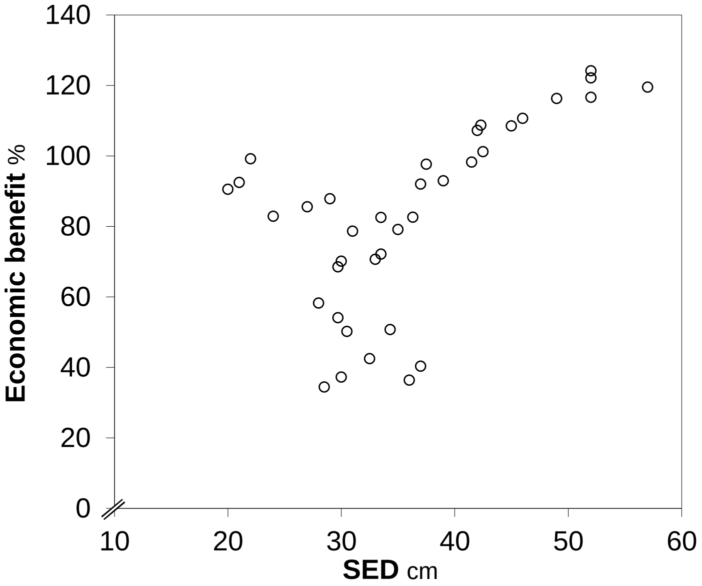


FIGURE 7.2-3: ECONOMIC BENEFIT (GROSS REVENUE MINUS LOG COST) ACCORDING TO LOG SMALL END DIAMETER (SED).

SOURCE: The author (2014)

7.2.3 Discussion

7.2.3.1 Yield and conversion factor

A linear trend of increasing sawtimber yield by increasing small-end diameter was observed (Figure 7.2-1). The same pattern has been described by previous studies (VIANNA NETO, 1984; FREITAS, 1986; MANHIÇA, 2010). The average yield was 57 %, similar to values previously reported, 50-54 % (PINTO *et al.,* 2006; OLANDOSKI *et al.,* 1998; MANHIÇA, 2010; MURARA *et al*., 2005). Moreover, the mean value found in the present study was within the range pointed out by Cardoso Jr. (2008), 33-62 %.

Log assortments with SED of ≥35 cm provided higher yields than the range from 20-34.9 cm, which were similar. A second differentiation was observed for the log assortments bigger than 45 cm. Comparatively, Manhiça (2010) analysed smaller log assortments, and found the highest yield level for assortments ≥30 cm.

When assortments up to 35 cm are considered, the values observed in the present study were comparable to the ones reported by Ribas *et al*. (1989), Fontes *et al*. (1994) Brand *et al.* (2002) and Manhiça (2010) who reported values between 30-48 %

Regarding log assortment classes ≥45 cm, a previous study reported yields up to 64 % (MURARA JR., *et al.* 2005), similar to the values found in the present study. However, lower values were found by Biasi and Rocha (2003), 47 %.

Studies with assortment classes over 50 cm are rare in Brazil. Pinto *et al.* (2002), evaluating the yield of *Pinus pinaster* logs in Portugal, found values between 40-59 %, slightly lower than the ones verified in the present study.

7.2.3.2 Economic aspects

The yields and the revenues were strongly affected by the products obtained from the logs. Only from the assortment ‘35-39.9 cm’ and onwards, the board with 300 x 50 mm (product 7, Table 7.2.2) was obtained and, because of its high commercial value, the gross revenues obtained by these assortments were not only affected by the higher yield (Table 7.3-1), but also by the production of this valuable product. However, logs with SED exactly 35 cm showed a gross revenue similar to the previous diameter class. In fact, only logs >36 cm were able to deliver the mentioned product.

It was verified that logs with diameter <25 cm provided a relative economic benefit higher than the intermediate assortments (25-34.9 cm) and similar to the bigger-sized ones. This was the result of the low purchase price of the small-sized assortments, in average 4 US$ log^{-1}, while the sawn products totalled ~16 US$ log^{-1}, which in relative terms means 92 %.

Log assortments between ‘25-34.9 cm’ showed the lowest economic benefits, in average 63 %, while logs >35 cm shifted again to a higher level (~97 %), similar to the small-sized assortments.

Results obtained in the present study help understanding why log assortments around 30 cm are of difficult commercialization, while there is a constant demand for logs >35 cm.

According to Murara Jr *et al.* (2010), the purchase cost of logs comprises ~75 % of the whole sawing production costs. It means that the intermediate assortments (25-34.9 cm) were close to a negative economic result.

7.3 ROTARY PEELING

7.3.1 Material and methods

7.3.1.1 Data collection

From 24 trees, a total of 57 logs with a length of 2.40 m were cut and transported to a medium sized plywood mill. The mean conversion ratio of m³ ton^{-1} for the transported logs was 1.07. All logs from the experimental trial were peeled, even the ones with a small-end diameter less than 25 cm, which generally are not used in the plywood industry. Logs were not debarked before peeling, all diameter were measured over bark.

Out of the 57 logs 24 were pruned (2nd log). The bottom logs were not included in the study about yield of rotary peeling, since they were used for the sliced one (item 7.4).

Average log diameter and log length were used for calculation of the input volume.

For economic evaluation, assortments were classified by small-end diameter and its respective price, provided by the forest enterprise (Florestal Gateados, personal communications, 2011), which are representative of the regional market.

Since diameter classes for log prices were not uniform and varied widely, for modelling purposes more narrow and constant classes of 5 cm width were considered more efficient (Table 7.3-1). The log assortment named '>50 cm', for unpruned logs, was composed of logs with a maximum diameter of 56 cm at small-end. Similarly, for the pruned '>50 cm' assortment, the largest small-end diameter reached 67 cm.

TABLE 7.3-1: LOG ASSORTMENTS CLASSIFIED BY SMALL-END DIAMETER AND PRUNING, NUMBER OF LOGS, LOG POSITION WITHIN A TREE, AVERAGE VOLUME (V_{LOG}) AND COMMERCIAL VALUE PER LOG

Diameter class cm	Number of logs	Log position	V_{log} m^3	Value US$ log^{-1}
UNPRUNED				
20-24.9	1	9	0.11	4
25-29.9	8	6-9	0.14	6
30-34.9	7	3-8	0.19	8
35-39.9	7	3-7	0.27	16
40-44.9	6	3-7	0.33	19
45-49.9	2	4-5	0.43	25
>50	2	3-4	0.57	32
PRUNED				
20-24.9	1	2	0.08	4
25-29.9	2	2	0.13	8
30-34.9	3	2	0.21	12
35-39.9	1	2	0.29	17
40-44.9	3	2	0.34	31
45-49.9	7	2	0.41	39
>50	7	2	0.52	61

Original diameter classes and prices provided by Florestal Gateados (2011) for **unpruned:**

- '18-24.9 cm': 29 US$ ton^{-1}.
- '25-34.9 cm': 40 US$ ton^{-1}.
- '>35 cm': 55 US$ ton^{-1}.

and **pruned** logs:

- '25-39.9 cm': 55 US$ ton^{-1}.
- '>40 cm': 90 US$ ton^{-1}.

SOURCE: The author (2014)

Although a slight difference between ton and m³ exists, a 1:1 relation for the economic analysis was regarded adequate. This is the standard method used by managers in the praxis.

Rotary peeling process included:

- Steaming of logs covered with tarpaulin during 15 hours at ≥60 °C.

- Rotary peeling with a 2.800 x 100 mm rotary lathe (log length x minimum core), manufactured by 'Henrique Benecke Máquinas Industriais'.
- A fixed knife parallel to the central axis of the logs reduced the veneer length to 2.30 m.

In general, after the peeling process, a standard core of 100 mm of diameter remains. However, since the normal industrial process was used, some cores of poorer quality (excessive knots and other defects) were left in bigger dimensions by the operator.

Due to technical limitations of the equipment, limits in fixing the big-sized logs were observed. The forces acting in the peeling process of bigger logs are much higher at the beginning of the peeling than in smaller logs. The two clamps of the chuck which fixed the log were not designed for peeling logs of bigger dimensions. Those of the machine used in the experiment only grabbed in the juvenile core zone of the pith, causing slipping of the logs. Even the rotary lathe machine used represents a high standard in the Brazilian plywood industry; it was not fully adapted to the conditions of the experiment, specifically for the logs bigger than 45 cm.

Veneer was peeled into 3-mm sheets. The amount of veneer was addressed to each one of the log from which it originated. Furthermore, veneers were visually graded by the operator just before cutting in the respective dimensions (Table 7.3-2). Grading rules followed the national standards (ABIMCI, 2002).

TABLE 7.3-2: DIMENSIONS, VOLUME AND COMMERCIAL VALUE OF THE PRODUCED VENEER SHEETS. THICKNESS (3 MM) AND LENGTH (2.30 M) WERE KEPT CONSTANT IN THE PRODUCTION PROCESS

Product	Specification	width mm	volume m³	value US$ m^{-3}
A	clear of knots and other imperfections	1,240	0.009	314
B	until 10 green knots per sheet, with <10 mm of Ø	1,240	0.009	230
C	no limits related to knots	1,800	0.012	169
R	no limits related to knots	280	0.002	48

SOURCE: ABINCI (2002)

Commercial values correspond to the average market prices in the region of Lages, SC, Brazil, sold by the rotary peeling veneer industry. Cores as well as other by-products were not regarded.

7.3.1.2 Data analysis

Length, width and thickness of veneers were taken as constant for the recovery analysis.

Theoretical recovery, as the maximum recovery rate to be obtained for a log, was determined by the difference between the volume of the log small-end diameter under bark and a residual core 10 cm of width.

From the difference between individual log prices, and the gross revenue obtained by them, it was possible to determine the economic benefit depending on the log diameter. Other costs were not considered in this study.

7.3.2 Results

7.3.2.1 Yield and conversion factor

The correlation analysis after Pearson showed that small-end diameter (SED) was the variable with highest correlation coefficient with log relative recovery (0.695). In fact, all of them were significantly correlated with the target variable, except log taper (Table 7.3-3).

Log number within the tree and relative knotty core zone were negatively correlated to the recovery rate.

Although mean log taper was 1.2 cm per 1 m of log length, it varied from 1.6 cm m^{-1} for the logs localised between 2.40 and 4.80 m of the tree height (2nd log), and 0.9 cm m^{-1} for the logs of higher sections. The largest analysed log, with a small-end diameter of 67 cm, had a taper of 4.6 cm m^{-1}, which explains, at least partially, the low recovery rate observed in this sample. The fact that the variable is not correlated significantly to recovery rate in this study might be due to the large number of logs with low taper. For a stratification of the logs after height of the log section in this study the number of observations in each class were too low for statistically representative results.

The stepwise regression procedure for modelling recovery rate selected ‘SED’ and ‘V_{total}’ as the two most significant variables (Table 7.3-3). ‘SED’ explained 48 % of the occurring variance, while ‘V_{total}’ contributed another 5.5 %, reducing the standard error of the model from 6.6 to 6.2.

TABLE 7.3-3: PEARSON COEFFICIENT OF CORRELATION AND PROBABILITY BETWEEN ANALYSED VARIABLES

Variable	Recovery	LED	AD	SED	V_{total}	$V_{cylinder}$	Knotzone	Log_{taper}	$Log_{position}$
Recovery	1								
LED	0,656***	1							
AD	0,677***	0,997***	1						
SED	0,695***	0,986***	0,996***	1					
V_{total}	0,630***	0,990***	0,988***	0,979***	1				
$V_{cylinder}$	0,651***	0,985***	0,991***	0,989***	0,996***	1			
Knotzone	-0,325***	-0,550***	-0,544***	-0,535***	-0,546***	-0,542***	1		
Log_{taper}	$0,077^{ns}$	0,503***	0,433***	0,354***	0,483***	0,404***	-0,315***	1	
$Log_{position}$	-0,349***	-0,524***	-0,535***	-0,542***	-0,517***	-0,526***	0,591***	-0,135	1

LED: large-end-diameter; AD: average diameter; SED: small-end-diameter; V_{total}: log total volume; $V_{cylinder}$: log volume obtained by small-end-diameter; Knotzone: relative knotty core zone; Log_{taper}: reduction in diameter (cm) per length (m); Log_{number}: between 2nd and 9th (*p<0.1; * *p<0.05; * * *p<0.01).

SOURCE: The author (2014)

However, the variance inflation factor was equal to 24, indicating a high multicollinearity between both variables. Because of marginal contribution of the 'V_{total}' variable to the recovery estimation, only 'SED' was used on the final equation, utilized in the further analysis. A second reason for omitting 'V_{total}' is the problem of multicollinearity between both variables. Although adding variables such as 'Knotzone' and '$Log_{position}$' to the model could be of practical relevance, it showed no improvement to the estimation quality and therefore were not considered (Table 7.3-4).

TABLE 7.3-4: SUMMARY OF THE DIFFERENT MODELS FOR PREDICTING RECOVERY RATE, CONSIDERING INFLUENCING VARIABLES

Model	lower	β_0	upper	lower	β_1	upper	lower	β_2	upper	R^2	S_{yx}
1 (SED)	23.5	30.403	37.3	0.4	0.602	0.8				0.48	6.56
2 (SED, V_{total})	-6.8	9.667	26.1	0.9	1.657	2.4	-107.2	-61.968	-16.7	0.55	6.20
3 (SED, Knotzone)	14.2	27.277	40.4	0.4	0.633	0.8	-5.9	2.313	10.5	0.49	6.60
4 (SED, $Log_{position}$)	18.4	29.035	39.7	0.4	0.621	0.8	-0.8	0.157	1.1	0.48	6.61

β_i: parameters values; lower and upper bounds of the 95% individual prediction interval (CLI); R^2: coefficient of determination; S_{yx}: Standard error of the estimate.

SOURCE: The author (2014)

Predicted recovery rate obtained throughout the equation 1 compared to real recovery rate is shown in Figure 7.3-1.

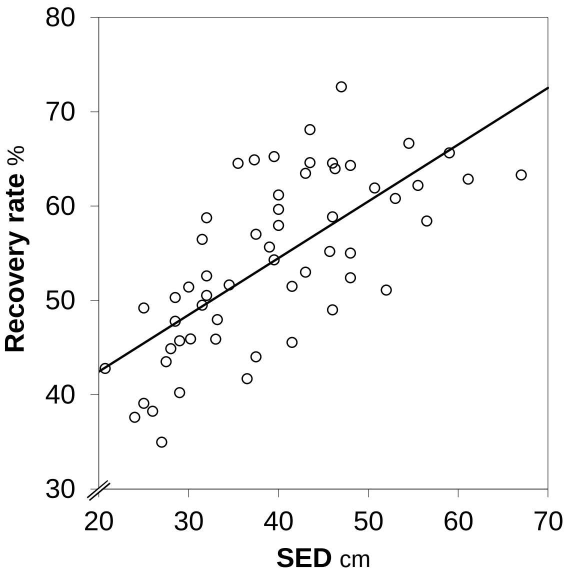


FIGURE 7.3-1: RECOVERY RATE OF PRODUCED VENEER (CIRCLES, %) AND PREDICTED LINE (EQUATION BELOW) ACCORDING TO LOG SMALL-END DIAMETER (SED)

Recovery rate= 30.403 + 0.602 (SED) $R^2 = 0.48$ $S_{yx} = 12.1$ %

SOURCE: The author (2014)

Residual analysis of the recovery model indicated unbiased prediction. However, it is important to note that the fitted equation is only valid if the independent variable is kept within the ranges of the data used for estimating the model parameters.

Results showed that average recovery was 54 %, ranging from 35-73 %, with a linear trend of increasing recovery with an increment on the log small-end diameter (SED). Although the linear trend has shown a relatively weak coefficient of determination ($R^2 = 0.48$), the trend indicates that the veneer recovery increases at a rate of 0.6 % per unit increases in log diameter.

Logs of the diameter class '20-24.9 cm' were not analysed due to the small number of logs (2) in this class. Significant differences were detected for the recovery rate ($p<0.01$) among assortments. In the class of '35-39.9 cm' the recovery rate resulted in statistically similar values compared to the logs >50 cm. Theoretical recovery was calculated for each assortment and the difference between the latter and the real one (Diff.) was calculated in order to evaluate assortment recovery efficiency. Results are presented in Table 7.3-5.

The veneer grading analysis showed an expected result. Unpruned logs did not produced 'A' grade veneer, while the pruned ones did, with an increasing proportion reaching its peak by 35 cm of SED (Figure 7.3-2).

TABLE 7.3-5: REAL AND THEORETICAL MEAN RECOVERIES OF THE ASSORTMENTS BY DIAMETER CLASSES WITH THE DIFFERENCE BETWEEN BOTH (DIFF.)

Diameter class cm	REAL RECOVERY %		THEORETICAL RECOVERY %	Diff.
20-24.9	-		-	-
25-29.9	43.4	a	71.7	28.3
30-34.9	51.1	b	74.6	23.5
35-39.9	55.9	b c	78.2	22.3
40-44.9	58.3	b c	79.9	21.6
45-49.9	59.6	b c	79.0	19.4
>50	61.4	c	79.5	18.1
STATIS. SIGNIF.	* * *		-	-

SOURCE: The author (2014)

For both unpruned and pruned logs, logs with >35-40 cm provided the greatest proportion of the best quality classes. After these diameters, an increase in ‘C’ and ‘B’ classes was verified.

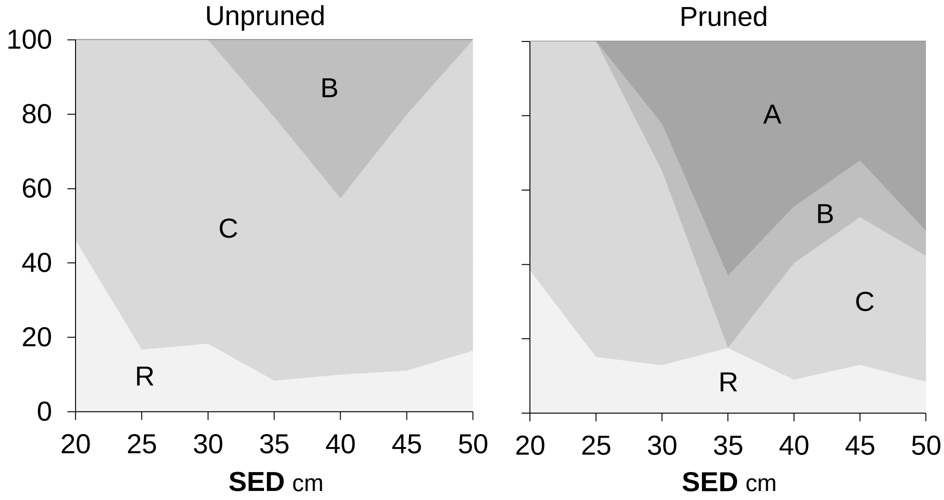


FIGURE 7.3-2: PROPORTION OF VENEER ACCORDING TO ITS QUALITY CLASS AND DEPENDING ON SMALL-END DIAMETER OF PRUNED AND UNPRUNED LOGS.

Grading according to ABIMCI (2002): A = clear; B = till 10 green knots per sheet (Ø <10 mm); C = no limits; R = sheets with only 280 mm width

SOURCE: The author (2014)

7.3.2.2 Economic aspects

An economic analysis was done in order to evaluate the current status of log purchase price and the value of the products obtained from it (Figure 7.3-3). Purchase costs, as well as revenue per log showed an exponential trend. Trends shown in Figure 7.3-3 were obtained by the equations presented in Table 7.3-6 (equations 1-6).

Logs with knotty core zones <39 % of the small-end diameter (5 logs) were utilised for simulating a maximum revenue model, while the other trees (13 logs), with knotty cores ranging from 44 to 88 % of diameter were used for showing the minimum trend. In other words, the maximum trend provided the performance of an appropriate pruning schedule, while the minimum one shows the performance of not-optimally pruned logs.

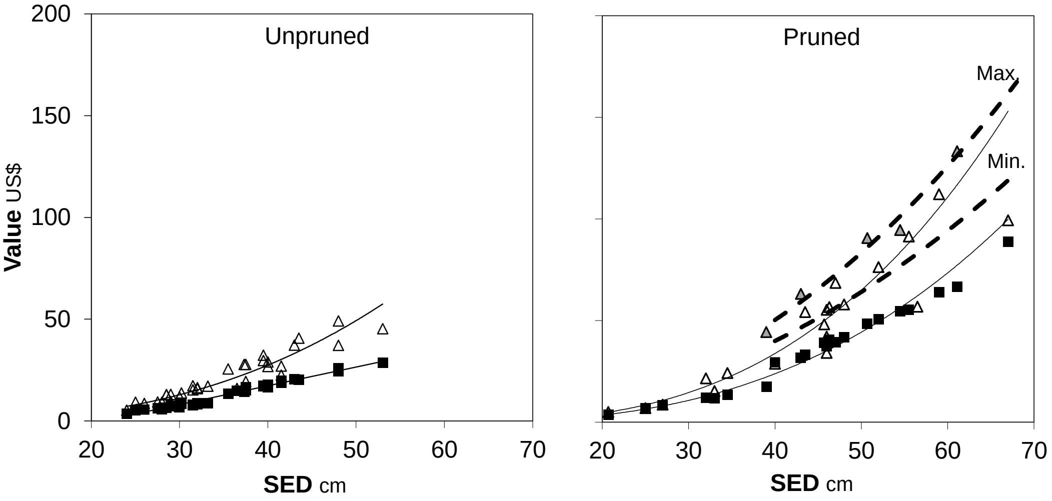


FIGURE 7.3-3: COSTS (SQUARE), GROSS REVENUE (TRIANGLE) FOR THE PRUNED AND UNPRUNED LOG ASSORTMENTS DEPENDING ON SMALL-END DIAMETER (SED); POWER TRENDS FOR DATA (FULL LINE); MAXIMUM (MAX.) AND MINIMUM (MIN.) TRENDS DEPENDING ON KNOTTY CORE RATIO; PRUNED LOGS WITH KNOTTY CORE ZONE LESS THAN 39 %, RELATIVE TO SED ARE HIGHLIGHTED AS GREY TRIANGLES

SOURCE: The author (2014)

TABLE 7.3-6: EQUATIONS FITTED THROUGH DATA SHOWN IN FIGURE 7.3-3

Single entry = small-end diameter (SED).

SOURCE: The author (2014)

Nr.	**EQUATION**	R²
1	Max. revenue= 195.6 $(SED)^{1.133}$	0.98
2	Min. revenue= 142.0 $(SED)^{1.058}$	0.84
3	$Revenue_{pruned}$= 0.001 $(SED)^{2.928}$	0.92
4	$Cost_{pruned}$= 0.001 $(SED)^{2.777}$	0.98
5	$Revenue_{unpruned}$= 0.001 $(SED)^{2.627}$	0.91
6	$Cost_{unpruned}$= -19.7+0.9 (SED)	0.98

The maximum and minimum trends shown in Fig 7.3-3 as absolute values are presented as relative ones in Figure 7.3-4. Maximum and minimum trend lines proved that logs with knotty core zones bigger than 40 % negatively influenced the potential economic revenue in a significant way.

The knotty core zone in % for each analysed log (Figure 7.3-5) allows a better understanding of the reasons which led to the unexpected low economic benefits for some of the pruned logs. As the log with knotty core less than 40 % were highlighted, it is clear that the majority of the pruned analysed logs had a knotty core higher than 50 %. Surprisingly some of the pruned logs had a knotty (or other defects) core of about 100 % of the log small-end diameter, which implies that even though they were pruned, they cannot be classified as 'pruned'.

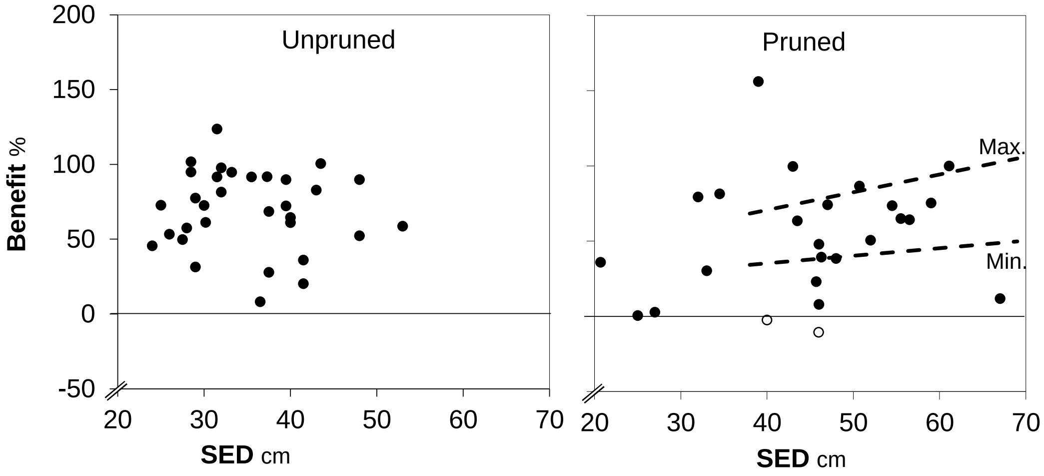


FIGURE 7.3-4: ECONOMIC BENEFIT (%) OF PRUNED AND UNPRUNED LOGS DEPENDING ON SMALL-END LOG DIAMETER (SED); MAXIMUM AND MINIMUM TREND LINES, DEPENDING ON KNOTTY CORE RATIO, LESS THAN 40 AND BETWEEN 44 AND 88 %, RESPECTIVELY (DASHED LINES). UNFILLED CIRCLES HIGHLIGHT NEGATIVE VALUES

SOURCE: The author (2014)

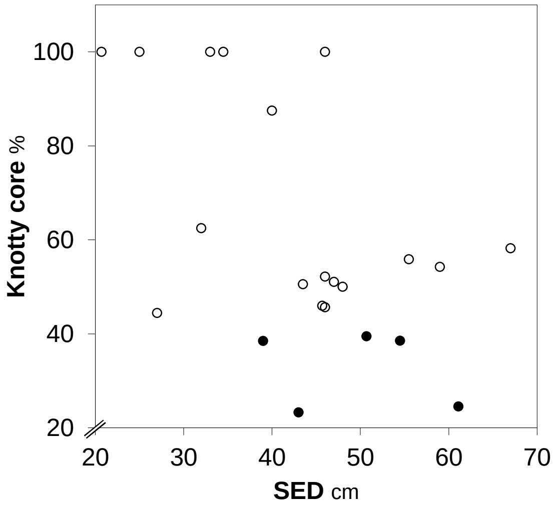


FIGURE 7.3-5: KNOTTY CORE ZONE (%) DEPENDING ON SMALL-END DIAMETER (SED); LOGS WITH KNOTTY CORE LESS THAN 40% ARE HIGHLIGHTED (BLACK).

SOURCE: The author (2014)

7.3.3 Discussion

7.3.3.1 Yield

Small-end diameter (SED) alone composed the recovery rate model with a coefficient of determination that shows a good predictability of the model ($R^2 = 0.48$, $S_{yx} = 6.6$).

Similar to this study, results obtained by Kewilaa (2011) revealed that 74 % of the variation in recovery veneering are explained by log diameter.

Other factors also contribute to recovery rate losses:

- Log ovality: Bonduelle *et al.* (2006) reported a loss of 35 % in volume during the rounding process, as far as the whole length of the log is being peeled. Although log taper showed a higher correlation with veneer recovery (0.27) than it was observed in the present study (0.08), it is obvious that log taper contributes to lower recovery because more of the block volume is outside the peelable cylinder and cannot be used for veneer production (FAHEY *et al.,* 1991).
- Bark width: it was not regarded in this study, but it might have impacted to recovery rate too. Bortoletto Jr. (2008) reported a loss of 13.5 % only due to this variable.
- Steaming: Olufemi (2012) analysed the recovery rate of *Brachystegia nigerica* logs with small-end diameter of about 60 cm. The author found yields for peeled veneers ranging from 14-46 %, significantly depending on steam temperature and duration, which resulted in varying core diameter dropout. Although the species studied in this trial cannot be related to the one mentioned above, the result obtained by Olufemi (2012) might be an indicator that bigger-sized logs could not have been efficiently steamed in this study, compared to the smaller ones, resulting in an additional source for the variation in recovery rate. According to Aydin *et al.* (2006), heating of logs with steam is one of the most important processes during the veneer manufacturing. The main function of steam heating is to soften veneer log temporarily and make them more plastic, pliable, more readily peeled, and improving the quality and quantity of material recovered from the log.

The average recovery rate was 54 % showing high variation around this value. Although a numeric and linear increasing trend could be shown, logs with diameters bigger than 50 cm had a recovery rate similar to the assortment of ‘35-39.9’ cm. Pruned logs with small-end diameters >35 cm resulted in higher rates of grade ‘A’ sheets. This trend was not so evident due to the high proportion of knot zone (knotty cylinder in relation to log small-end diameter), especially in the bigger-sized logs.

Similar recovery values have been reported, ranging from 46-64 % (FAHEY *et al.,* 1991; BRAND *et al.,* 2004; WANG; DAI, 2008; VILELA *et al.,* 2012).

An average theoretical recovery of 76 % was calculated for the studied log assortments. The theoretical recovery rate obtained for each diameter class increased with increasing log small-end diameter, but the real recovery grew even more sharply, resulting in a reduction on the difference between both (Table 7.3-4).

In a study conducted by Cardoso (2009) only 21 % of the theoretical recovery rate of pine logs was reached, which corresponded for 11 % of the total log volume, ranging from 1-18 %. According to the author, only ⅓ of the logs used in the study were pruned. In the present study, however, real recovery rates were higher than the ones reported by Cardoso (2009), ranging between 60-77 % of the theoretical ones.

7.3.3.2 Conversion factor

A frequently used terminology in the Brazilian wood industry is the quantity of logs in tons, needed for the production of one cubic metre of final product, called ‘conversion factor’. This measure was obtained with the inversion of the recovery rate, which varied from 1.6-2.3, for the assortments ‘>50 cm’ and ‘25-29.9 cm’, respectively. Managers of plywood industries in Brazil report an expectation of no less than 2:1, which means that 2 tons of roundwood is necessary for the production of 1 m^3 of peeled veneer.

7.3.3.3 Veneer quality

The trend of producing higher rates of sheets graded as ‘A’ was not so evident due to the low quality of pruning, especially in the bigger sized logs (Figure 7.3-2). Because the origin of the logs was a thinning trial, the bigger sized logs were obtained in extremely intense thinning regimes, with high growth rates starting from year 5. The second pruning lift (2.5 to 6.5 m) was only carried out at year 7, when the stems already showed more than 30 cm of diameter at the second log basis, resulting in knotty core of big dimensions. Furthermore, it is important to note that this experiment started at the beginning of pruning and thinning treatments on pine stands in southern Brazil. This fact helps to explain the low efficiency of the pruning due to untrained forest workers, leaving behind small branch stubs or hitting the branch collars, leading to extended periods of cicatrisation.

Veneer sheets graded as ‘C’ increased in logs above 40 cm in diameter because the strong thinning intensities and, consequently, larger knots, resulted in a lower veneer quality. This grade of peeled veneer is generally used for internal layers of the plywood, while grade ‘B’ and preferably ‘A’ perform the external ones. Although the quantity of internal sheets is higher than the external ones, the production of class ‘C’ is frequently higher than the demand.

Rate of class ‘R’ veneers decreased with increasing small-end diameter for both pruned and unpruned logs. It is important to note that the residues in this case were veneer sheets of comparable thickness and length of the normal products; the only difference was the standard width of 280 mm (Table 7.3-2).

The effect of pruning in veneer grading is obvious in terms of sheet quality (clearwood), but not so obvious in the amount of veneer produced (m^3 or %). This is because logs with too many knots were not fully peeled, resulting in bigger unpeeled cores, which were dropped off and, thus, influencing negatively the recovery rate.

7.3.3.4 Economic aspects

The knotty core zone of 39 % (about ⅓) was taken for the economic analysis following the study of Schulz (1959), and confirmed by Seitz (2000), who indicated a maximum knotty core of one third of the diameter as economically acceptable. The “one third” rule is of less importance for logs of bigger dimensions, although it is a minimum condition for logs between 30 and 45 cm. Noteworthy is that, from the economic point of view, pruning is an investment which should always be aimed at the optimisation of the return of investment. In this respect, it cannot be justified to make a late pruning only because the bigger target diameter still allows having an acceptable recovery of clear wood while processing.

It was found that the best economic results were not obtained from the bigger-sized pruned logs. Seitz (2004) took the market prices of the bigger dimensioned pine logs for a detailed economic analysis, concluding that the higher costs per volume are compensated by higher recovery rates. This conclusion might be valid if pruning is conducted in the way suggested by him (SEITZ, 2000). In the present study this was not the case, where the percentage of the knotty core zone is exceeding the expectations (Figure 7.3-5). Since bigger sized-logs are more expensive than small ones, the same level of benefit rate does not mean the same absolute revenue, but the same proportion in relation to log price – more expensive logs providing more valuable products in an increasing and proportional rate.

Even for the best 5 pruned logs, with knotty core less than 40 % (Figure 7.3-5, highlighted circles), the economic benefit remains on the same level as observed for the unpruned logs (Figure 7.3-4). Throughout this analysis it can be concluded that the higher prices charged for the pruned logs (pruning premium) already compensated the higher potential of producing better graded veneer, as compared to the unpruned ones. If this potential is compromised by low efficient pruning methods, plywood industry cannot afford to pay higher prices for such logs. However, when pruning is carried out in order to restrict the knotty core zone to 30% of the log small-end diameter, industry can afford to pay higher prices, which benefit the whole production chain.

The two negative values shown in Figure 7.3-4 indicate that the price for poorly pruned logs is higher than the revenue that can be achieved from the peeled veneer. The economic loss would be even higher if all the costs involved in the industrial process are considered. According to Polzl (2002), log prices are only 50 % of the total costs in the plywood industry.

In a study conducted by Fahey and Willits (1991) it is shown that logs with <30 cm should not be peeled. The results in Table 7.3-5 confirm the low recovery rate of these log assortments. However, this could not be confirmed by the economic analysis (Figure7.3-3 and 7.3-4), where both unpruned and pruned logs resulted in similar levels of economic benefit, although a slight increase trend could be noted for the pruned logs.

The material used for this study could only partially reflect the potential of pruned logs of bigger diameters coming from fast-growing plantations. Nevertheless, it can be concluded that the higher prices charged for the pruned logs already compensate its industrial potential to produce higher grade veneers, which can be sharply compromised by low efficient pruning methods, especially when the log is not fully peeled.

Even so, by regarding the 5 best pruned logs (knotty core of <40 %), the economic potentials of bigger dimensioned pines with adequate pruning could at least be partially assessed (Figure 7.3-3 and 7.3-4, maximum dashed lines).

From a silvicultural point of view, and considering the growth potential of loblolly pine in Brazil, it is possible to restrict the knotty core to 12 cm, maintaining at the same time a satisfactory tree development (SEITZ, 2000). This value matches with the minimum unpeeled core left in the modern rotary peeling process. The best pruning regime was described by Seitz (2000) as being yearly from the 3rd to 7th year, lifting 1-1.5 m each year. Starting early with artificial pruning is necessary due to the fast growth of the species. Noteworthy is that the remaining crowns should be at least 3-4 m in length to maintain an acceptable rate of tree growth (SEITZ, 2000).

It can be concluded that silvicultural regimes designed for the production of big-sized and pruned logs for high value utilisation are interesting for rotary peeling industry. Higher recovery rates and improved veneer quality obtained from logs produced under specific management practices most likely result in higher log prices.

7.4 SLICED PEELING

7.4.1 Material and methods

7.4.1.1 Data collection

Altogether, 25 first logs were harvest, identified and transported to a medium-sized veneer industry, totalling 11.7 t. The mean conversion ratio of m^3 ton^{-1} for the transported logs was 1.1.

The small-end diameter of the logs varied between 26-78 cm, equivalent to 0.14-1.21 m^3.

For economic evaluation, logs were classified by small-end diameter and their respective prices, according to the values used by the forest enterprise Florestal Gateados (personal communications, 2011).

Since diameter classes for log prices are not uniform and varied widely, for modelling purposes more narrow and constant classes of 5 cm were considered as more efficient (Table 7.4-1). The diameter class ‘>65 cm’ contained 1 log with 78 cm of diameter.

Although a slight difference between ton and m^3 exists, a 1:1 relation for the economic analysis was regarded adequate because this is the standard method of analysing it by the praxis.

The logs were randomly processed, without grouping them into diameter classes. Before the first cut, the saw operator visually analysed the logs and decided for the best sawing schema.

TABLE 7.4-1: DIAMETER CLASSES, NUMBER OF LOGS, MEAN VOLUME (V_{LOG}) AND COMMERCIAL VALUE PER LOG

Original diameter classes and prices provided by Florestal Gateados (2011):

- 20-24.9 cm: 39.2 US\$ ton^{-1}.
- 25-35 cm: 51.2 US\$ ton^{-1}.
- 35-41.9 cm: 69.9 US\$ ton^{-1}.
- >42 cm: 104.2 US\$ ton^{-1}.

SOURCE: The author (2014)

Diameter class cm	Number of logs	V_{log} m^3	Value US\$ log^{-1}
25-29.9	1	0.136	7
30-34.9	2	0.208	15
35-39.9	3	0.263	18
40-44.9	4	0.378	37
45-49.9	4	0.480	50
50-54.9	4	0.545	57
55-59.9	4	0.731	76
60-64.9	2	0.885	92
>65	1	1.210	126

Previous to the slicing procedure, the logs were cut into blocks in the following way:

(1) First cut with a band saw; cut width of 1.25 cm.

(2) Division of boards into blocks through a multiple circular saw; cut width of 3.2 mm.

(3) Classification of the blocks. Continuation of only those totally free of knots and defects.

(4) Boiling at 100° C, during 3 hours.

(5) Slicing in the longitudinal direction, with a 'Fezer ®' equipment, model FM 30. The equipment used for slicing the blocks is able to slice the blocks until a residual width of 10 mm. However, blocks with defects were dropped out before they reached the residual width.

(6) Drying of the veneers in a 7 chamber dryer (90, 80, 70, 60° C, followed by forced ventilation). The whole drying process took 20 minutes.

(7) Individual Classification of veneer sheets, following the interprise practice, as given in Table 7.4-2.

TABLE 7.4-2: WIDTH, AREA, VOLUME AND COMMERCIAL VALUE OF THE VENEER SHEETS.

Product	Specification	width mm	area m^2	Volume m^3	Value US\$ m^{-2}
A	free of knots and other imperfections	140	0.294	0.0004	1.15
B	free of knots, allowed some spots or slight 'banana' defect				0.71

Thickness (1.2 mm) and length (2.10 m) were kept constant in the production process.

SOURCE: The author (2014)

Both sheets were totally free of knots. However, while ‘A’ had no other imperfections, ‘B’ had some spots or ‘banana’ defect, which means a tortuosity in the longitudinal direction.

Sheet dimensions shown in Table 7.4-2 indicate the ones used for commercialization. In fact, sheets were 1.27 mm thick, in order to guarantee 1.2 mm after drying. Values (US\$ m^{-2}) reflected mean values used for several industries in the region.

7.4.1.2 Data analysis

In yield analysis individual logs were regarded as inputs (m^3) and the area (m^2) and volume (m^3) of the veneer sheets produced as outputs.

From the difference between individual log prices, and the gross revenue obtained from them, it was possible to determine the economic benefit depending on the log diameter and pruning. Other costs related to the industrial process were not considered in this study.

7.4.2 Results

7.4.2.1 Yield and conversion factor

In the sawing process, previous to slicing, logs were cut into blocks 2.20 m length, 157 mm width and 70 or 50 mm thick. The blocks were than sliced into veneer sheets. In average, 37 sheets were sliced from each block.

The assortment classes ‘25-29.9 cm’ and ‘>65 cm’ are shown in Table 7.4-3 and Figure 7.4-1 (unfilled circles). However, because there was no replication within these classes, they were not statistically evaluated and used on the regression analysis.

Taking off some extreme oscillations due to lack of log homogeneity, a linear increase of the yield in m^2 was observed (Figure 7.4-1). The industrial yield in m^2 and in % according to the log small-end diameter are shown in Figure 7.4-1.

From Figure 7.4-1 it can be noted that 2 logs with SED of ~50 cm showed lower yields in comparison to others with similar dimension (~15 %). These 2 logs showed a poor quality already at the sawing process, basically a big knotty core.

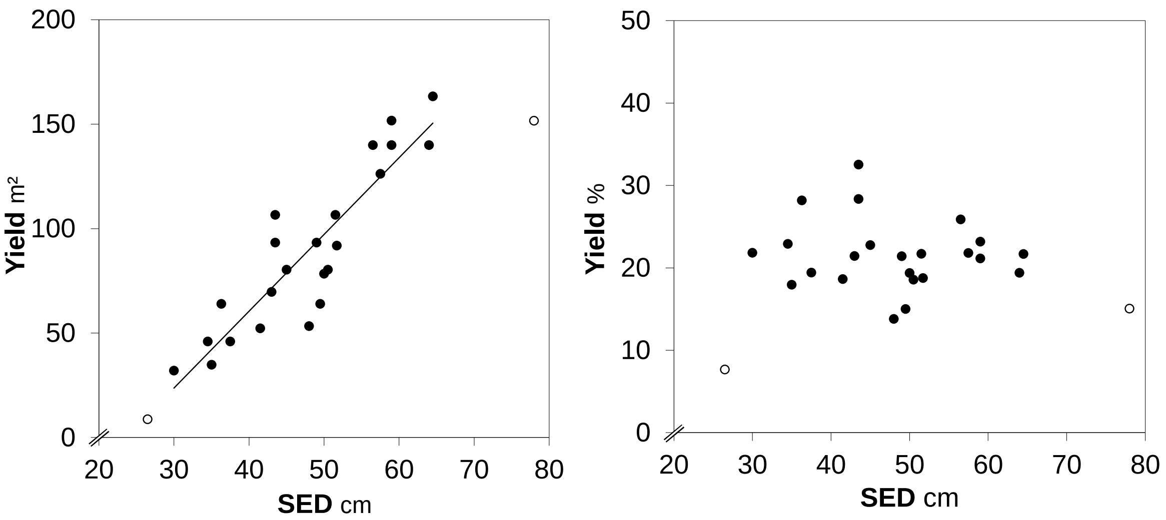


FIGURE 7.4-1: INDUSTRIAL YIELD IN M² AND % ACCORDING TO THE LOG SMALL END DIAMETER (SED). LINEAR TREND IS DESCRIBED BY THE EQUATION BELOW

$$\text{Yield}_{m^2} = 3.679\,(\text{SED}) - 86.756 \qquad R^2 = 0.81$$

SOURCE: The author (2014)

The industrial yield in m² increased as log small-end diameter also increased. According to the linear trend, an increase in industrial yield of 3.7 m² is expected for each cm increase in the log SED. However, because of the high yield variability obtained from similar SED values, the standard error of estimation of the model was 19 %.

Absolute yields, conversion factor and the volume of timber lost due to log taper are shown in Table 7.4-3.

The quantification of the volume loss due to log taper reinforces the hypothesis of decreasing log yield with increasing SED. The difference between the big and the small-end diameter is simply the waste of the first sawing process – note that, under the bark, it is 100 % clear wood. The assortment ‘60-64.9 cm’ showed the highest loss due to ‘taper volume’. It was also detected that logs with ‘45-49.9 cm’ had a similar value to the ‘55-59.9 cm’.

Correlation analysis of log variables and the yield in m² of produced veneers indicated the total log volume was the strongest one (0.92, p<0.01), followed by log middle diameter (0.91, p<0.01). High correlation values (>0.90) were also found for the cylinder volume formed by the log small-end diameter, the big-end diameter and the small-end diameter. Log taper, on the other hand, showed a lower correlation value (0.82), although still quite high.

Because small-end diameter is the most common variable used in the classification of log assortments, and owing a high correlation with industrial yield as well, it was regarded for the regression model.

In relation to the log taper, an average difference of 18 cm was observed between the big and small-end diameter of the logs, oscillating between 7-28, being the greater the bigger the SED of the log (Figure 7.4-2).

Considering the logs were 2.20 m length, it means that, in average, log decreased 8 cm in diameter per m length. Thus, showing an important factor which might have negatively affected the industrial yield.

Table 7.4-3: Log assort-ments by diameter class and their average yield, conversion factor and the average volume loss due to log taper

Diameter class cm	**Yield** m^2	**Conversion** $m^2\ m^{-3}$	V_{TAPER} m^3
25-29.9	*8.7*	*63.8*	*0.043*
30-34.9	39.0 a	186.4	0.074 a
35-39.9	48.2 ab	182.1	0.085 a
40-44.9	80.4 ab	195.9	0.127 ab
45-49.9	72.7 ab	176.3	0.163 abc
50-54.9	89.3 b	163.3	0.195 bc
55-59.9	139.5 c	191.7	0.238 c
60-64.9	151.7 c	171.2	0.328 d
>65	*151.6*	*125.3*	*0.317*
Statis. Signif.	* * *	n.s.	* * *

Diameter classes ‘25-29.9’ and ‘>65’ are shown in italics and were not statistically evaluated.

Source: The author (2014)

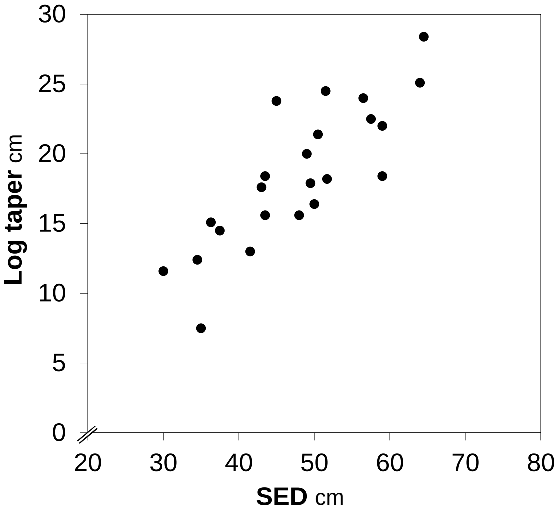


Figure 7.4-2: Difference between big and small end diameter - log taper - according to its small end diameter

Source: The author (2014)

Finally, and decisive for the industrial yield, the industrial process used in producing the veneer sheets might have not been the most suitable one for the tested big-sized logs. A great amount of wood loss was observed in every single step of the process. An input *vs.* output analysis is shown in Table 7.4-4.

TABLE 7.4-4: INPUT AND OUTPUT VOLUME PER LAMINATING PROCESS STEP, REMAINING PERCENTAGES PER STEP AND CUMULATIVE REMAINING

Step	**INPUT** m³	**OUTPUT** m³	**REMAINED** %	**CUMULATIVE REMAINED** %
Sawing	12.9	6.0	46	46
Block class.	6.0	4.6	78	36
Slicing	4.6	2.9	62	22
Veneer class.	2.9	2.7	92	**21**

class.: classification

SOURCE: The author (2014)

7.4.2.2 Economic aspects

The purchase costs and the gross revenues per log are shown in Figure 7.4-3.

From Figure 7.4-3 it can be seen that both the purchase cost and the gross revenue per log show a linear increasing trend. The lower coefficient of determination of the revenue trend is the result of the high variability of log quality, which led to a wide range of revenues obtained for similar SED values.

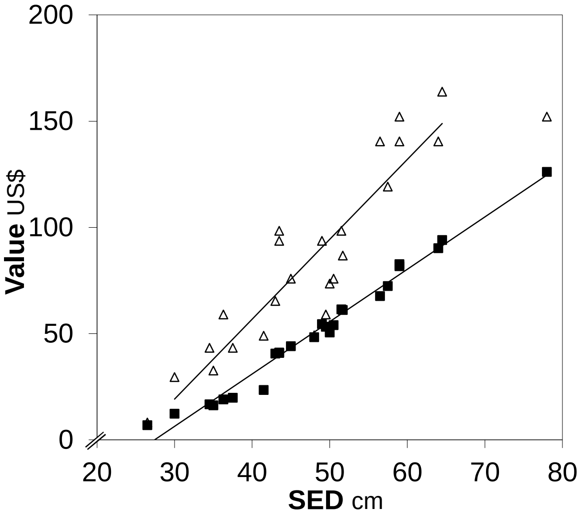


FIGURE 7.4-3: COSTS (BLACK SQUARES) AND REVENUES (WHITE TRIANGLES) OVER THE SMALL END DIAMETER (SED) OF THE LOG

Revenue trend did not consider extreme values (SED = 26 and 78 cm)

Cost= 2.5 (SED)-67.6
$R^2 = 0.98$

Revenue= 3.8 (SED)-93.6
$R^2 = 0.80$

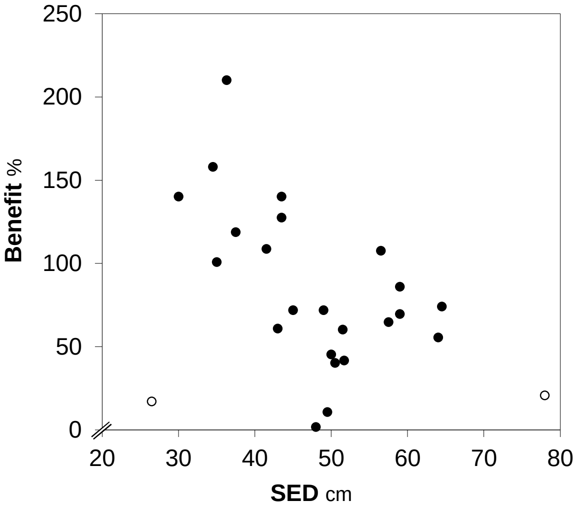
SOURCE: The author (2014)

The relative economic benefit was assessed (gross revenue minus purchase cost ÷ purchase cost) aiming at a better understanding of these economic behaviour observed for the individual logs,. The results are shown in Figure 7.4-4.

FIGURE 7.4-4: ECONOMIC BENEFIT (%) OVER THE SMALL END DIAMETER (SED) OF THE LOGS

Unfilled circles = extreme values, SED= 26 and 78 cm, not regarded in the statistical analysis.

SOURCE: The author (2014)



A great variation of economic benefits within similar SED values was verified, especially in the range of 40-50 cm. It is in this range that the 2 lowest values were detected, as a result of the poor quality of logs, as mentioned.

Noteworthy is that in the present analysis the economic benefits obtained exclusively by selling the veneer sheets were regarded. There were obviously other by-products that could have been sold, as solid wood or even for energetic purposes, which would improve the economic benefit of the logs.

It was also observed that logs with SED of ‘30-45 cm’ showed the highest relative benefit (~130 % in average, 61-210 %), even though they delivered statistically lower absolute yields (Table 7.4-3). It means that the lower industrial yield is rather high in relation to the log price. From SED of 45 cm onwards, the relative benefit was lower than the ones verified in the smaller classes (~70 %, 40-110 %). The higher absolute industrial yield was, therefore, compensated by the higher log prices, and this more than proportionally to log yield.

7.4.3 Discussion

It has been verified that, in average 21 % of the log volume was sliced into veneer sheets, oscillating between 14-32 % (Figure 7.4-1), which is quite low in comparison to other industrial uses. The graphic analysis of the relative yield surprisingly showed no increasing trend with increasing log SED. There were 3 factors that could have affected the yield:

- Unappropriated pruning, resulting in a low amount of clear wood.
- High taper of the logs – it were only 1st logs within a tree, normally very tapered.
- It might be an inefficient industrial process for the big-sized logs.

Yields regarding m² of veneer sheets showed an evident differentiation between log diameter classes. Logs >55 cm showed higher yields in comparison to the others. A SED of '50-55 cm' delivered a yield lower than the first group, but still higher than logs with 30 cm of diameter.

However, no differences between diameter classes were found for veneer production per m³ of log. The average yield was 89 m² of veneer per log, or 172.1 m^2 m^{-3}.

Hapla *et al.* (2002) studied the yield of *Fagus sylvatica* logs, and concluded that logs with SED between 50-59 cm were better for the lamination process than 60-69 cm ones were. The authors reported a conversion of 841 m^2 m^{-3} of processed log. However, veneer with about ⅓ of the thickness of the present study were produced. Nevertheless, and for comparison reasons, by regarding the volume of produced veneers, the value reported by the authors (0.462 m^3 m^{-3}) was more than 2 times bigger than the ones found for loblolly pine in the present study (0.207 m^3 m^{-3}).

Polzl (2002), studying loblolly pine logs reported that 44 % of the log volume was processed into veneer sheets. The mentioned value is 2 times bigger than the one obtained in the present study (21 %).

Altogether, results suggest that the industrial process might not have been appropriated, providing a comparatively very low yield.

In fact, the logs of the present study were not pruned as later on described by Seitz (2000), when it was recommended that pruning should optimally start at age 3-4 years. Because pruning procedure started only at age 5 years, and because the site was of high productivity, the knotty core overtook the ideal 12 cm, or the optimum ⅓ proportion. As shown in the rotary peeling process, the majority of the analysed 2nd logs had over 50 % of knotty zone, reaching even higher values.

The low conversion of logs into the blocks, during the sawing step, which alone was responsible for more 50 % of the losses. Finally, only 21 % of the volume inputted as logs resulted in veneer sheets (Table 7.4-4).

Logs with >45 cm might had been better used with other slicing procedures, as reported by several studies in Asia, Europe and United States (GROSSHENNING, 1971; FUCHS, 1981; BUCHELT; WAGENFÜHR, 2007). Moreover, and for increasing economic output, eccentric cuts could be used, which deliver specific asthetic drawings of the annual growth rings and further wood structures and, therefore, reached high commercial prices.

In relation to the veneer quality, and because no individual evaluation per log was possible, the quality analyses were only related to the total amount produced. Veneer classes ‘A’ and ‘B’ were 55 and 45 %, respectively. The higher proportion of the ‘A’ class was due to the intensive classification previous to slicing.

Although the poor thechnique of slicing could have negatively affected the amount of sheets produced, it results in veneers sheets of the highest quality, mainly because the slicing is carried out parallel to the wood grain (PFRIEM; BUCHELT, 2011).

7.5 CONCLUSIONS

In general, the bigger the log diameter, the higher its industrial yield into solid wood products.

It was verified, for the sawmill, that

- The mean industrial yield for logs ranging from 20-57 cm is 57 %.
- There is a linear increase in the industrial yield. Substantial industrial yield gains occur after 35 and 45 cm in the small-end diameter of logs.
- 2.5-1.3 m^3 of logs are necessary to produce 1 m^3 of solid boards.
- In relation to the economic benefit, intermediate classes (25-35 cm) are less profitable in comparison to the small (20-25 cm) and bigger-sized ones (>45 cm).

For rotary peeled veneers, it has been found:

- The average recovery rate of logs ranging from 21-67 cm is 54 %, increasing 0.6 % by each cm increases of small-end diameter of the log.
- The log characteristic which better explain the industrial yield are, in a descending order: total volume, mean diameter, volume formed by the small-end diameter, big-end diameter, small-end diameter and taper.
- Logs with small-end diameter between 30-45 cm are the ones with the highest economic benefit. For the analysed logs, the price charged for the bigger-sized logs

does not proportionally compensate its yield potential. Inappropriate pruning strategy are decisive in this context.

- The current price charged for big-sized and pruned logs appropriately reflects a low quality of pruning, which results in high proportion of knotty cores. If more efficient pruning regimes are regarded, there is potential for increasing log industrial yield and economic benefit, and both, log producer and industry can profit.

In relation to the sliced veneers, it was observed that

- The mean industrial yield of logs ranging from 30-65 cm of small-end diameter is 21 %. According to the adjusted linear trend for yield, an increase of 3.7 m^2 of veneer is expected by each cm increase in log small-end diameter.
- Logs with ‘35-39.9 cm’ are just as efficient as the ‘>50 cm’ ones, mainly because of losses during the block sawing step.
- Big-sized logs do not provide necessarily the highest economic benefit for the industry. However, this conclusion is strongly related to the poor pruning quality of logs.

8 FINANCIAL PERFORMANCE OF STANDS AS A RESULT OF DIFFERENT THINNING INTENSITIES

8.1 INTRODUCTION

Stand growth and the wood quality obtained from different silvicultural regimes are important approaches, however, forest owners are mainly interested in the financial aspects related to different management options. In fact, from the economic viewpoint, silviculture means making a set of interrelated investment decisions.

The economic aspect of silviculture and particularly the long-term characteristic of forestry require consideration on the value of money along time. Discounting methods are used to simplify problems with interest calculation, providing a satisfactory criterion of profitability, which fully reflect the magnitude and timing of cash flows (CLUTTER *et al.,* 1983; DAVIS; JOHNSON, 1987; PRICE, 1989; STRAKA 2010).

Three methods are widely applied for financial evaluation. The first and most used one is the net present value (NPV), which is defined as the sum of the revenues minus the sum of costs, suitably discounted along time (DAVIS; JOHNSON, 1987; PRICE, 1989; BETTINGER *et al.,* 2009).

Complementarily to the NPV, the internal rate of return (IRR) is calculated in order to provide a comparison value for other investment options. It is defined as the rate of discount which makes discounted cost equal to discounted revenue, or NPV = 0. Moreover it can be faced as the investment's internal ability to generate financial outputs (CLUTTER *et al.,* 1983; PRICE, 1989; BETTINGER *et al.,* 2009).

Finally, the land expectation value (LEV), proposed by Martin FAUSTMANN in 1849, express the net present value of an investment in an even-aged stand from the time of planting (when the land is bare of trees), through infinite rotations of the same management regime (STRAKA 2010). Moreover, if the rotation lengths are different between competing management regimes, then using the land expectation value is more appropriate, because it accounts for an infinite time line, while net present value computation stops at the end of the rotation, which ignores the opportunity to reinvest revenues (BETTINGER *et al.,* 2009).

All of the cited methods are quite simple approaches and have been used for decades for forest valuation. Although they do not comprise the currently social and environmental complexity in which silviculture have steped into (KANT, 2013; MEAD, 2013), they are still valid for pure financial evaluations. According to Cubbage *et al.* (2010) NPV and LEV are considered the best criteria for capital budgeting. Moreover, according to Binkley (2008), there is no substitute for careful, professional discounted cash-flow analysis in valuing timberland assets.

The financial approach of forest projects requires some assumptions, for example, determining the interest rate for discounting cash flows. The choice of a discount rate has major implications because of the long-term nature of forest crops and the inherent exponential nature built into calculations (MEAD, 2013).

The choice of the interest rate is an old problem faced in financial evaluations of forest stands. Since the second half of the 19th century, it was determined in Germany that interests on forest stands should be 1 % year^{-1} lower than the current economy basic rate. Thus, 3 % year^{-1} was established for a rational forest financial evaluation. The reasons for this decision were the supposed low risks, the high liquidity, the comparable easy management practices, and the stead increase in the wood price (OESTEN; ROEDER, 2012a). Whether these conditions remain or can be applied for different countries strongly depend on regional circumstances.

Atmadja and Sills (2013) reported an average discount rate for the Southern United States of 2.6 %, ranging from less than 1 to up to 7 % year^{-1}. Bettinger *et al.* (2009) addressed an average discount rate of 4 % as common value for taxation forestlands in the U.S., while Mills and Stiff (2013) reported rates within 5-7 % for analysing loblolly and longleaf pine regimes in southern U.S.

Mainley (2010, 2012) pointed out that financial analysis of *P. radiata* plantations in New Zealand regarded interest rates varying between 7-11 %. Similar values were reported by Mead (2013) for the same species in Australasia and Chile.

Cubbage *et al.* (2010) used a discount rate of 8 % year^{-1} for a comparable worldwide analysis, but pointed out that companies often employ higher discount rates for developing countries.

In Brazil, discount rates between 6-10 % year^{-1} have been regarded (ACERBI JR. *et al.,* 1999, 2002; SCOLFORO *et al.,* 2001; GOMES *et al.,* 2002, SILVA and FONTES 2005).

According to Bullard and Gunter (2002), privat landowners in the U.S. place importance on protecting the natural environment and providing for the future generations, which reflect a willingness to accept a lower rate of return to achieve these goals.

Regardless of the discount rate used in the cited studies, it is commonly not clear whether real or nominal rates are regarded. According to Clutter *et al.* (1983), many decision makers have erred in the evaluation of investment projects because they failed to include the effects of anticipated inflation in their analyses. The most common error is done when cash flows are estimated based on constant dollars, but the discount rate includes the impact of anticipated inflation.

As a result, revenues are strongly discounted when present values are calculated, because they are obtained mainly at the end of the rotation period. Differently, silvicultural costs are much less affected, as they occur at the beginning of the rotation. When unrealistic high discount rates are regarded, for example by considering nominal rates (including inflation), the conclusions of the financial analysis do not express the reality because of the effects of anticipated inflation, just as reported by Clutter *et al.* (1983).

Hence, and despite of the high discount rates widely used, the present financial analysis regarded relatively lower discount rates, which, instead ‘low’ values, are rather considered realistic. The rate was chosen after a carefully analysis of the Brazilian economy and alternative investment options during, at least, the last decade.

The fact that the study evaluated a relative long harvest age for Brazilian conditions provided the opportunity to assess stand development beyond the current practice. The crown thinnings applied to the stands showed a remarkable response on tree dimensions by early and heave release from competition, which is an unique approach for loblolly pine plantations in the country, and even for other species.

A well-developed market for pines in southern Brazil established some log assortment differentiation. However, it comprises a relative small range of diameters, in which big-sized assortments are lacking. Because the applied silviculture regimes produced logs beyond the current market needs, new assortment classes were simulated to understand the price-size relationship for individual trees.

With the study, it was aimed to analyse the financial performance of the stands as a result of different crown thinning intensities.

Specific objectives were

- to quantify gross revenues obtained by each thinning intensity,

- to assess financial criteria of the different silviculture regimes,
- to evaluate the effect of pruning, bigger-sized assortment classes, costs and discount rates on the different management options.

8.2 MATERIAL AND METHODS

Study site and design are described in detail in Chapter 2 MATERIAL AND METHODS. Volume quantifications, which were the basis for the financial analysis, are shown in Chapter 6 LOG ASSORTMENTS.

8.2.1 Costs

The yield of each activity related to establishment, cultural and silvicultural treatments and their costs are shown in Table 8.2-1. Values were rounded for simplicity purposes.

Cost data were provided by the private enterprise Florestal Gateados (personal communication 2013). Data reflect a moderately sloped area, the average condition for forestry in southern Brazil.

Thinnings and even the final cut in the experimental plots were operationally different from the ones applied to the commercial area. However, because of lack of better data, the costs regarded in the analysis were the ones supplied by the enterprise.

Administrative costs of 100 US$ year^{-1} ha^{-1} were considered.

8.2.2 Revenues

Revenues were exclusively the amount of logs in each log assortment class multiplied by the respective assortment price. The market prices of assortments were provided by the same private enterprise and expressed the real condition in April 2013. It is important to note that the region has a well-developed forest based sector, which implies that the market prices are well regulated by supply and demand, just as recommended by Gregersen and Contreras (1992).

Table 8.2-1: Yield and costs for each of the activities within a rotation cycle of wood production in Southern Brazil

Establishment	Yield man ha^{-1}	Cost US$ ha^{-1}	Considerations
Area cleaning (manual)	16.9	530	30 % of the area
Area cleaning (mechanized)	0.5	380	70 % of the area
Planting	8.3	470	
Leaf-cutting ants control	0.8	30	
Replanting	0.2	20	
Total establishment		950	**year 0**
Cultural treatments			
Manual mowing	3.8	125	30 % of the area at year 0 and 1
Semi-mechanized mowing	1.1	50	70 % of the area at year 0 and 1
Post-emergent herbicide	2.7	115	whole area at years 0, 1 and 2
Leaf-cutting ants control	0.8	25	Whole area at years 0, 1 and 2
Total cultural treatments		215	**year 0**
		215	**year 1**
		140	**year 2**
Pruning			
1st	2.3	95	0.0-1.0 m, **year 3**
2nd	3.2	130	1.0-2.5 m, **year 4**
3rd	2.0	80	2.5-4.0 m, **year 5**
4th	2.2	90	4.0-5.7 m, **year 6**
Harvest		US$ m^{-3}	
Thinning 1st		15	9th row systematically +30 % selective
2nd		15	~40 % selective
3rd		14	"
4th		12	"
5th		12	"
Final cut		10	

The cost of one worker day^{-1} comprises income, taxes, social insurance and safety equipment, alimentation and transport; harvest intensities (in %) are a rough estimative related to the number of removed trees; the road building and conservancy costs were constant and are integrated to the harvest costs = US$ 1.80 m^{-3}; harvest costs means logs loaded on costumers truck, next to the stand.

SOURCE: The author (2014)

The data provided by the enterprise were comprised by log assortment ranges quite specific for the region. Moreover, 1st and 2nd logs were sold with different prices, although both were similarly pruned. The price of the first one was higher. Regression curves with the original data of log small-end diameter and prices were generated in order to fit standardized assortments, for the unpruned and pruned logs, disregard of log position within a tree. The curves were projected beyond the current commercialized limits for modelling the financial impact of bigger-sized logs and, therefore, more valuable, assortments. Regression curves are shown in the Figure 8.2-1.

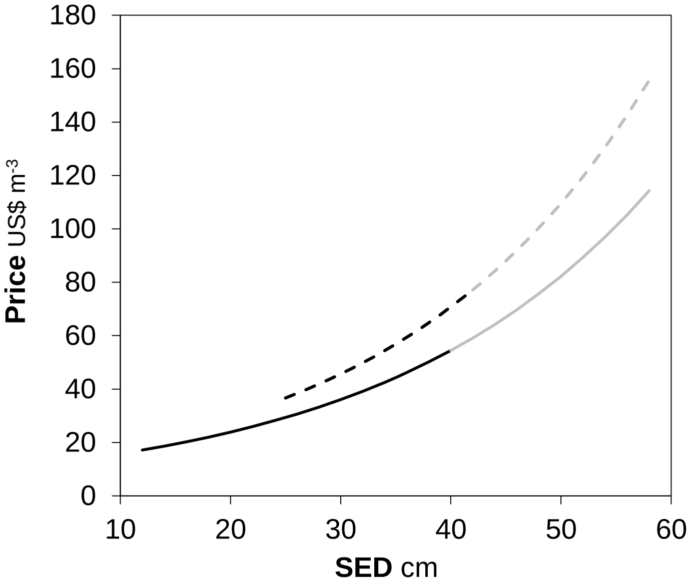


FIGURE 8.2-1: REGRESSION CURVES OF ASSORTMENT PRICES DEPENDING ON SMALL-END DIAMETER (SED) FOR UNPRUNED (FULL LINE) AND PRUNED (DASHED LINE) LOGS. REAL RANGE (BLACK SEGMENT) AND PROJECTION (GREY SEGMENT).

$\mathrm{Price}_{\mathbf{unpruned}} = 21.38\ e^{\ 0.0412\ (SED)}$ $R^2 = 0.98$

$\mathrm{Price}_{\mathbf{pruned}} = 25.018\ e^{\ 0.0438\ (SED)}$ $R^2 = 0.93$

SOURCE: The author(2014)

For standardization purposes, new assortments considered 9.9 cm wide classes, beginning from a small end diameter (SED) of 10 cm. All assortments were 2.5 m in length. With help of the regression curves traced above, the standardized assortment classes were defined and are shown in Fig 8.2-2.

The biggest-sized assortments currently regarded by the south Brazilian market are >35 cm for unpruned logs and >40 cm for pruned ones. However, the evaluated silviculture regimes produced substantially bigger logs and, thus, new assortments were simulated, creating a new log assortment >50 cm, for both unpruned and pruned ones. The aim of such projection was to evaluate the financial impacts of bigger-sized assortments classes on the production cycles.

The premium price paid by the market for pruned logs in April 2013 was up to 40 %. The bigger the small-end diameter, the higher the premium for the pruning.

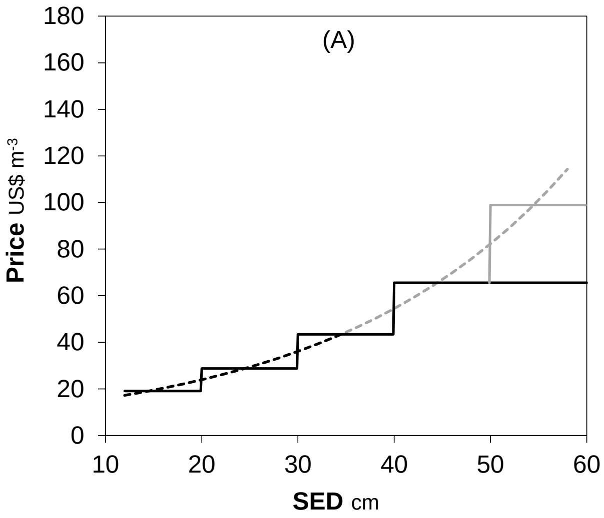


FIGURE 8.2-2: REGRESSION CURVE (DASHED LINE) AND STANDARDIZED ASSORTMENT (FULL LINE) EXPRESSING THE PRICES FOR THE UNPRUNED (A) AND PRUNED (B) LOGS DEPENDING ON SMALL-END DIAMETER (SED)

Real (black segment) and projected (grey segment) values

SOURCE: The author (2014)

8.2.3 Financial criteria

Three indexes were regarded for financial evaluations using capital budgeting criteria: net present value (NPV), internal rate of return (IRR) and land expectation value (LEV).

8.2.3.1 Net present value (NPV)

The net present value is the application of present value equations, and was calculated as (KLEMPERER, 1996, adapted):

$$NPV = \sum_{t=0}^{n} \left[\frac{(R-C)_t}{(1+i)^t} \right]$$

Where: NPV = net present value of the silviculture regime, in US\$ ha^{-1}, n = number of years involved, t = year at which revenues and costs occurred, starting at age 0, R = revenues obtained in period ‘t’, C = costs occurred in period ‘t’, i = discount rate.

When NPV is positive, revenues were high enough to pay for the invested capital at the minimum acceptable rate of return. When negative, the internal rate of return is lower than the opportunity costs. It is used as decision criterion by simple comparison between NPV of different projects.

8.2.3.2 Internal rate of return (IRR)

The internal rate of return was obtained by (CLUTTER *et al.*, 1983):

$$\sum_{t=0}^{n}\left[\frac{(R-C)_t}{(1+i)^t}\right]=0$$

The internal rate of return is the expected yield of the capital invested in the project (CLUTTER *et al.*, 1983; KLEMPERER, 1996).The silvicultural regime is considered financial attractive when the difference between IRR and the minimum acceptable rate is equal or greater than zero. It means also that NPV was positive.

8.2.3.3 Land expectation Value (LEV)

The land expectation value was calculated as (CLUTTER *et al.,* 1983, adapted):

$$LEV_t=\frac{\sum_{j=0}^{t}\left(R_j-C_j\right)\cdot(1+i)^{t-j}}{\left((1+i)^t-1\right)}$$

Conceptually, LEV is the present value of all cash flows produced by an infinite series of rotation age of *t* years (CLUTTER *et al.,* 1983). The LEV is commonly used to represent the NPV of a bare land intended for forestry use purposes (DAVID; JOHNSON, 1987). In other words, it represents the maximum price per ha when land is bought for some specific purpose, and hence, named by Klemperer (1996) as willingness to pay for land.

8.2.4 Assumptions

Financial assessments require the definition of an alternative rate of return, used to appropriately discount the cash flows (GREGERSEN; CONTRERAS, 1992). The definition of these discount rates commonly consider the rate at which money can be borrowed, excluding inflation, or a rate obtained by an alternative investment.

Following assumptions were regarded (Brazilian Central Bank, Mai 2013):

- Exchange rate of R$ 2.04 = US$ 1.00 (Real to United States Dollar)
- Economy basic rate = 7.5 % year^{-1}.
- Savings interest = 5.25 % year^{-1} (last 12 months).
- Inflation = 5.7 % year^{-1} (2007-2012).

It is important to note that governmental interest rates are quoted in nominal terms, including inflation.

Savings interest is an important reference because it is the safest option, free of taxes, although, it currently does not compensate even the inflation rate.

Savings may not be appropriate as an alternative rate of return for bigger investors. Thus, and for comparison reasons, the capital market in Brazil (BOVESPA) was regarded. According to Rocha (2012), the average nominal growth of BOVESPA within 2004-2012 was 164 %. However, in real terms it was roughly 7 % year^{-1}. The author pointed out how distorted can be long-term financial analysis when inflation is not properly regarded.

Because there is no certainty on estimated future inflation rates, analyses were carried out regardless of inflation, supposing the revenues and costs will oscillate on similar patterns. Thus, it is recommended to use real rates in long term financial analyses, since they are not disturbed by the influence of inflation, as is the case for nominal rates (GREGERSEN; CONTRERAS, 1992; BINKLEY, 2009).

As a result of the assumptions, a real alternative interest rate of 4 % was considered reasonable for the Brazilian scenario, although sensitive analyses also evaluated 2, 6 and 8 % year^{-1}.

Obviously, if capital needs to be taken in the market, the minimum discount rate should be at last the same one pays for it. However, the present study was oriented for landowners who have the capital and regard forestry as an investment option. Because of the same reason, values for purchasing land were not regarded.

Costs and benefits occurring within a given year were considered as having occurred at the same time.

All analyses were conducted considering a before-tax situation.

Statistical analyses regarded ANOVA procedures with help of the software SPSS 19®.

8.2.5 Sensibility analysis

Financial analysis provides good information for the evaluated moment. However, and because of the intrinsic long-term nature of investment in plantation forest, a sensibility analysis, in which assumptions vary within a determined range while others remain constant, might offer more strategic information:

- Cost increases of 50 and 100 %.
- No premium prices are paid for pruned assortments, when pruning costs remain.

- New assortments >50 cm are created for both unpruned and pruned logs.
- Interest rates of 2, 6 and 8 %, additionally to the 4 %.

The simulation of such scenarios can be regarded as pessimistic and optimistic or simply in order to better understand how the financial criteria are affected by different market conditions.

8.3 RESULTS

8.3.1 General information

Log prices are quite variable between regions, because of the particularities of each industrial park and the products produced at it. They depend, as well, on the amount and quality of offered log assortments. Nevertheless, the company which provided the log assortment prices supplies industries in a radius up to 500 km, which assure the representativeness of data.

The revenues and, therefore, the financial performance of planted forest are strongly related to the management schedule and the site productivity. The stands evaluated in this study were submitted to different thinning intensities named: ‘moderate’, ‘heavy’ and ‘extreme’, which means the removal of 1, 2 or all competitor trees at age 5 years. Further thinnings were also applied. An unthinned variant was conducted as control. More detail about experiment design in Chapter 2 MATERIAL AND METHODS.

This is an important consideration as comparative studies from southern Brazil have regarded exclusively mechanical or thinnings from below, which do not have the same potential of improving individual tree growth, as is the case of crown thinnings, widely shown in the previous chapters.

The stand productivity varied from 34-47 m^3 ha^{-1} $year^{-1}$ at age 30 years, depending on the management regime, indicating the stands were of high productivity, also for loblolly pine grown in Brazil.

Although the experiment was conducted until age 30 years, harvest ages of 16, 18, 20, 22, 24, 26 and 28 were analysed.

8.3.2 Revenues

The gross revenues were obtained by multiplying the amount (m³) of each log assortment and their respective prices. The values obtained at each thinning intervention, as well as at the different ages at which final cuts were simulated are shown in Appendix: considering current log prices. For simplicity reasons, only a summary of these data was kept in the present chapter.

Gross revenues for the thinnings intensities considering a 30-years harvest age is shown in Tab 8.3-1.

TABLE 8.3-1: GROSS REVENUES OF THINNINGS, STANDING STOCK AT AGE 30 YEARS AND TOTAL PRODUCTION CONSIDERING CURRENT LOG ASSORTMENT PRICES

THINNING VARIANT	GROSS REVENUE **THINNINGS**[1]	 **STANDING STOCK**	 **TOTAL**
without	0	40,400 a	40,400 a
moderate	11,100	51,900 b	63,000 b
heavy	8,700	56,800 b	65,500 b
extreme	10,400	47,700 ab	58,100 ab
STATIS. SIGNIF.	n.s.	*	* *

[1]only the thinned variants were statistically analysed.

SOURCE: The author (2014)

Although a different number and intensity of thinning procedures were applied to the stands, thinned stands showed a similar gross revenue.

On the other hand, the standing stock revenues varied substantially between thinning variants. Considering the current assortment prices, the ‘heavy’ variant showed the highest gross revenue, similar to the other thinned treatments. The area ‘without’ thinning had the lowest value, similar to the ‘extreme’ one.

When the total gross revenue was regarded, thinned stands were similar to each other and superior in comparison to the unthinned stand. The only exception was the gross revenue of the ‘extreme’ variant, which was similar with both, unthined and thinned variants.

8.3.3 Financial criteria

In a long-term investment such as timber production it is necessary to consider the value of money over time. Only then, the financial performance of the different silviculture regimes can be properly assessed and conclusions about their viability can be taken.

Moreover, instead of evaluating financial criteria of different silvicultural regimes for a given harvest age (for example, 30 years), of more interest is the analysis of the financial criteria development over the years.

The obtained financial criteria for the stands submitted to different thinning intensities with harvest ages varying from 16-30 years and current log assortment prices are shown in Table 8.3-2.

With the comparison of the NPV between thinning intensities it was verified that thinning improved the wealth obtained from the stands. The NPV was highest on the ‘extreme’ variant ($ 15,300), and lowest on the unthinned stand ($ 6,100).

The financial optimum age for ending the rotation was at 26 years for the control stand, ‘without’ thinning. ‘Moderate’ and ‘heavy’ thinnings led to a postponement of the final cut, at least to age 30 years. While the ‘extreme’ anticipated to age 24 years.

Table 8.3-2: Net present value (NPV), internal rate of return (IRR) and land expectation value (LEV) for the different thinning variants and regarding current log assortment prices. Harvest ages varied from 16-30 years

Production period	Net present value without	 moderate	 heavy	 extreme
16	3,200	6,200	6,100	9,900
18	4,200	8,000	8,200	12,200
20	4,800	9,500	9,700	13,500
22	5,500	11,300	11,400	15,000
24	5,800	12,200	11,900	**15,300**
26	**6,100**	12,700	12,400	15,100
28	5,800	12,500	11,900	14,800
30	5,800	**12,900**	**13,700**	12,700

Production period	Internal rate of return without	 moderate	 heavy	 extreme
16	9.9	14.1	14.3	**17.4**
18	**10.1**	**14.5**	**14.8**	17.3
20	9.9	14.5	14.6	16.2
22	9.7	14.4	14.4	16.2
24	9.3	14.0	13.8	15.4
26	9.0	13.4	13.2	14.7
28	8.4	12.8	12.5	14.0
30	8.1	12.4	12.4	13.0

Production period	Land expectation value without	 moderate	 heavy	 extreme
16	6,900	13,400	13,200	21,300
18	8,300	15,800	16,200	24,100
20	8,900	17,500	17,900	24,900
22	9,600	19,600	19,700	**25,800**
24	**9,700**	**20,000**	19,500	25,100
26	9,600	19,800	19,300	23,700
28	8,700	18,800	17,800	22,300
30	8,300	18,700	**19,800**	18,400

Current assortment prices and discount rate of 4 %

Source: The author (2014)

From the IRR perspective, the optimum rotation length was substantially shorter for all thinning variants. IRR was higher in the thinned variants too, and was highest, again, in the 'extreme' variant (17.4 % year^{-1}) at age 16 years. The stands with 'moderate' and 'heavy' regimes showed intermediate values (~15 % year^{-1}), while the 'without' one, the lowest (10 % year^{-1}) – all of them at age 18 years.

The LEV express the present value for managing an area unit with the specific regime to perpetuity. It showed that in the long term, loblolly pine stands management should consider production periods between 22-30 years, depending on the regarded thinning intensity: 22 years for the 'extreme' variant, and ~24 years for the others, including the unthinned one. Through LEV calculation it was also verified that thinning delivered more than twice as much financial output in comparison to unthinned stands.

8.3.4 Sensibility analysis

8.3.4.1 Log assortment prices

The assortment prices are strongly affected by market conditions. It can vary from local to global scale depending on which product is made and where it is commercialized. Moreover, the simple existence of an assortment depends on the supply capacity of stands in an economic amount and proximity to industrial parks suitable to its utilization.

Three scenarios were simulated:

- Current assortments considering only unpruned values, i.e. no premium prices paid for pruned assortments, although pruning costs were accounted.
- Current assortments and prices.
- The market would be interested on paying more for two new assortments >50 cm, unpruned ($ 99 m^{-3}) and pruned ($ 135 m^{-3}).

The figure 8.3-1 shows the results for the net present value.

From Figure 8.3-1 it can be seen that no pruning premium substantially and negatively influences all treatments. The more intense the thinning, the greater the absolute impacts of these scenarios. However, in relative terms, no pruning affects more the unthinned variant.

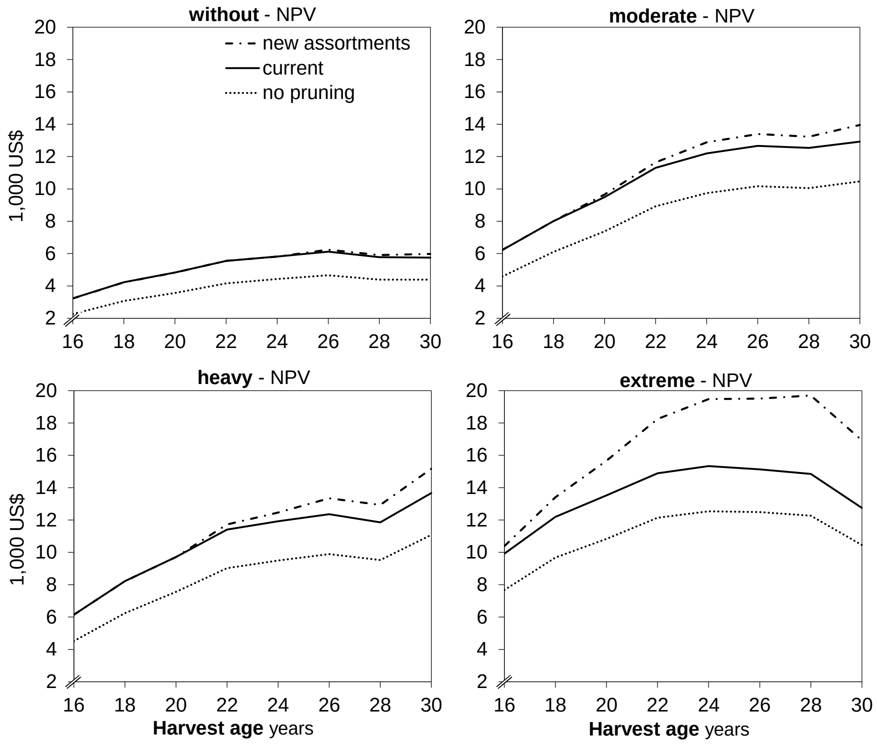


FIGURE 8.3-1: SENSIBILITY ANALYSIS FOR NET PRESENT VALUE (NPV) AS AFFECTED BY LOG ASSORTMENT PRICES: NEW ASSORTMENTS, CUR-RENT PRICES AND NO PRUNING PREMIUM

Harvest ages varying from 16-30 years.

SOURCE: The author (2014)

The inverse was observed for the new assortment scenario. The more intense the thinning, the greater the positive effect of big-sized log assortments on the NPV. The unthinned stand showed no profit if these new assortments are included, which was expected since tree dimensions were smaller. For treatments ‘moderate’ and ‘heavy’, new assortments scenario shows a significant effect only after age 22-24 years. While for the ‘extreme’ one, the advantadges of bigger-sized assortments were already visible at age 18 years.

For all treatments, and according to NPV development, it became graphically clear that after age 22-24 years, there is a level off tendency, although the highest values were observed later (Table 8.3-2). While some inaccuracy may resulted from the growth projection made from annual ring measurements, the values shown for age 30 years are ‘real measured values’ and, for the ‘heavy’ variant, do show that NPV still increased substantially at age 30 years. In the ‘extreme’ variant, however, increasing trends may not be as sharp as plotted after age 22. Nevertheless, because NPV reached its peak at age 24, it is expected that the growth rate of trees translated into currency might be overtaken by the interest rate after this age.

In Figure 8.3-2 the development of internal rate of return (IRR) for the different scenarios and thinning intensities is presented.

Internal rate of return (IRR) oscillated between:

- ~8 %: 'without' thinning, no pruning premium, at age 30 years, and.
- ~18 %: 'extreme' variant, new assortments, at age 16-18 years.

All treatments showed a trend of highest IRR around age 18-20 years and, after this, decreased with aging.

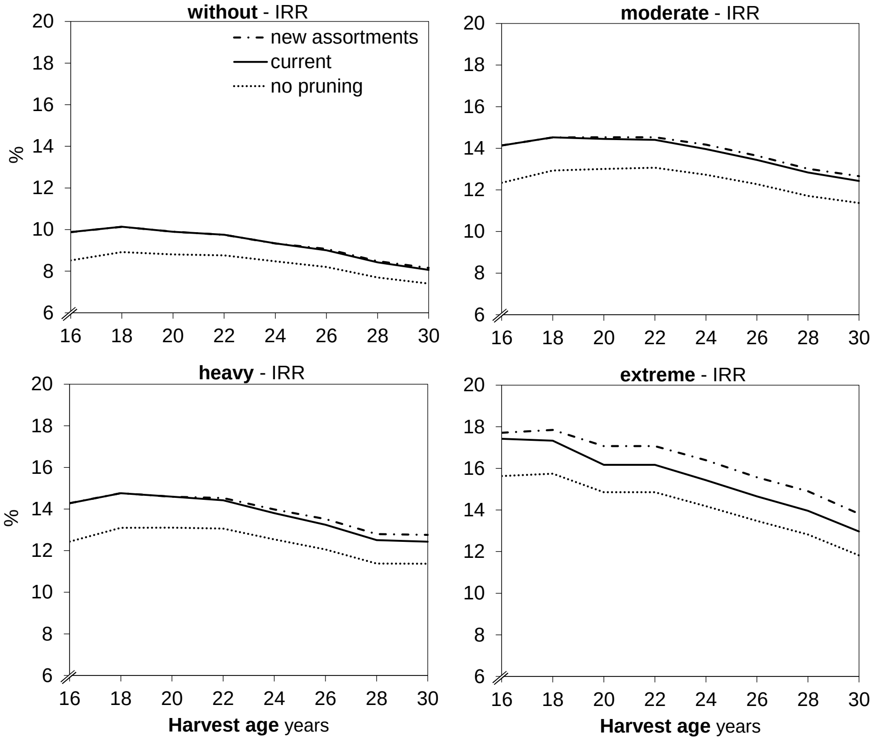


FIGURE 8.3-2: SENSIBILITY ANALYSIS FOR INTERNAL RATE OF RETURN (IRR) AS AFFECTED BY LOG ASSORTMENT PRICES: NEW ASSORTMENTS, CURRENT PRICES AND NO PRUNING PREMIUM

Harvest ages varying from 16-30 years.

SOURCE: The author (2014)

In general, no pruning premium apparently had a greater impact on early harvest ages in comparison to longer rotations, independently of thinning intensity. This scenario resulted in a decrease of IRR in the different variants and on a similar way (roughly -10 %).

Similar to the NPV analysis, the IRR of the stand 'without' thinning showed a very small effect of new assortments. However, differently from the NPV, the stands with 'moderate' and 'heavy' thinnings presented almost no increase in the IRR. Only the 'extreme' thinned stands had a substantial increase in IRR.

The development of land expectation value (LEV) for the different scenarios and thinning variants is shown in Figure 8.3-3.

The LEV analysis showed similar trends as observed with NPV. All variants had their highest LEV with production periods around 24 years, showing that, at a real discount rate of 4 %, it is worth to achieve greater log sizes and assortment values. This is true even when no premium price for pruning is considered. However, markets that pay for pruned log assortments increased substantially the financial output obtained from the stand. In other words, and considering current assortment prices, a hectare of bare land where loblolly pine will be managed with thinnings and pruning has the capacity of producing over US$ ~25,000 of finantial output, in terms of present value. While the stand 'without' thinning reached not even half of this amount.

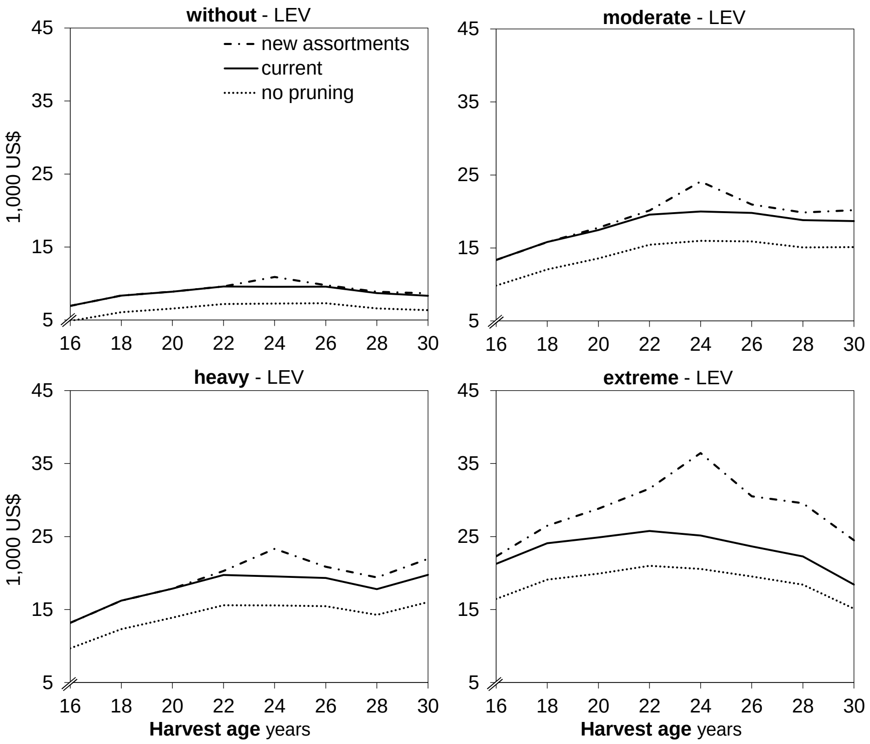


FIGURE 8.3-3: SENSIBILITY ANALYSIS FOR LAND EX-PECTATION VALUE (LEV) AS AFFECTED BY LOG ASSORTMENT PRICES: NEW ASSORTMENTS, CURRENT PRICES AND NO PRUNING PREMIUM

Harvest ages varying from 16-30 years.

SOURCE: The author (2014)

8.3.4.2 Costs

The impact of increasing the production costs (establishment, cultural and silvicultural treatments) in 50 and 100 % on NPV and IRR are shown in Figure 8.3-4. For simplicity reasons, only the treatments 'without' and 'extreme' are presented.

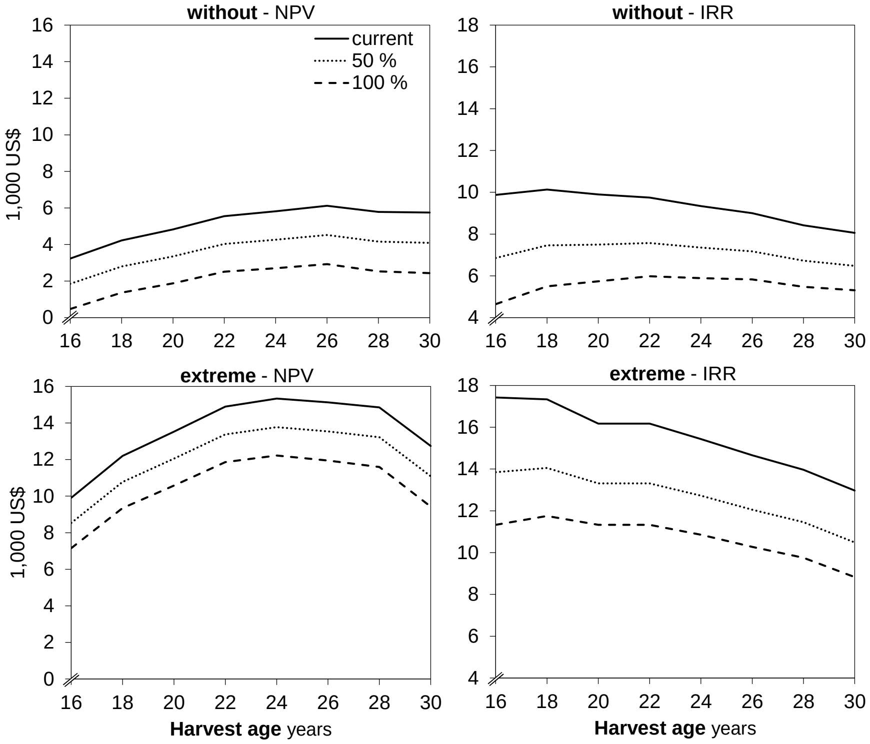


FIGURE 8.3-4: SENSIBILITY ANALYSIS FOR NET PRESENT VALUE (NPV) AND INTER-NAL RATE OF RETURN (IRR) AS AFFECTED BY COST INCREASES OF 50 AND 100 %. SOLID LINE AS REFE-RENCE WITH CURRENT COSTS.

Harvest ages varying from 16-30 years.

SOURCE: The author (2014)

As expected, the increase in the production costs caused a substantial impact on IRR. It was greater on shorter rotation periods than in longer ones.

An increase of 100 % in the costs of an unthinned stand reduced the NPV to nearly to 0. This means the alternative interest rate (4 %) was almost reached by the internal rate of return at age 16 years. On the other hand, thinned stands, because they had a higher financial performance, would allow substantial increases in silvicultural costs keeping its profitability at satisfactory levels.

8.3.4.3 Interest rates

The impact of different interest rates on the net present value (NPV) and land expectation value (LEV) for the different thinning intensities are shown in Figures 8.3-5 and 8.3-6.

From the Figure 8.3-5 it can be noted that the interest rates affected the NPV more than any other tested before.

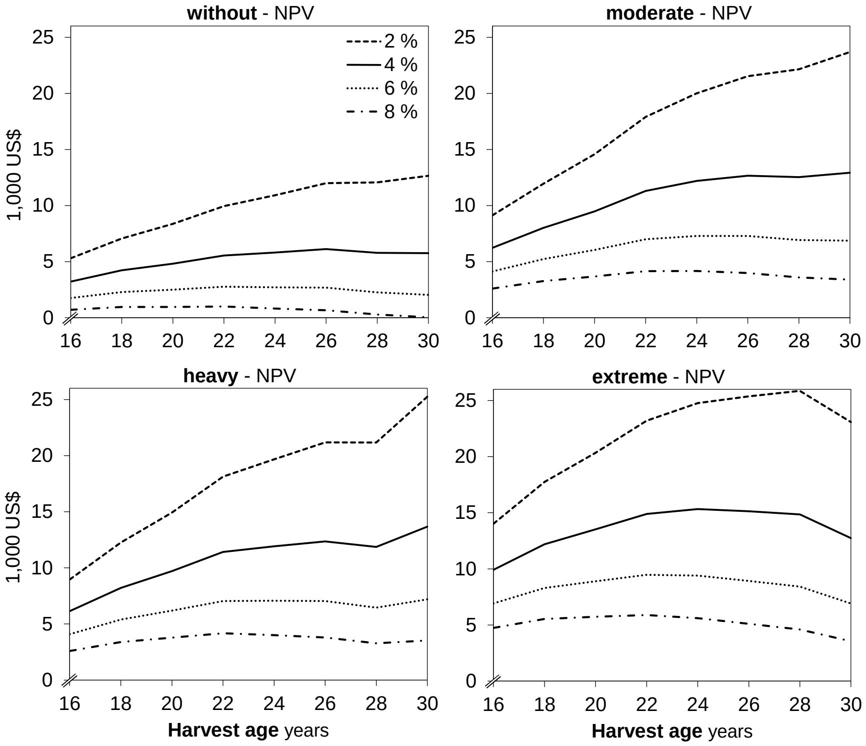


FIGURE 8.3-5: SENSIBILITY ANALYSIS FOR NET PRE-SENT VALUE (NPV) AS AFFECTED BY INTEREST RATES: 2, 4, 6 AND 8 %

Solid line as reference with 4 %; rotation length vary-ing from 16-30 years.

SOURCE: The author (2014)

It became obvious that on high interest rate markets, unthinned stands are almost not profitable beyond the IRR. Although all thinned stands were negatively impacted, their cash flows were still relative profitable even at 8 % rate.

Similar trends observed with NPV were also verified with LEV. Discounting cash flows with low interest rates resulted in impressive high values for managing *P. taeda* stands in Southern Brazil. It means that the interaction of tree growth and assortment prices were remarkably more efficient in the long-term as a 2 or 4 % investment would be.

When higher interest rates were applied to the cash flows, especially 8 %, unthinned stands were economically unfeasible, while thinned ones still had the potential of producing wealth.

Noteworthy is also that the increase in the interest rate from 2-4 % had a greater negative influence in both NPV and LEV than shifting from 4-6 % and so on.

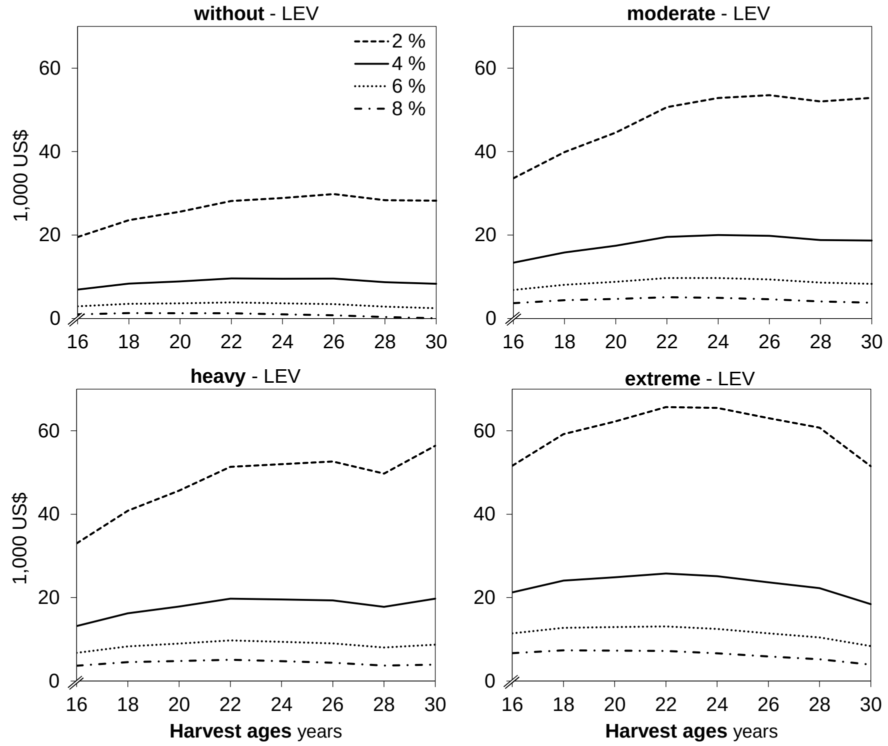


FIGURE 8.3-6: SENSIBILITY ANALYSIS FOR LAND EX-PECTATION VALUE (LEV) AS AFFECTED BY INTE-REST RATES: 2, 4, 6 AND 8 %

Solid line as reference with 4 %; harvest ages varying from 16-30 years.

SOURCE: The author (2014)

8.3.5 Sustainable forestry

Because of the instability of conclusions when different interest rates are regarded, an additional approach is considered in which a regulated forest have been evaluated in terms of annual revenues and costs. The discussion related to this analysis is shown below.

A regulated forest is characterized by:

- Similar amounts of timber are yearly harvested.
- The amount of timber harvest every year is equal to the growth rate of the forest.

It means the area harvest every year may differ, according to the site quality. Following harvest the stand is re-established and thus, the sustainability of production is assured.

For a practical example, the ‘extreme’ variant was selected, together with the following assumptions:

- Target diameter: 60 cm.

- Production period: 25 years.

Because the forest is fully regulated, all the activities related to the management occur individually in $^1/_{25}$ of the whole area every year. In such a scenario, the financial approach can be simply the revenues minus costs within the same year, regardless of interest rates. At the end of the year, after all activities have been carried out, the financial performance is the profit or loss restricted to that period.

The advantage of this analysis is that all efforts are concentraded in the production of a valuable stand, obviously with the minimum outgoing. In other words, the silviculture is the most important gear and external factors, such as interest rates, are put aside.

Results are given in Tab. 8.3-3.

Table 8.3-3: Revenues and costs ha^{-1} within one year in a regulated forest, for stands without thinning and pruning and for regarding the extreme variant

	Activity	WITHOUT US$ ha^{-1}	EXTREME US$ ha^{-1}
Revenue[1] (+)	Final cut[2]	21,000	36,000
	3rd thinning		5,000
	2nd thinning		1,000
	1st thinning		400
	sub-total	21,000	42,400
Costs (-)	Establlishment	1,900	1,300
	Cultural treatm.[3]		600
	Pruning[4]		400
	Administration	2,500	2,500
	sub-total	4,400	4,800
	Total	**16,600**	**37,600**

[1] harvest and road costs discounted.
[2] average value between harvest ages 24 and 26 years.
[3] regarding 3-years period after planting.
[4] all 4 interventions.

Rounded values

Source: The author (2014)

8.4 DISCUSSION

8.4.1 Brazilian particularities

A previous profitability analysis of the same experimental area, carried out about 10 years ago by Seitz and Huss (2004), regarded assortment prices (US$) more or less similar to the ones regarded in the present evaluation. However, a contradictory difference was observed on the prices of the pruned >40 cm assortment. Although in 2004 it was up to 50 % higher than now in the Brazilian currency (Real, R$), currently it is lower in R$ but ~30 % higher in US$. The reason for this contradiction is the difference in currency ratio between the two moments.

Although the decreased value of US$ in relation to the R$ during this period was unfavourable for exporting, the negative impact was not worse because of the relative good condition of the Brazilian economy during the same period. Moreover, the global crisis of 2008, coincided with a relative heated and stable domestic economy and led to a substantial redirection of the Brazilian timber production and timber-based products from exports to internal supply. The construction sector has been the main demander. However, high-quality uses of softwood are not well developed in Brazil and, therefore, pruned log assortments have not been as required as the unpruned ones. The main use for the unpruned assortments has been building wood forms and thus, bigger-sized assortments are preferred for sawtimber production of 30 cm wide boards.

According to Tomaselli (2012) there was a remarkably increase in the price of pine logs during the period between 2003-2007. The price in US$ of log assortments with 26-35 cm, for rotary peeling, increased ~200 % in nominal terms. In the same period, Brazilian inflation was ~30 %. The author pointed out that the reasons for this are not clear, and was most likely due to increases on production costs, i.e. wages. After his opinion, the cambial fluctuation is another issue, but not the most important one.

According to official data, between 2000-2013, the national minimum wage showed a real increase of ~220 %, already considering inflation. This information reinforce the arguments addressed by Tomaselli (2012).

It is also important to note that in 2002-2004, the US$ reached the highest quotation in comparison to Brazilian currency (Real). In the period from 2005-2012, the ‘Real’ increased its value ~50 % over the US$ (TOMASELLI; HIRAKURI, 2012).

8.4.2 Revenues

Thinning gross revenues were similar between thinned stands, regardless of thinning intensity (Table 8.3-1). However, the ‘extreme’ variant showed the highest individual gross revenue between thinning procedures ($ ~7,000, at age 13 years, Appendix, Tab 11.6-2). Because of the early and intense release from competition of the selected crop trees in this variant, the thinning at age 13 years already delivered higher valuable pruned assortments, ~60 % of the thinning gross revenue. Which is quite impressive and shows the high growth response of the young loblolly pine trees when sufficient growth space is early provided.

The total gross revenues were higher on the 'moderate' and 'heavy' thinned stands. These variants showed a total gross revenue over 55 % in relation to the unthinned stand.

The magnitude of increase on individual tree value was remarkable. Although the 'extreme' variant presented an intermediate total revenue, similar to the other thinned variants and to the unthinned stand, the mean tree stumpage price at age 30 years was $ 300, while, on the stand withouth thinnig it was only $ 60 tree^{-1}.

Although prunned log assortments (first ~6 m of the bole) represented only 17 % of the total tree height, it accounted for:

- ~30 % of the total volume production,
- ~50 % of the total gross revenue.

Together, the results comproved that thinning alone, and thinning + pruning are financialy interesting practices on loblolly pine stands in southern Brazil.

The exponential effect of increasing tree value as affected by tree diameter is commonly underestimated. While the relation of $-increase by each cm increase in tree diameter is only 2 units between 20-30 cm, it is '4' between 30-40 and is '10' between 40-50 cm.

According to Makinen and Isomaki (2004) beyond higher prices, larger trees are also associated with lower harvesting costs. However, the merits of different thinning intensities depend on the size-price relationship of logs paid by the regional market.

8.4.3 Financial criteria

Although thinning does not necessarily increase net present value (KLEMPERER, 1996), results found in this study showed that regardless of thinning intensity, NPV was always higher in comparison to unthinned stands.

The NPV of the stands under the 'extreme' regime ($ ~15,000, at age 24 years) was highest between the analysed treatments. It was also more than twice as high as the unthinned stands ($ ~6,000, at age 26 years). According to Clutter *et al.* (1983), although correct decisions cannot be made with any single criteria, NPV always results in correct decisions if the goal of the organization is financial maximization.

Acerbi Jr *et al.* (1999) evaluated loblolly pine under multi-products regimes in southern Brazil. The authors found a maximal NPV of \$ 3,600. This optimum was obtained by

- planting 1,667 trees ha^{-1},
- applying 2 thinnings (at ages 12 and 14 years), and
- harvesting at age 21 years.

A discount rate of 6 % was regarded. Nevertheless, and for comparison purpose, the NPV obtained by the ‘moderate’ variant at age 22 years was twice as high (\$ 7,000). It is important to note that the log assortment prices used by the cited authors were much lower than the one considered in the present study. Moreover, discount rate applied in the present study was lower (4 %).

Cubbage *et al.* (2010), evaluated the profitability of loblolly pine plantation in Brazil:

- Establishing costs of US\$ 1,050 ha^{-1} (0-5 years),
- mean annual increment of 30 m^3 ha^{-1} year^{-1},
- discount rate of 8 % year^{-1}.
- harvest age at 15 years.

Altogether, their data resulted in a NPV of \$ 3,590.

It is important to note that the study conducted by Cubbage *et al.* (2010) described average conditions for the Brazilian pine segment, which means mainly pulpwood production. While the data used in the present study assessed a specific case study, where crown thinnings and pruning have been carried out during the last decades and, therefore, an especial market has been developed.

Similar results were obtained by Vitale and Miranda (2010):

- Establishing costs of 1,936 \$ ha^{-1}
- discount rate of 6.75 % year^{-1},
- resulting in a NPV of 15.600 \$ ha^{-1}.

Because pruning costs were described, it is supposed that pruned assortments were considered, although no information about them was available.

Considering the internal rate of return (IRR), the variant ‘extreme’ showed the highest value (17 %), and it was observed already at age 16 years, 8 years before the maximum NPV was detected. The stand ‘without’ thinning presented the lowest IRR

(10 %), and identical to the other practice oriented variants, the maximum value was observed at age 18 years.

Cubbage *et al.* 2010 reported an IRR for loblolly pine plantations in southern Brazil of 21 % year^{-1}, at age 15 years. According to the authors, it was the most profitable one in comparison with other plantations of the same species in:

- Argentina (20 % year^{-1}),
- Uruguay (13 % year^{-1}),
- Paraguay (12 % year^{-1}) and
- United States (8 % year^{-1}).

Furthermore, IRRs were less, but still attractive for plantations of coniferous in China, South Africa and New Zealand, ranging from 7-12 %.

Other studies reported IRR for loblolly pine plantations in Brazil of 16 % (CUBBAGE *et al.* 2007), 21 % (SCOLFORO 1998), 27 % (VITALE and MIRANDA 2010).

As a consequence of the previous results, the maximum land expectation value (LEV) was obviously verified on the extremely thinned stand (~26,000 US$ ha^{-1}), which was similar to the other thinned variants (~20,000 US$ ha^{-1}). Again, and with a long term perspective, thinned loblolly pine stands produced twice as much wealth in relation to the unthinned ones.

Cubbage *et al.* (2010) pointed out that LEV is also an indicator of what one could pay for bare land plus make the computed return equal to or better than the discount rate. After this perspective, land prices for plantation forest are still viable in southern Brazil. These conclusion should be carefully taken, since the high LEV values obtained in the present study were a result of valuable log assortment production, different from the common management applied to loblolly pine stands in Brazil. Indeed, previous analysis provided much lower values: from 2,500 (CUBBAGE *et al.* 2007) to 4,400 $ ha^{-1} (ACERBI JR. *et al.* 2002), also affected by higher discount rates.

Similarly to the present study, Scolforo (1998), Gomes *et al.* (2002) and Acerbi Jr. *et al.* (2002) concluded that the most profitable management option for loblolly pine stands in southern Brazil is the one which consider thinnings and pruning (premium prices of 40 %).

8.4.4 Harvest age

Another reason for assessing financial criteria of silvicultural regimes is to define the optimum age for final harvesting. According to Oesten and Roeder (2012b), the optimum final age from the financial perspective depends on the interest rate regarded in the analysis and varies substantially depending on site quality.

In general, and considering the maximum NPV, the optimum harvest age was observed between 24-30 years, longer than the recommended by former studies, and the current practiced in southern Brazil, 15-20 years. This is an important result and indicates that under the analysed circumstances the final cut should be postponed. However, as addressed by Price (1989), net present values of harvest ages few years shorter or longer than optimal are not much less than that, what gives some flexibility to silviculturists.

Regional particularities need obviously to be regarded, basically log price-size relationship. It shows that for independent log producers located within well-established forest markets, the current 15-20 years rotations are underutilizing the potential of the stands, at least from the financial perspective.

Several authors have already recommended harvest ages of 20 years, longer than the currently regarded ones (SCOLFORO, 1998; GOMES *et al.,* 2002; ACERBI JR. *et al.,* 2002).

The influences of thinning on the harvest age was not linear. While ‘moderate’ and ‘heavy’ thinnings led to a postponement of the final cut (~30 years), the ‘extreme’ and early thinning anticipate the optimum final cut to age 24 years. Both relative to the unthinned stand, which should be harvest at age 26 years for optimizing NPV.

These results are strongly related to the regarded log assortment classes. As there was no financial advantage for producing logs with diameters over 40 cm, trees that already reached the biggest and most valuable assortment should be harvested. This was the case for the ‘extreme’ variant at age 24 years.

It is commonly argued in Brazil that 2 rotations of 15 years are more efficient than one of 30 years. This affirmative may be truth when considering IRR alone. However, it makes little sense to compare single rotation cash flows for alternatives with different rotation lengths. The recommended procedure is to compare cash flows for continuing series of plantation – land expectation value (CLUTTER *et al.,* 1983; KLEMPERER, 1996; BETTINGER *et al.,* 2009).

The trend of increasing LEV with increasing harvest age, suggested that bare land put into forest production in perpetuity with rotations of 16 years are less interessant than >22-24-years production periods. Differently than argued by Bettinger *et al.* (2009) the analysis of successive rotations of the same type of management (LEV), did not lead to short rotation lengths, in comparison with simply valuing the initial harvest age. In fact, rotation lengths were similar or postponed.

8.4.5 Sensibility analysis

Although the results presented above may offer great insights for financial decisions in managing *P. taeda* stands in Southern Brazil, sensibility analyses provide a more strategic perception of how variables impact the results, According to Mead (2013), sensitivity analysis is also frequently used to explore uncertainty in the long horizon of planning.

It also shows how sensitive the results are to changes in selected inputs. Only then, the most reasonable scenario can be chosen (KLEMPERER, 1996).

8.4.5.1 Log assortment prices

Sensibility analysis related to log assortment prices analysis regarded

- no premium prices for pruning, and
- a simulated new assortment >50 cm, for both unpruned and pruned logs.

This projection was mainly due to the conclusion obtained during the industrial analysis of the logs produced in the same experiment. Economic analysis of logs on sawmill (DOBNER *et al*., 2012) and on rotary peeling process (DOBNER *et al*., 2013) detected that the industrial yield of >50 cm logs was substantial higher than other assortments. Moreover, current prices for pruned log assortments reflect only the industrial potential of low-quality pruned logs. Thus, optimising the pruning strategy would result in higher industrial efficiency, which would allow higher log prices.

One could argue that the obtained financial criteria were too high, even for current assortment prices. However, assortment prices regarded in this study were lower than the values published by Tomaselli (2012). According to the author, logs with 26-35 cm destined to veneer mills were commercialized in Brazil at ~80 US\$ m^{-3}, while sawn logs were sold at ~40 US\$ m^{-3}. Smaller-sized logs (8-15 cm) reached a price of ~18 US\$ m^{-3}. Moreover, differently from the present study, where assortment prices considered harvest and loading, the cited prices are stumpage.

The new assortments scenario showed that thinning increased substantially the financial performance, while the unthinned area was not affected. ‘Moderately’ and ‘heavily’ thinned stands increased the NPV, IRR and LEV after age 22-24 years, while the ‘extreme’ one showed a dramatic increase already at age 16-18 years.

For the ‘extreme’ variant, including new assortment classes led to a postponement of the optimum final cut age, from 24 to 28 years. These results clearly show that rotation length is strongly affected by the assortment classes and its prices (price-size relationship). Because of the limited analysed time period, until 30 years, the effects of new assortment classes could not be observed for the practice oriented variants, which may have had the same behaviour.

Indeed, the age of 30 years was considered far beyond the optimum rotation before these analyses were carried out.

Pruning unquestionably increased the gross revenues of all thinning intensities by ~12 % at age 30 years, when compared to the unpruned-price scenario. Moreover, pruning can be regarded as a market differentiation strategy, which is an important issue regarding the long-term characteristic of the forest investment, even more relevant for independent log producers.

No premium price for pruning led obviously to a decrease on NPV of the different thinning intensities. Surprisingly, the effect was higher on the unthinned treatment (-24 %), while the NPV of the thinned variants was reduced to 19 %. Thus, thinning could be considered as a strategic option to reduce the losses when markets face a period of low pruned assortments demand, just what has happened during the last 5 years.

While NPV and LEV was affected by no premium price for pruned assortments showed a higher impact as stand ages, IRR reductions were higher at the beginning of the analysed period.

8.4.5.2 Costs

Understanding of how increasing costs affect the financial performance of forest projects is important to assure the economic sustainability of plantation forestry in the long term.

As mentioned, forestry costs have increased substantially within the last decades in Brazil. The costs regarded for the financial evaluation were current ones, probably remarkably higher than the real ones dispended 30 years ago, when the experiment was established. Moreover, the cost that will be spent in the next decades are likely to continuously improve, just as happened in developed countries. Another issue that already limit the expansion of the South Brazilian planted area is the labour availability. Altogether, these features will inevitably increase silviculture costs in the long run.

Comparatively, while the present study included establishment costs of 1,520 \$ ha^{-1}, other comparable studies considering the South Brazilian conditions reported 550 \$ ha^{-1} (ACERBI JR. *et al.,* 2002), 1,050 \$ ha^{-1} (CUBBAGE *et al.,* 2010) and 1,936 \$ ha^{-1} (VITALE; MIRANDA, 2010).

The results obtained in the present study showed that increasing costs within the two extreme variants (‘without’ and ‘extreme’ thinnings) resulted in a linear decrease of the NPV along time and thus, the optimum harvest age was not affected by them.

Because of the lower profitability of the unthinned stand, the impact of increasing costs was much heavier in this treatment. Costs increase of 50 % decreased the maximum NPV of the unthinned stand by 26 % (at age 26 years), while it resulted in only 10 % decrease for the ‘extreme’ variant (at age 24 years).

The IRR was apparently more affected by shorter rotation periods than on longer ones. From the IRR perspective, increasing costs had a substantial impact on the optimum harvest age. The optimum final cut age for the unthinned stands was reduced from 26 to 22 years and, for the ‘extreme’ variant, it was reduced from 24 to 18 years.

By increasing silvicultural costs by 100 %, unthinned stands with a rotation length of ~16 years showed NPV nearly zero, which means that the invested capital paid exactly the 4 % minimum attractive rate. Although still profitable, it shows that this type of management is more fragile from the financial perspective in an increasing costs scenario. Still, because thinned stands produced higher levels of financial outputs, they are able to endure higher silvicultural costs.

Furthermore, by applying thinnings on planted forests, big companies use to clear cut a buffer zone at each road side, as wide as the current tree height. The objective is to allow fast dry of forest roads and increase the availability for heavy traffic. This practice has obviously a significant effect on stand productivity due to area loss. Data related to this questions were not collected in the present study, however, the remarkably superiority of the financial performance observed in the thinned stands may be able to endure these additional costs without losing its higher profitability.

8.4.5.3 Interest rate

As mentioned, the interest rates evaluated in this study were real ones. Contrarily, and according to Klemperer (1996) one of the most common errors is to project cash flows in constant dollars and use a nominal interest rate.

In fact, nominal interest rates (considering inflation) can be used only when cash flows are expressed in term of inflated dollars. However, the appraisal of forest properties using inflated cash flows has not found wide acceptance. This is partly because inflated values seem unduly high. However, if all costs and returns inflate at a constant rate, then no adjustment is necessary, and inflation can be cancelled in both revenues and costs (CLUTTER *et al.,* 1983).

Thus, if cash flows are in constant dollars, it is recommended to compute net present value with a real interest rate. This general approach on treating inflation rates considers that prices of all inputs and outputs are expected to increase at the same rate – general inflation (GREGERSEN; CONTRERAS, 1992; KLEMPERER, 1996).

Although the majority of the previous financial studies considered higher discount rates than the ones used in the present study, it was concluded that this approach overestimates the real alternative interest rate to the forest activity. In fact, and according to Cubbage *et al.* (2007), long-term real rates of return are probably between 4-8 % for most investments, despite higher corporate hurdle rates. Ultimately, it seems realistic for Brazilian conditions to consider real rates around 4 % year^{-1}, which, in nominal terms, would mean ~10 % year^{-1}.

Additionally to the real interest of 4 %, scenarios with 2, 6 and 8 % were also evaluated. The results showed that interest rates were responsible for the greatest impacts on the financial analyses.

At a discount rate of 2 %, the unthinned stand reached a similar profitability observed on the ‘moderate’ and ‘heavy’ thinned stands at a discount rate of 4 %.

Because the unthinned variant showed an IRR of ~9 % for harvest ages of 16-30 years, at a discount rate of 8 % the NPV of this treatment was close to zero. A substantial decrease on NPV of the thinned variants was also verified, however, these stands remained more profitable than the unthinned one at 4 %.

In general, lower discount rates postponed the final cut age. For the ‘extreme’ variant, and at a discount rate of 2 %, 28 years was the optimum harvest age. For the other thinning intensities and at the same interest rate, the optimum financial harvest age may be more than 30 years.

Contrarily, higher discount rates (8 %) shortened the optimum rotation age: 22-24 for the intermediate thinned variants, and 20-22 for the ‘extreme’ thinned stands. Even though, harvest ages were greater than the common practice in Brazil.

At 8 % rate, LEV found in the present study resembled the values found by Cubbage *et al.* (2010).

8.4.6 Sustainable forestry

The analysis clearly shows the great dominance of revenues over costs. When interest rates are put aside, the potencial of producing financial outputs of thinned loblolly pine stands in southern Brazil is even more remarkable. It may be supposed that there are other costs not regarded in this example.

Indeed, a relevant reflexion about this is that stands subjected to crown thinnings, from which several log assortments are obtained, have certainly a more complex approach than pulp-wood regimes. Potential crop tree selection, pruning, thinning certainly require trained people and control. The same is true for harvesting different log assortments which, in case of high quality and pruned ones, it is necessary to deliver in short periods of time before wood-staining fungi establish.

Nevertheless, the surplus of revenues is high enough for including some additional costs without compromising the profitability of these management alternative.

8.5 CONCLUSIONS

The production of big-sized assortment is a profitable silvicultural option. When 6 m of the stem is pruned, at age 30 years, it represents ~30 % of the volume, but ~50 % of the total gross revenue.

For the evaluated circumstances, ‘extreme’ and early release from competition of pruned loblolly pine trees led not only to the best financial performance (NPV =

~15,000 US$ ha^{-1}), but did it earlier (age 24 years) than other thinning intensities (30 years) and no thinning at all (26 years).

Stands subjected to crown thinnings, independently of intensity, results at least twice as much financial outputs (>13,000 US$ ha^{-1}) than no thinning at all (~6,000 US$ ha^{-1}).

Although optimum harvest ages according to internal rate of return (IRR) are 16-18 years for thinned and unthinned stands, from a long term perspective (NPV and LEV), optimum financial performance requires extending production periods in comparison to the ones currently regarded in southern Brazil. Even though extreme thinnings have a shortening effect on the optimum harvest age, it should be at least 24 years for the current log price-size relationship.

The best financial performances are already obtained from thinned stands. However, considering that there is potential for bigger-sized and more valuable log assortments, even better financial results are possible. Regarding an additional log assortment >50 cm for unpruned and pruned logs, the NPV of extremely thinned stands increases by ~30 %, while only slight differences are verified in intermediate and unthinned stands.

Because of the lower profitability of unthinned stands, sensibility analyses regarding increases in production costs have a greater impact on them in comparison to thinned stands.

Thinnings are a profitable silvicultural option even when no pruning is carried out. Moreover, the profitability of thinned stands is less negatively affected during periods at which pruning premium decreases.

9 FINAL DISCUSSION AND CONSIDERATIONS FOR THE PRAXIS

9.1 RESULTS OVERVIEW

Results demonstrated that crown thinnings impressively improve the growth of loblolly pine individuals. Tree height was slightly affected by thinning intensity. Tree diameter and, therefore, tree individual volume, were remarkably greater the more intense the release from competition. It is necessary to emphasize the crown thinning approach, since the conclusions and recommendations of this work are strongly dependent on it.

In general, it has been found:

- Stands without thinning result in
    - the lowest diameter growth. Trees reached the age of 30 years with a mean top diameter of 47 cm.
    - a peak in basal area at age 13 years (~70 m^2 ha^{-1}), without any substantial increase afterwards.
    - a substantial wood loss due to mortality (~400 m^3 ha^{-1}), >⅓ of the total volume pruduced until age 30 years. ~70 % concentrated in the period between 20-30 years.
- Stands subjected to practice oriented thinnings provide
    - top diameters substantially greater (~20 %) than stands without thinning.
    - the highest total volume production (1,400 m^3 ha^{-1}), up to 40 % more than unthinned stands at age 30 years.
    - the best combination of total volume production and log assortments >30 cm if production periods longer than 20-22 years are regarded.
- Stands where early and extreme release of potential crop trees from competition was carried out result in
    - the greatest mean top diameter (67 cm at age 30 years), 40 % bigger than unthinned stands.

  - top individual volume 90 % higher (5.3 m³) than trees in stands without thinning, and 30 % greater than trees subjected to practice oriented thinnings.
  - the same volume production as observed in stands without thinning,

    ~700 m³ ha-1 at age 16 years, or

    ~1,000 m³ ha-1 at age 30 years.
  - the best approach for producing big-sized assortments (delivered more and earlier).
  - is the only suitable option when the production of log assortments >50 or even >60 cm within harvest age <30 years is intended.

Responses to thinnings in diameter growth are verified first at tree basis. Upwards in the stem, increases in the growth rate take longer to be observed and require thinnings of higher intensity. Nevertheless, once present, enhanced growth rates last longer than at tree basis. Thus, while there is an increase of tree taper after thinning, it decreases with time. Moreover, it was verified:

- when thinning is applied to 5-years-old stands with 32 m^2 ha^{-1} of basal area, no immediate increase in diameter growth of potential crop trees is to be expected by removing less than 2 competitors. Later on, and after at least 2 successive removals of 1 competitor, there is a substantial increase on the diameter growth rate of potential crop trees over the one observed in unthinned stands.
- following extreme thinnings, diameter growth increases are immediately detected – 60 % increase at 1.3 m over the growth rate of trees in unthinned stands. Trees subjected to the extreme regime show the highest diameter growth for, at least, 10 years after the first intervention. Growth rates increase >300 % compared with trees in stands without thinnings.
- Big-sized trees response more to thinning than medium and small-sized individuals, and this in a long lasting way, both in absolute and relative terms.

In relation to wood quality, results indicated that crown thinnings not only provide bigger-sized trees than unthinned stands, but a

- more homogeneous growth rate,
- greater homogeneity of wood density,
- proportional wider mature wood layer.

Even though the extreme variant led to the postponement of the mature wood production, the enhanced growth rate of trees in this treatment resulted in similar mature wood amount compared to the ones obtained in the practice oriented variants, which where greatest.

The industrial yield of logs was higher the bigger the small-end diameter (SED). It was verified, for the sawing process

- a mean industrial yield of 57 % for logs ranging from 20-57 cm,
- a linear increase in the industrial yield. Substantial yield gains occur after 35 and 45 cm in de small-end diameter of logs, indicating there is potential for increasing log prices, especially >45 cm,
- 2.5-1.3 m^3 of logs are necessary to produce 1 m^3 of solid boards,
- In relation to the economic benefit, intermediate classes (25-35 cm) are less profitable in comparison to the small (20-25 cm) and bigger-sized ones (>45 cm).

For rotary peeled veneers, it has been found:

- A mean recovery rate of 54 % for logs ranging from 21-67 cm. The industrial yield increases 0.6 % by each cm increases in the log small-end diameter.
- Logs with small-end diameter between 30-45 cm are the ones with the highest economic benefit.
- The current prices charged for big-sized and pruned logs reflect a low quality of pruning. If more efficient pruning regimes are regarded, there is potential for increasing log industrial yield and economic benefit, and both, log producer and industry can profit.

In relation to the sliced veneers, it was observed:

- A mean industrial yield of 21 % for logs ranging from 30-65 cm of small-end diameter. According to the adjusted linear trend for yield, an increase of 3.7 m^2 of veneer is expected by each cm increase in the log small-end diameter.
- Big-sized logs do not provide necessarily the highest economic benefit for the industry. However, this conclusion is strongly related to the poor pruning quality of logs.

Results obtained by monitoring the process of veneer production were substantially and negatively affected by inadequate pruning of the trees. Thus, the real potential of big-sized and pruned logs could not be properly assessed. Therefore, a theoretical approach was needed. Results related to this are shown in the chapter 9.2.7 Theoretical potential of pruned logs.

The financial performance of stands subjected to crown thinning was assessed. The following results have been gained:

- The production of big-sized log assortments is a very profitable option. When 6 m of the stems is pruned, at age 30 years, it represents ~30 % of the volume, but ~50 % of the total gross revenue.
- ‘extreme’ and early release from competition of pruned loblolly pine trees led not only to the best financial performance (NPV = ~15,000 US\$ ha^{-1}), but did it earlier (age 24 years) than other thinning intensities (30 years) and no thinning at all (26 years).
- stands subjected to thinnings, independently of intensity, result at least twice as much NPV (>13,000 US\$ ha^{-1}) than no thinning at all (~6,000 US\$ ha^{-1}).
- according to the internal rate of return (IRR) of the different thinning variants (10-17 % year^{-1}), the optimum harvest age was from between 16-18 years. However, from a long term perspective (NPV and LEV), production periods need to be extended. Even though extreme thinnings have a shortening effect on the optimum harvest age, it should be at least at age 24 years for the current log price-size relationship.
- the best financial performances are already obtained from thinned stands. However, considering there is potential for bigger-sized and, thus, more valuable log assortments, even better financial results are possible. Regarding an additional log assortment >50 cm for unpruned and pruned logs, the NPV of extremely thinned stands increases ~30 %, while only slight differences are verified in the practice oriented and unthinned variant.

9.2 CONSIDERATIONS FOR THE PRAXIS

Some land owners may hesitate to accept that big-dimensioned timber is a realistic management goal and that it is a profitable option. At least in southern Brazil, there is an increasing demand for big-sized timber, unpruned and pruned. Although still depended on market oscillation, the fact that big-sized and pruned pine log assortments were originally exclusive for export have changed. There are currently several products made with pine timber from fast-grown stands, which require a wide range of log assortments.

Crown thinning was shown to be a promising approach in managing loblolly pine stands in southern Brazil. Therefore, it is discussed in detail, by regarding important aspects for the praxis.

9.2.1 Initial stand density

In the present study, loblolly pine stands have been established with an initial density of 2,500 trees ha^{-1}. Because of a commonly high survival rate and homogeneous early growth, it is not necessary to use these high initial densities anymore.

Moreover, the quality of seeds, or even clones, which are now available, has substantially improved in the meantime.

Therefore, initial density has been reduced. The current practice is to plant no more than 1,600 trees ha^{-1}, which seems to be suitable for the majority of sites. It results in lower competition levels so that thinnings can be postponed without diameter growth losses.

Furthermore, it has been proven that trees have a remarkable potential in using the growing space, which suggest initial stand density can be even less than the current 1,600 tree ha^{-1} practice. Moreover, if the extreme regime is selected, it makes little sense to plant and intensively reduce the number of trees at an age of 5 years, as it was the case in this experiment. More suitable would be to start with a wider initial stand density. It has to be kept in mind, however, that the greater the number of planted trees, the higher the selection possibility of potential crop trees. Additionally, tending cost may increase if crown closure is postponed.

9.2.2 Selection of potential crop trees

The selection of potential crop trees (‘pct’) involves questions about the criteria, the time and number of individuals ha^{-1}.

The main selection criterion is vitality. Only dominant trees are able to form big individuals. Dominant trees, however, normally produce thick branches. Therefore, pruning is a must if clear wood is intended.

Nevertheless, co-dominants or even intermediate individuals are often selected as potential crop trees as they look better in ‘quality’. Later on, however, they do not grow sufficiently to meet the production goals.

9.2.2.1 Time of selection

The selection of potential crop trees in the analysed experiment was carried out at age 5 years, at an average stand height of 8-9 m. It was presumed to be an appropriate time for favouring individual tree growth. Indeed, tree responses in diameter growth were substantial and immediate after thinning.

By reducing the initial density from 2,500 to 1,600 trees ha^{-1}, however, thinnings could be postponed by 2-3 years, allowing the first release from competition of the selected potential crop tree at 7-8 years of age, optimally when top height is 12-14 m and dominant trees are well defined as varied in Chapter 3.3.9.

Nevertheless, the need for an early selection remains because pruning is necessary before potential crop trees can be efficiently selected and released from competition. Optimally, pruning needs to take place at age 3-4 years. Thus, it is recommended to start selecting at least 2-times the number of trees intended for the final cut – ‘called potential crop trees candidates’ – in order to allow an appropriate further selection of potential crop trees in a second step.

9.2.2.2 Number of potential crop trees per ha

The determination of the target diameter of the crop trees is one of the decisive points of crown thinnings as the number of crop trees is directly related to it. One of the possibilities to assess the number of potential crop trees is to calculate the number of trees by dividing the basal area of the final stand by the basal area of the mean target tree. Results are shown in Tab. 9.2-1.

Results should be taken carefully because equations were used to estimate the top diameter, which might have led to underestimation of the production period.

The maximum basal area reached by the analysed stands was ~70 m² ha^{-1}. For comparison purposes, tree number ha^{-1} was also calculated for a basal area of 60 m² ha^{-1} level, which may be more realistic for sites of average growth capacity.

From Tab. 9.2-1 it can be seen that bigger target diameters might be obtained in extremely thinned stands in ½ of the time compared with unthinned ones. Noteworthy is that target diameters >50 cm are almost unfeasible in unthinned stands. Even for practice oriented stands, target diameter >60 cm are unrealistic because of the long production period. Therefore, when diameters >60 cm are intended, thinning regimes need to be necessarily ‘extreme’.

Table 9.2-1: Number of crop trees as related to the basal area of the final stand and the target diameters.

Target diameter	Tree basal area	N° of final crop trees at a basal area (m² ha^{-1}) of		Estimated harvesting age			
cm	m² tree^{-1}	60	70	without	moderate	heavy	extreme
40	0.13	477	557	19	15	14	11
50	0.20	306	357	41	23	21	15
60	0.28	212	248	-	36	34	21
70	0.38	156	182	-	50	49	37

Derived from own measurements in the experiment; production periods were obtained with help of the Chapman-Richards equations fitted for top diameter in Chapter 3 item 3.3.3.

Source: The author (2014)

As recommended, it makes sense to select 2-times the number of intended crop trees. For example, for 250 crop trees ha^{-1}, the first selection should regard 500 potential crop trees candidates ha^{-1}. This means a distance of 4-5 m between individuals. Later on, the number of candidates is reduced and only potential crop trees remain.

9.2.3 Thinning intensity

It has been shown that when crown thinnings are properly applied to the stand, tree diameter growth is high enough to compensate for extreme basal area reductions.

In comparison to stands without thinning, extremely thinned ones show no loss of timber production in production periods from 16-30 years. It means the remarkable growth of trees extremely and early released from competition provides, at the same time, maximum diameter growth and no volume loss. However, if site occupations of 70-80 % of the maximum basal area (practice oriented variants) from age 10 years onwards are kept, the maximum volume production ha^{-1} is obtained (a surplus of ~35 % in relation to the former variants).

When target diameter is up to 50 cm, ‘moderate’ and ‘heavy’ thinnings are the best management option because

- it can be reached within ~25 years of production period, which is the financial optimum age.
- it delivers a surplus of volume in relation to other thinning strategies.

Nevertheless, if target diameters are >50 cm, the only feasible option is to go to extreme schedules.

It has to be kept in mind that a target diameter of 50 cm (at 1.3 m) provides 2 pruned logs (2.5 m length) only >40 cm. Therefore, it can be stated that the best thinning schedule, from the financial perspective is the one that delivers pruned logs >50 cm – target diameters of ≥60 cm. In order to obtain it, extreme crown thinning and production periods of ~30 years are required.

9.2.4 Wood quality

From the practical perspective, and considering the current requirements of the pine timber market in southern Brazil, there is no concern related to wood quality following thinnings. Even if extreme thinning procedures are applied to loblolly pine stands.

9.2.5 Harvest age

The analysis of the internal rate of return (IRR) of different management regimes led to the conclusion of finalizing the production period at age 18 years. However, the long term characteristic of forest investment requires conservative analyses. A solid approach is given by net present value (NPV) and land expectation value (LEV). According to these criteria, the optimum financial result is obtained with production periods of ≥24 years.

This conclusion differs from the common sense idea that short production periods provide better financial performances.

When the experiment was terminated after a production period of 30 years, it was supposed that the optimum harvest age had been reached for all thinning variants. Surprisingly the highest net land expectation value (LEV) for the practice oriented and unthinned variants were at age 30 years, which means even higher values may be obtained if the production period would be extended. Although there is enough evidence that an interest rate of 4 % year^{-1} is a realistic approach, the extension of the production period was mainly a result of this assumption. By using rates ≥8 % year^{-1}, optimum values are obtained within the 30 years period.

9.2.6 Theoretical potential of pruned logs

Results obtained from industrial analyses (Chapter 7) were substantially and negatively affected by the poor quality of pruned logs – big proportion of knotty core. This was particularly true for the sliced veneering process, and led to an enormous loss of timber. Only ~20 % of the volume of logs became veneers.

Although the production of big-sized and pruned logs was the most profitable option for managing loblolly pine stands in southern Brazil, already with the current log prices (Chapter 8), it is supposed that the surplus would be even higher, provided pruning would be carried out adequately

The low yield measured in Chapter 7.4 'Sliced peeling' might be depending not only from the size of the knotty core of logs. Additionally and as mentioned, the industrial process may not be the most appropriated one for big-sized logs. However, and for simplicity reasons, the theoretical industrial potential of properly pruned logs are discussed regarding the same veneering process.

As described in Chapter 7, before slicing, logs were sawn into blocks. The potential number of blocks for logs with different small end diameters are shown in Fig. 9.2-1. Comparisons between theoretical and measured yield and economic benefit of logs are described in detail in Tab. 9.2-3.

Results assume all blocks could be entirely sliced into veneers.

From Fig. 9.2-1 and Tab. 9.2-3 it can be observed that while logs with 30 cm deliver only 4 blocks of 5 cm of thickness, logs with 70 cm deliver 16 blocks 7 cm thick and 11 blocks with 5 cm. Results indicate logs ~30 cm are not suitable for this slicing process. By increasing the small-end diameter of logs, however, an exponential increase in the veneer yield is to be expected.

Comparing the theoretical and measured yield of veneers (m²), it is verified that small-sized logs, with SED of 30-40 cm were efficiently processed by the monitored industrial process. However, when bigger-sized logs are regarded, the greater the log, the more timber was lost in the monitored industrial process. Logs with 70 cm have a theoretical yield ~130 m² higher than the one estimated with the regression model, obtained from real measurements. In terms of economic benefit, it means an increase of 100 US$ or more than 50 % per log.

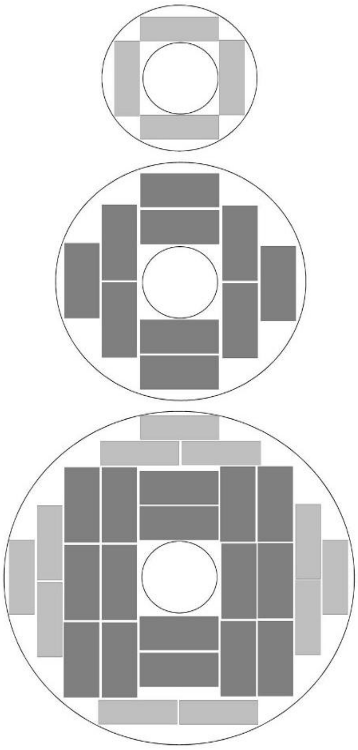


Figure 9.2-1: Theoretical potential for providing slicing blocks of logs 30, 50 and 70 cm of small end diameter, under bark. Blocks 15.7 cm width; thickness varied between 7 cm (dark) and 5 cm (hell). Knotty core is limited to 15 cm in diameter in the center of the log.

Source: The author (2014)

Table 9.2-3: Theoretical and measured industrial yield and economic benefit according to the small end diameter (SED) of logs

	Variable		SED cm under bark				
			30	40	50	60	70
Theoretical	Block	5 cm	4	8		4	11
		7 cm			10	14	16
	yield m²		36	72	136	226	317
	Economic benefit US$		34	67	126	210	294
Measured	yield m²		38	75	112	149	185
	Economic benefit US$		31	74	112	150	188

Blocks 5 and 7 cm thick, delivering 31 and 46 veneers, respectively, putting away 1 cm residue due to equipment constrain.

Theoretical economic benefit was obtained considering 50 % of the veneers class ‘A’ and 50 % class ‘B’, or an unique price of 0.93 US$ m^{-2}.

Measured values obtained with regression models fitted in Chapter 7. SED was 4 cm greater for bark compensation.

Sliced veneers are sold 140 x 2100 mm = 0.294 m²; thickness = 1.2 mm.

Source: The author (2014)

Results support the idea that the production of logs with bigger dimensions and restricted knotty core (in the example 15 cm), it is possible to increase the industrial yield of logs and, therefore, higher log prices can be charged.

Moreover, big-sized logs of high quality allow the production of veneers with parallel annual rings which, in comparison to the ‘cathedral’, the one produced, is more valuable. Currently, veneers with ‘parallel’ growth rings are ~20 % higher in price than the ‘cathedral’ one, however, it has been over 70 % higher in previous years.

Altogether, findings indicate that producing big-sized and pruned log assortments is a very profitable option and would benefit both, log producers and industry. Results suggest, however, that the new log assortment simulated in Chapter 8 Financial Performace for pruned logs >50 cm at ~140 US$ m^{-3} might be over proportional. The theoretical economic benefit was only 10 US$ log^{-1} higher than the measured one. Nevertheless, there is certainly space for higher prices if logs reach diameters of >60 and >70 cm.

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11 APPENDIX

11.1 STAND DEVELOPMENT

The first ANOVA table is shown in detail for illustrative purpose. The following ones are resumed and only the degrees of freedon, F-value and probability (*p*) are given.

TABLE 11.1-1: ANALYSIS OF VARIANCE FOR THE VARIABLE NUMBER OF TREES HA^{-1}

df: degrees of freedom; SS: sum of squares; MS: mean square; F: F ratio; n.s.: not significant; *p*: probability.

Source of var.	df	SS	MS	F	*p*	
Thinning variant	3	286,864.4	95,621.4	977.8	**0.000**	***
Replication	1	1,081.1	1,081.1	11.1	**0.045**	*
Residual	3	293.4	97.8	97.8		
Total	7	288,238.9				

TABLE 11.1-2: ANALYSES OF VARIANCE FOR THE DIFFERENT VARIABLES

df: degrees of freedom; F: F ratio; n.s.: not significant; *p*: probability.

Variable	Source of variation	*df*	F	*p*	
d_g	between	3	123.1	**0.001**	***
	within	1	1.4	**0.315**	^{ns}
d_{100}	between	3	52.9	**0.004**	**
	within	1	0.2	**0.673**	^{ns}
CV_{100}	between	3	3.6	**0.158**	^{ns}
	within	1	1.6	**0.297**	^{ns}
g	between	3	85.6	**0.002**	**
	within	1	1.4	**0.324**	^{ns}
g_{100}	between	3	53.0	**0.004**	**
	within	1	0.2	**0.716**	^{ns}
d_{100} 5 yrs.	between	3	14.5	**0.027**	*
	within	1	9.3	**0.055**	^{ns}
d_{100} 10 yrs.	between	3	94.4	**0.002**	**
	within	1	17.4	**0.025**	*
d_{100} 15 yrs.	between	3	59.4	**0.004**	**
	within	1	6.3	**0.087**	^{ns}
d_{100} 20 yrs.	between	3	52.7	**0.004**	**
	within	1	2.9	**0.185**	^{ns}
h	between	3	22.5	**0.015**	*
	within	1	3.1	**0.012**	*
h_{100}	between	3	11.4	**0.038**	*
	within	1	5.9	**0.094**	^{ns}
crown length	between	3	1.5	**0.379**	^{ns}
	within	1	0.9	**0.401**	^{ns}
h:d	between	3	10.7	**0.041**	*
	within	1	0.8	**0.432**	^{ns}
G 5 yrs.	between	3	140.8	**0.001**	***
	within	1	1.2	**0.350**	^{ns}
G 30 yrs.	between	3	14.0	**0.029**	*
	within	1	0.7	**0.452**	^{ns}

continuing TABLE 11.1-2...

Variable	Source of variation	*df*	F	*p*	
v_i	between	3	91.5	**0.002**	**
	within	1	1.4	**0.319**	ns
v_{100}	between	3	49.1	**0.005**	**
	within	1	0.2	**0.720**	ns
$V_{thinned}$	between	3	14.9	**0.063**	ns
	within	1	3.2	**0.218**	ns
$V_{standing}$	between	3	14.9	**0.063**	ns
	within	1	3.2	**0.218**	ns
V_{total}	between	3	18.7	**0.019**	*
	within	1	0.02	**0.897**	ns
MAI	between	3	18.5	**0.019**	*
	within	1	0.02	**0.901**	ns

TABLE 11.1-3: ADJUSTED COEFFICIENTS (β_i), COEFFICIENT OF DETERMINATION ($R^2_{ADJ.}$) AND STANDARD ERROR OF ESTIMATION (S_{YX} %) FOR THEADJUSTED HYPSOMETRIC EQUATIONS TO ESTIMATE TOTAL HEIGHT AT AGES 11 AND 14 YEARS

Age	β_0	β_1	β_2	$R^2_{adj.}$	S_{yx}%
11	7.46004	0.54942	-0.00752	0.65	4.6
14	12.56335	0.29690	-0.00007	0.48	5.9

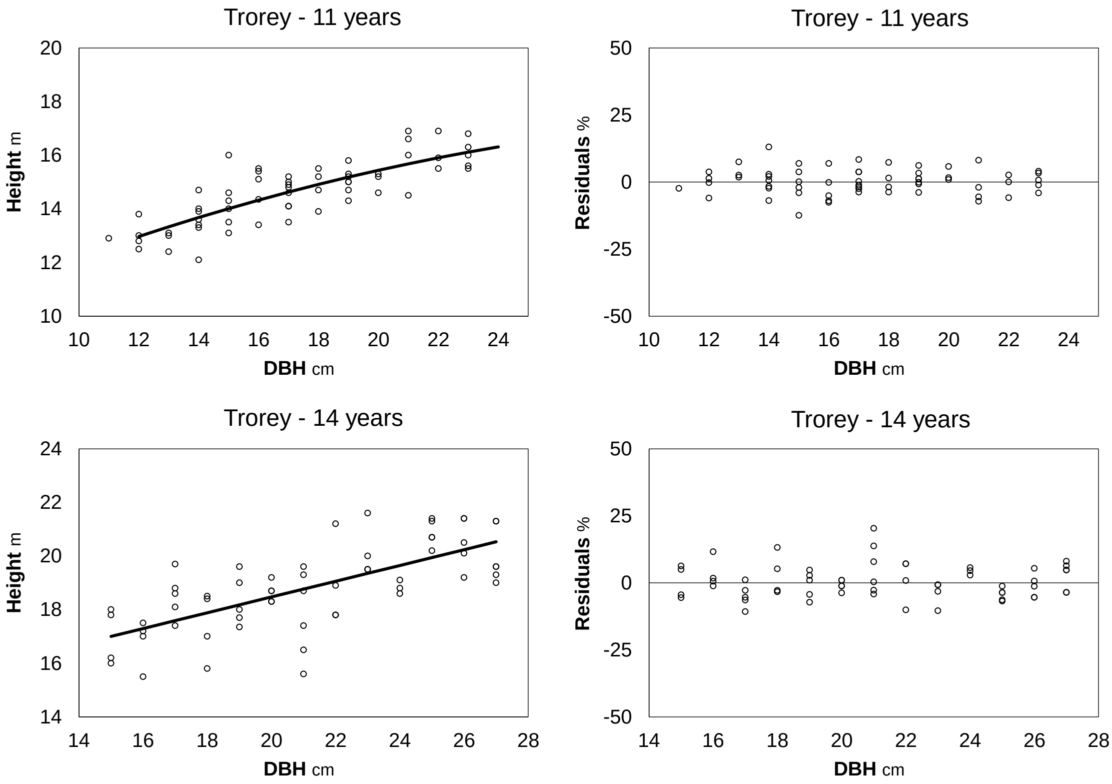

FIGURE 11.1-1: OBSERVED DBH X TOTAL HEIGHT, ESTIMATED HEIGHTS (LINE) THROUGH TROREY EQUATION AT AGES 11 AND 14 YEARS, AND ITS RESPECTIVE RESIDUES PLOTS (%)

Table 11.1-4: Adjusted coefficients (β_i) of the Schöpfer taper equations at ages 11 and 14 years, their coefficient of determination ($R^2_{adj.}$) and standard error of estimate (S_{yx} %)

Age	β_0	β_1	β_2	β_3	β_4	β_5	$R^2_{adj.}$	S_{yx}%
11	1.257	-4.456	22.192	-54.559	58.900	-23.561	0.94	8.0
14	1.244	-4.218	19.341	-42.775	40.748	-14.117	0.92	95.9

Table 11.1-5: Coefficients (β_i), coefficient of determination ($R^2_{adj.}$) and standard error of estimation (S_{yx} %) for the adjusted hypsometric equations to estimate total height at age 30 years
* selected model

Equation	β_0	β_1	β_2	$R^2_{aj.}$	S_{yx} %
Trorey*	24.709	0.428	-0.004	0.16	5.9
Stoffels	3.333	0.058		0.04	6.3
Curtis	3.623	-3.041		0.08	6.2

Table 11.1-6: Coefficients (β_i), coefficient of determination ($R^2_{adj.}$) and standard error of estimate (S_{yx}%) for the adjusted hypsometric equations to estimate crown basis height at age 30 years
* selected model

Equation	β_0	β_1	β_2	$R^2_{aj.}$	S_{yx} %
Trorey*	20.052	0.293	-0.004	0.23	12.6
Stoffels	3.857	-0.182		0.10	13.6
Curtis	3.029	5.728		0.06	13.9

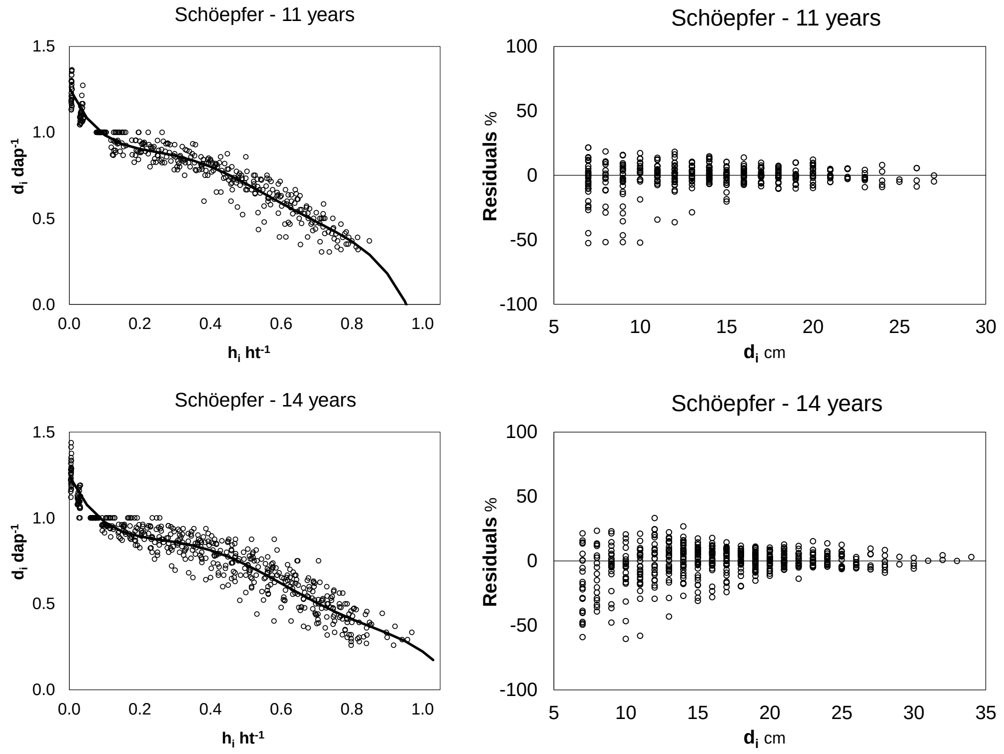

Figure 11.1-2: Observed d_i x h_i, estimated taper (line) for the different equations at ages 11 and 14 years, and their respective residues plots (%)

TABLE 11.1-7: COEFFICIENTS (β_i), COEFFICIENT OF DETERMINATION ($R^2_{ADJ.}$) AND STANDARD ERROR OF ESTIMATE (S_{YX}%) FOR THE ADJUSTED VOLUMETRIC EQUATIONS TO ESTIMATE INDIVIDUAL VOLUME AT AGE 30 YEARS

Equation	β_0	β_1	$R^2_{aj.}$	S_{yx} %
HUSCH	-6.519	1.941	0.93	12.3
SPURR	0.326	0.00003	0.96	9.7

TABLE 11.1-8: COEFFICIENTS (β_i), COEFFICIENT OF DETERMINATION ($R^2_{ADJ.}$) AND STANDARD ERROR OF ESTIMATE (S_{YX}%) FOR THE ADJUSTED TAPER EQUATIONS AT AGE 30 YEARS

Equation	β_0	β_1	β_2	β_3	β_4	β_5	R²	Syx%
KOSAK	1,053	-0,730	-0,218				0,95	11,8
SCHÖPFER	1,195	-5,037	24,312	-55,173	55,405	-20,805	0,98	7,7

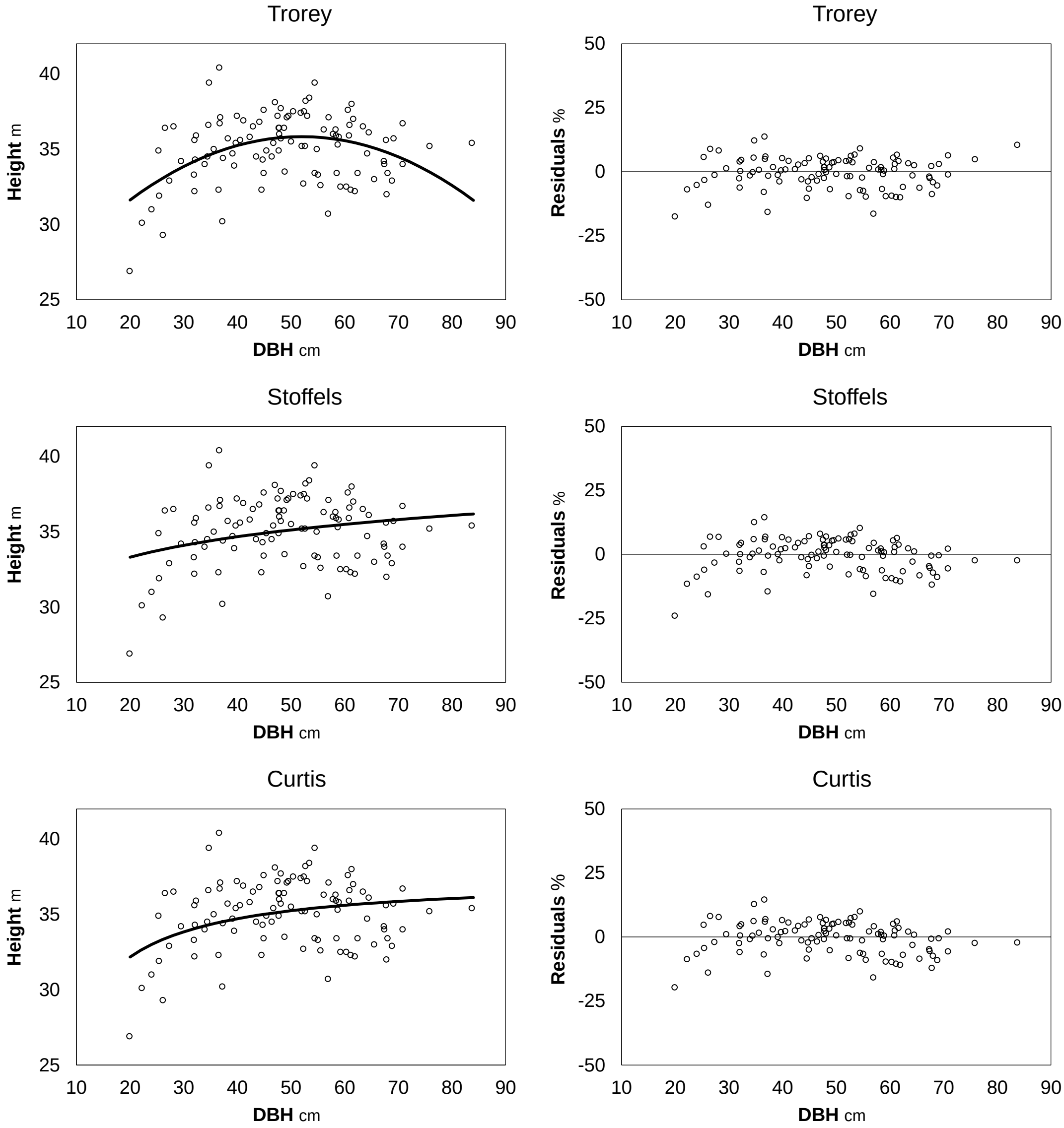

FIGURE 11.1-3: OBSERVED DBH X TOTAL HEIGHT, ESTIMATED HEIGHTS (LINE) FOR THE DIFFERENT EQUATIONS AT YEAR 30, AND THEIR RESPECTIVE RESIDUES PLOTS (%)

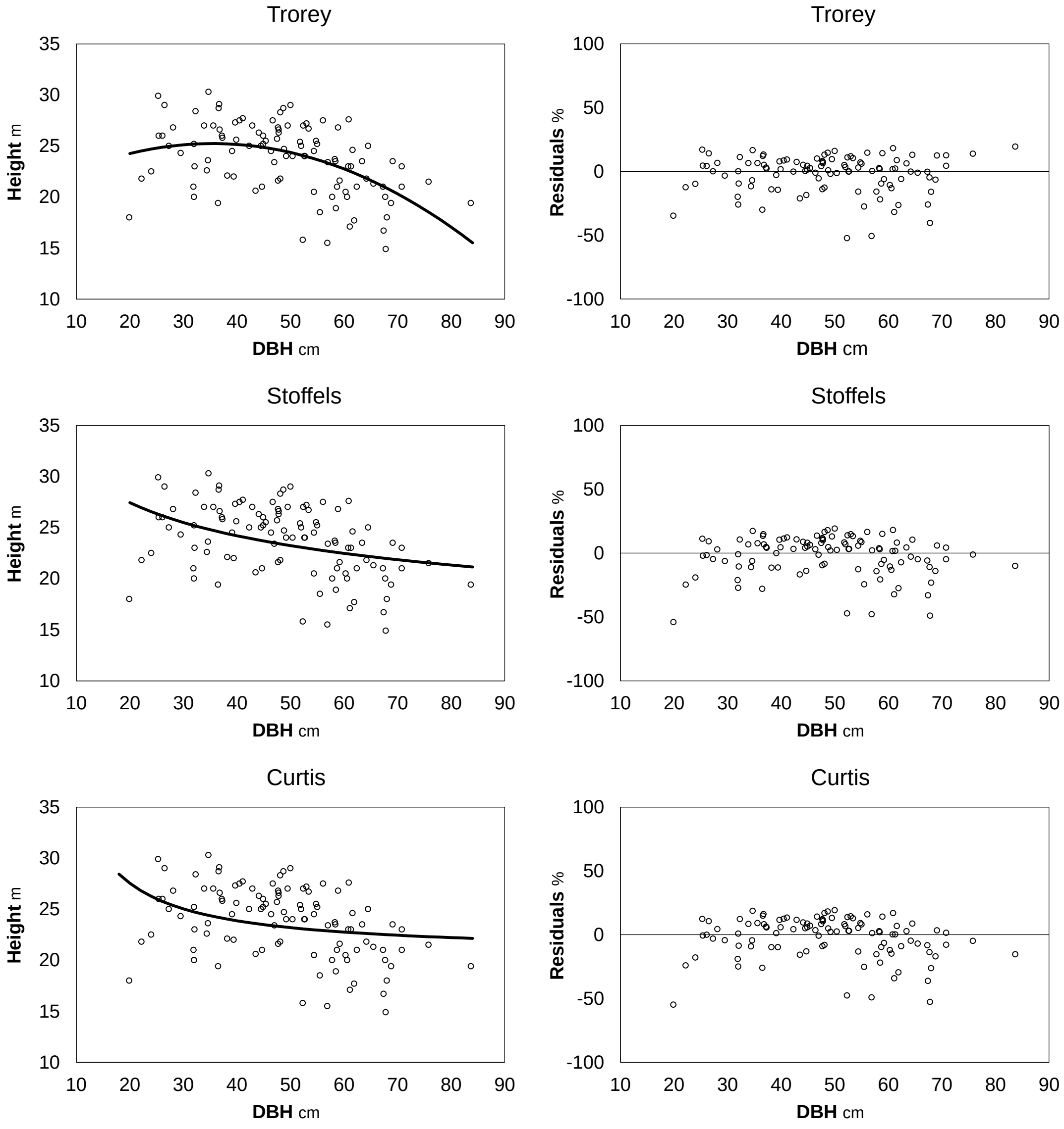

FIGURE 11.1-4: OBSERVED DBH X GREEN CROWN BASIS HEIGHT, ESTIMATED HEIGHTS (LINE) FOR THE DIFFERENT EQUATIONS AT AGE 30 YEARS, AND THEIR RESPECTIVE RESIDUES PLOTS (%)

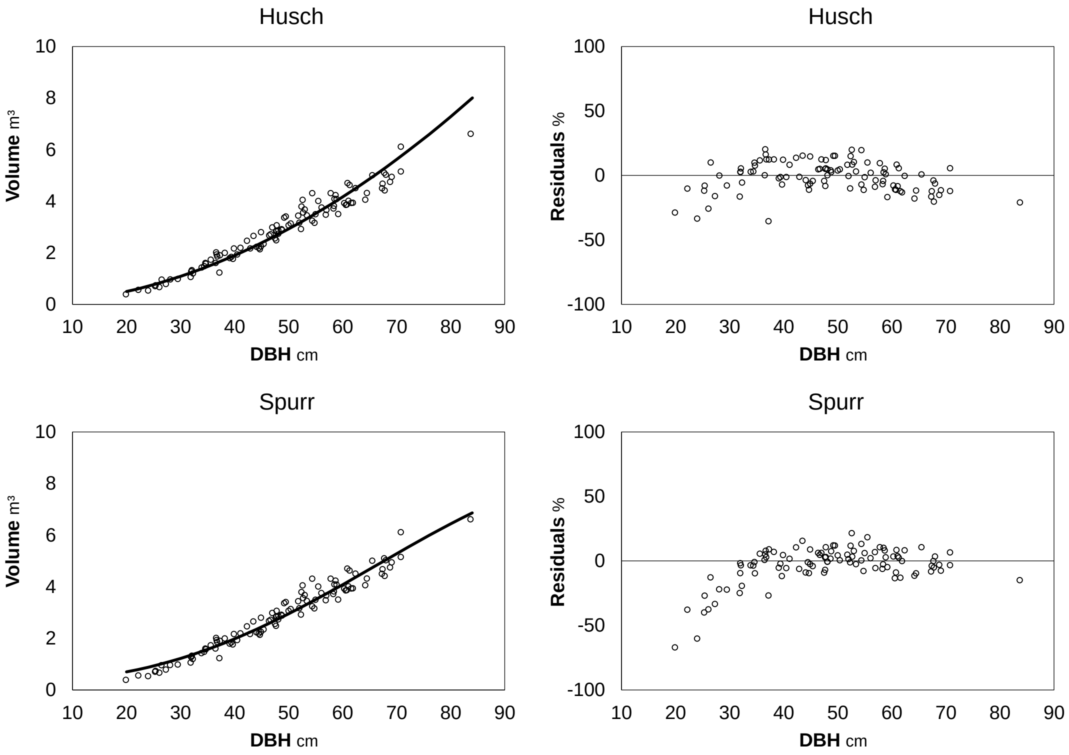

Figure 11.1-5: Observed dbh x individual volume, estimated volumes (line) for the different equations at age 30 years, and their respective residues plots (%)

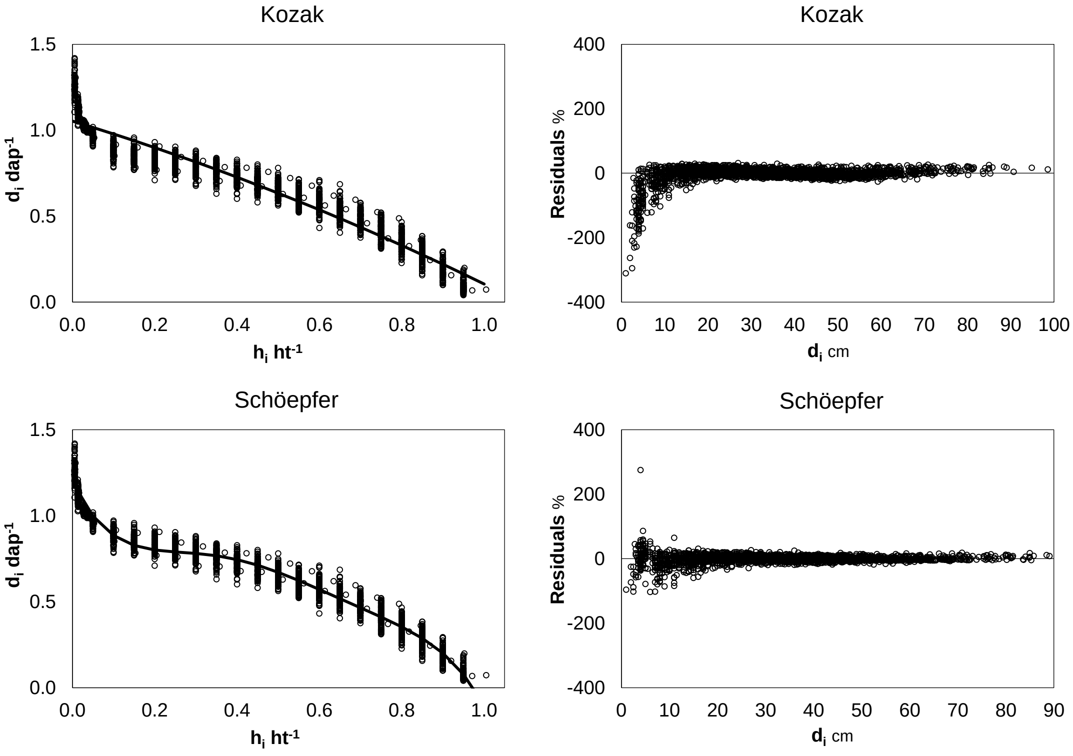

Figure 11.1-6: Observed di x hi, estimated taper (line) for the different taper equations at age 30 years, and their respective residues plots (%)

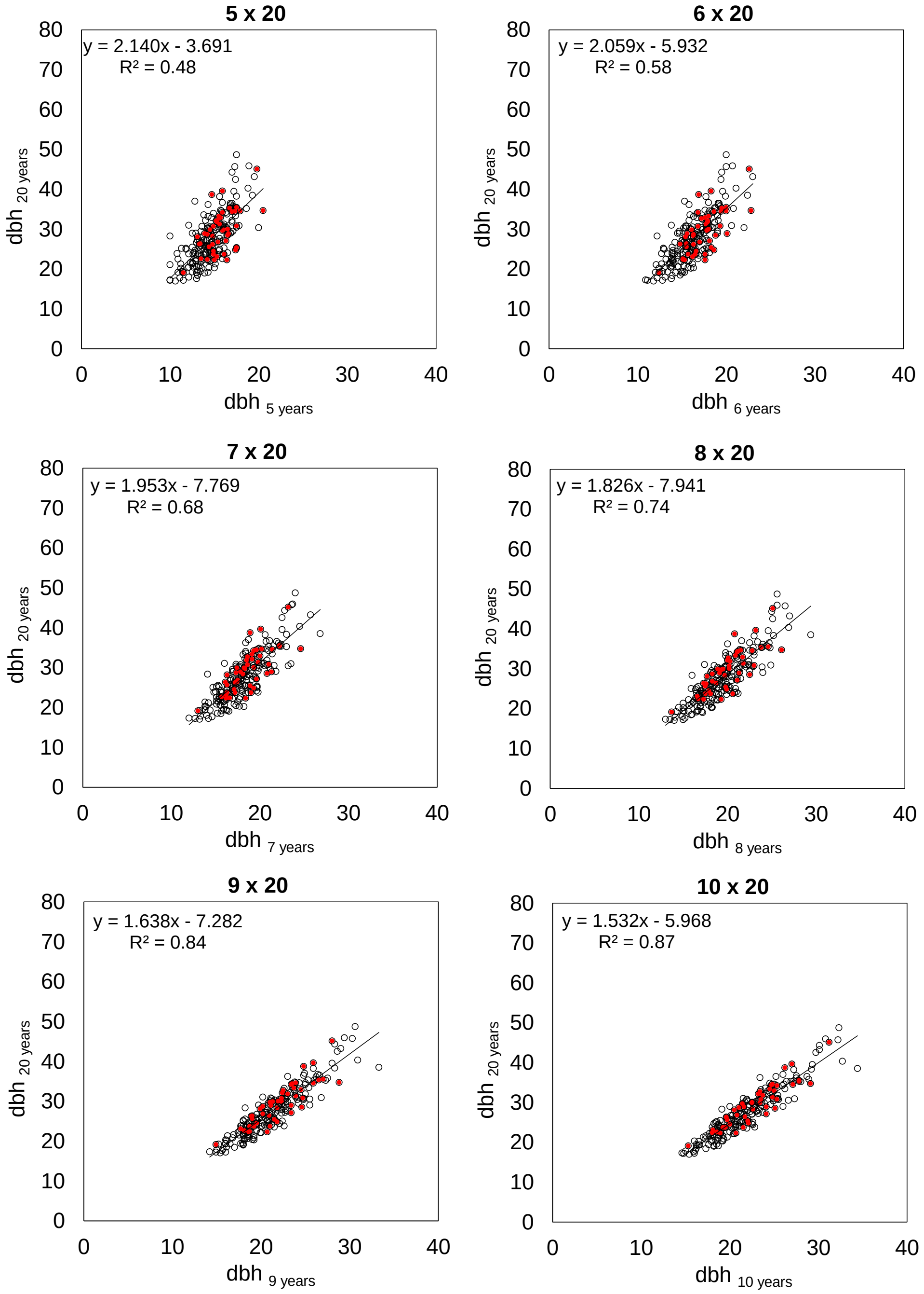

Figure 11.1-7: Diameter at ages 5-10 years ('x' axis) and the diameter of the same tree at age 20 years ('y' axis) for the variant 'without'. Selected potential crop trees are highlighted in red. The equation of the regression line and its coefficient of determination are given

11.2 Individual growth rate

Table 11.2-1: Analyses of variance for the variable ring width at 1.3 m (DBH) level, from ages 2-30 years

df: degrees of freedom; F: F ratio; *p*: probability.

Age	Source of variation	*df*	F	*p*
2	between	3	0.6	**0.648** ns
	within	58		
3	between	3	0.1	**0.934** ns
	within	69		
4	between	3	0.3	**0.814** ns
	within	69		
5	between	3	0.6	**0.587** ns
	within	69		
6	between	3	22.2	**0.000** ***
	within	69		
7	between	3	2.7	**0.051** ns
	within	69		
8	between	3	17.3	**0.000** ***
	within	69		
9	between	3	33.0	**0.000** ***
	within	69		
10	between	3	23.2	**0.000** ***
	within	69		
11	between	3	44.4	**0.000** ***
	within	69		
12	between	3	31.5	**0.000** ***
	within	69		
13	between	3	21.0	**0.000** ***
	within	69		
14	between	3	27.6	**0.000** ***
	within	69		
15	between	3	26.8	**0.000** ***
	within	69		
16	between	3	14.6	**0.000** ***
	within	69		
17	between	3	12.6	**0.000** ***
	within	69		
18	between	3	12.1	**0.000** ***
	within	69		
19	between	3	10.3	**0.000** ***
	within	69		
20	between	3	12.5	**0.000** ***
	within	69		
21	between	3	6.3	**0.001** **
	within	69		
22	between	3	7.6	**0.000** ***
	within	68		
23	between	3	3.8	**0.015** *
	within	68		
24	between	3	4.8	**0.004** **
	within	68		
25	between	3	4.5	**0.006** **
	within	67		
26	between	3	1.1	**0.347** ns
	within	66		
27	between	3	0.4	**0.756** ns
	within	64		
28	between	3	0.4	**0.741** ns
	within	63		
29	between	3	0.8	**0.520** ns
	within	62		
30	between	3	1.4	**0.244** ns
	within	61		

Table 11.2-2: Analyses of variance for the variable ring width at 25 % level, from ages 6-30 years

df: degrees of freedom; MS: mean square; F: F ratio; *p*: probability.

Age	Source of variation	*df*	F	*p*	
6	between	3	1.3	**0.295**	ns
	within	67			
7	between	3	2.6	**0.058**	ns
	within	69			
8	between	3	4.0	**0.010**	**
	within	69			
9	between	3	11.6	**0.000**	***
	within	69			
10	between	3	15.2	**0.000**	***
	within	69			
11	between	3	32.8	**0.000**	***
	within	69			
12	between	3	31.2	**0.000**	***
	within	69			
13	between	3	24.0	**0.000**	***
	within	69			
14	between	3	25.9	**0.000**	***
	within	69			
15	between	3	30.3	**0.000**	***
	within	69			
16	between	3	18.7	**0.000**	***
	within	69			
17	between	3	12.1	**0.000**	***
	within	69			
18	between	3	12.4	**0.000**	***
	within	69			
19	between	3	13.1	**0.000**	***
	within	69			
20	between	3	11.6	**0.000**	***
	within	69			
21	between	3	8.3	**0.000**	***
	within	69			
22	between	3	11.0	**0.000**	***
	within	69			
23	between	3	5.9	**0.001**	**
	within	69			
24	between	3	6.1	**0.001**	**
	within	69			
25	between	3	5.8	**0.001**	**
	within	69			
26	between	3	2.0	**0.124**	ns
	within	68			
27	between	3	1.6	**0.205**	ns
	within	68			
28	between	3	1.6	**0.201**	ns
	within	65			
29	between	3	1.7	**0.168**	ns
	within	64			
30	between	3	2.6	**0.059**	ns
	within	64			

Table 11.2-3: Analyses of variance for the variable ring width at 50 % level, from ages 10-30 years

df: degrees of freedom; MS: mean square; F: F ratio; *p*: probability.

Age	Source of variation	*df*	F	*p*	
10	between	3	2.1	**0.113**	ns
	within	51			
11	between	3	2.6	**0.062**	ns
	within	67			
12	between	3	0.9	**0.438**	ns
	within	69			
13	between	3	5.4	**0.002**	**
	within	69			
14	between	3	15.3	**0.000**	***
	within	69			
15	between	3	20.0	**0.000**	***
	within	69			
16	between	3	10.8	**0.000**	***
	within	69			
17	between	3	19.9	**0.000**	***
	within	69			
18	between	3	21.9	**0.000**	***
	within	69			
19	between	3	22.1	**0.000**	***
	within	69			
20	between	3	21.3	**0.000**	***
	within	69			
21	between	3	14.4	**0.000**	***
	within	69			
22	between	3	17.9	**0.000**	***
	within	68			
23	between	3	12.7	**0.000**	***
	within	68			
24	between	3	14.4	**0.000**	***
	within	68			
25	between	3	9.	**0.000**	***
	within	67			
26	between	3	6.9	**0.000**	***
	within	66			
27	between	3	7.3	**0.000**	***
	within	64			
28	between	3	5.8	**0.001**	**
	within	63			
29	between	3	4.5	**0.006**	**
	within	62			
30	between	3	6.5	**0.001**	**
	within	61			

TABLE 11.2-4: ANALYSES OF VARIANCE FOR THE VARIABLE RING WIDTH AT 75 % LEVEL, FROM AGES 17-30 YEARS

df: degrees of freedom; MS: mean square; F: F ratio; *p*: probability.

Age	Source of variation	*df*	F	*p*	
17	between	3	1.4	**0.254**	ns
	within	58			
18	between	3	4.1	**0.010**	**
	within	66			
19	between	3	3.8	**0.013**	**
	within	68			
20	between	3	5.4	**0.002**	**
	within	68			
21	between	3	9.1	**0.000**	***
	within	68			
22	between	3	14.0	**0.000**	***
	within	68			
23	between	3	12.5	**0.000**	***
	within	68			
24	between	3	19.3	**0.000**	***
	within	68			
25	between	3	15.5	**0.000**	***
	within	68			
26	between	3	11.4	**0.000**	***
	within	68			
27	between	3	13.6	**0.000**	***
	within	68			
28	between	3	11.0	**0.000**	***
	within	68			
29	between	3	8.4	**0.000**	***
	within	68			
30	between	3	9.4	**0.000**	***
	within	68			

11.3 WOOD QUALITY

TABLE 11.3-1: RING DENSITY PER YEAR AND THINNING VARIANT.

Means with the same letter do not significantly differ within the same age - test of TUKEY

Years with bold number are the ones at which thinnings took place; parentheses mean only some of the treatments were thinned - at age:

7 yrs – moderate and heavy
15 yrs – moderate.

AGE years	RING DENSITY g cm^{-3}				STATIST. SIGNIF.
	without	moderate	heavy	extreme	
3	0.442	0.444	0.460	0.471	n.s.
4	0.392 a	0.414 ab	0.425 ab	0.446 b	*
5	0.437 a	0.429 a	0.438 a	0.477 b	*
6	0.408	0.406	0.409	0.419	n.s.
(7)	0.446	0.451	0.454	0.496	n.s.
8	0.473	0.475	0.443	0.457	n.s.
9	0.463	0.446	0.439	0.438	n.s.
10	0.507	0.480	0.473	0.481	n.s.
11	0.556 b	0.515 ab	0.501 ab	0.475 a	*
12	0.527	0.488	0.495	0.478	n.s.
13	0.554	0.516	0.516	0.492	n.s.
14	0.606 b	0.544 ab	0.560 ab	0.517 a	* *
(15)	0.610	0.571	0.576	0.540	n.s.
16	0.571	0.529	0.524	0.499	n.s.
17	0.604	0.574	0.591	0.591	n.s.
18	0.576	0.548	0.518	0.520	n.s.
19	0.594	0.545	0.549	0.516	n.s.
20	0.587	0.556	0.550	0.530	n.s.
21	0.605	0.575	0.572	0.570	n.s.
22	0.649 b	0.574 ab	0.585 ab	0.569 a	*
23	0.622	0.577	0.556	0.554	n.s.
24	0.583	0.576	0.545	0.553	n.s.
25	0.659 b	0.585 ab	0.583 ab	0.558 a	*
26	0.624	0.614	0.612	0.599	n.s.
27	0.619	0.576	0.553	0.523	n.s.
28	0.542	0.508	0.503	0.469	n.s.
29	0.614	0.580	0.590	0.587	n.s.
30	0.647	0.594	0.580	0.572	n.s.

TABLE 11.3-2: ANALYSES OF VARIANCE FOR THE RESIN EX-TRACTED AND NOT EXTRACTED SAMPLES

df: degrees of freedom; F: F ratio; *p*: probability.

Variable	Source of variation	*df*	F	*p*
not extrac. radius	between	3	0.1	**0.934** ^{ns}
	within	10		
not extrac. 5 cm	between	3	1.1	**0.386** ^{ns}
	within	10		
extrac. radius	between	3	0.2	**0.916** ^{ns}
	within	10		
extrac. radius %	between	3	0.4	**0.736** ^{ns}
	within	10		
extrac. 5 cm	between	3	0.8	**0.501** ^{ns}
	within	10		
extrac. 5 cm %	between	3	0.4	**0.767** ^{ns}
	within	10		

TABLE 11.3-3: ANALYSES OF VARIANCE FOR THE RING WIDTH: MEAN, MAXIMUM AND MATURE WOOD VALUES

df: degrees of freedom; F: F ratio; *p*: probability.

Variable	Source of variation	*df*	F	*p*	
mean	between	3	15.7	**0.000**	***
	within	69			
maximum	between	3	0.3	**0.833**	ns
	within	69			
mature	between	3	8.8	**0.000**	***
	within	69			

TABLE 11.3-4: ANALYSES OF VARIANCE FOR THE VARIABLES MEAN, LOWEST, HIGHEST AND STANDARD DEVIATION (Σ) OF APPARENT DENSITIES

df: degrees of freedom; F: F ratio; *p*: probability.

Variable	Source of variation	*df*	F	*p*	
mean	between	3	1.8	**0.164**	ns
	within	40			
lowest	between	3	2.4	**0.078**	**
	within	40			
highest	between	3	2.4	**0.082**	ns
	within	40			
σ	between	3	5.9	**0.002**	**
	within	40			

TABLE 11.3-5: ANALYSES OF VARIANCE FOR THE VARIABLE DENSITY OF DIAMETER CLASSES BETWEEN AND WITHIN THINNING VARIANTS

df: degrees of freedom; F: F ratio; *p*: probability.

Variable	Source of variation	*df*	F	*p*	
>60	between	2	0.6	**0.863**	ns
	within	8			
50-59.9	between	3	7.6	**0.026**	*
	within	5			
40-49.9	between	2	2.3	**0.197**	ns
	within	5			
30-39.9	between	2	0.4	**0.703**	ns
	within	7			
without	between	2	1.0	**0.434**	ns
	within	4			
moderate	between	3	0.9	**0.477**	ns
	within	7			
heavy	between	3	1.6	**0.263**	ns
	within	8			
extreme	between	1	4.2	**0.085**	ns
	within	6			

TABLE 11.3-6: ANALYSES OF VARIANCE FOR THE VARIABLE RING DENSITY BETWEEN AGE 3-30 YEARS

df: degrees of freedom; F: F ratio; *p*: probability.

Age	Source of variation	*df*	F	*p*	
3	between	3	1.0	**0.390**	ns
	within	39			
4	between	3	3.4	**0.027**	*
	within	40			
5	between	3	4.1	**0.012**	*
	within	40			
6	between	3	0.3	**0.816**	ns
	within	40			
7	between	3	2.1	**0.118**	ns
	within	40			
8	between	3	1.2	**0.319**	ns
	within	40			
9	between	3	0.7	**0.560**	ns
	within	40			
10	between	3	0.9	**0.461**	ns
	within	40			
11	between	3	3.2	**0.033**	*
	within	40			
12	between	3	1.7	**0.190**	ns
	within	40			
13	between	3	2.1	**0.119**	ns
	within	40			
14	between	3	4.5	**0.008**	**
	within	40			
15	between	3	2.3	**0.093**	ns
	within	40			
16	between	3	2.7	**0.058**	ns
	within	40			
17	between	3	0.4	**0.780**	ns
	within	40			
18	between	3	1.6	**0.193**	ns
	within	40			
19	between	3	2.8	**0.052**	ns
	within	40			
20	between	3	1.6	**0.195**	ns
	within	40			
21	between	3	0.9	**0.432**	ns
	within	40			
22	between	3	3.5	**0.025**	*
	within	40			
23	between	3	1.7	**0.178**	ns
	within	38			
24	between	3	0.6	**0.630**	ns
	within	37			
25	between	3	3.8	**0.018**	*
	within	36			
26	between	3	0.2	**0.880**	ns
	within	35			
27	between	3	2.0	**0.135**	ns
	within	35			
28	between	3	2.1	**0.119**	ns
	within	35			
29	between	3	0.5	**0.673**	ns
	within	35			
30	between	3	1.8	**0.174**	ns
	within	35			

TABLE 11.3-7: ANALYSES OF VARIANCE FOR THE VARIABLE LATEWOOD DENSITY BETWEEN AGE 3-30 YEARS

df: degrees of freedom; F: F ratio; *p*: probability.

Age	Source of variation	*df*	F	*p*	
3	between	3	2.0	**0.130**	ns
	within	39			
4	between	3	2.9	**0.048**	*
	within	40			
5	between	3	1.0	**0.409**	ns
	within	40			
6	between	3	1.2	**0.337**	ns
	within	40			
7	between	3	0.6	**0.651**	ns
	within	40			
8	between	3	1.1	**0.344**	ns
	within	40			
9	between	3	2.2	**0.101**	ns
	within	40			
10	between	3	1.8	**0.167**	ns
	within	40			
11	between	3	0.4	**0.767**	ns
	within	40			
12	between	3	3.1	**0.038**	*
	within	40			
13	between	3	1.8	**0.163**	ns
	within	40			
14	between	3	3.6	**0.021**	*
	within	40			
15	between	3	2.9	**0.047**	*
	within	40			
16	between	3	0.4	**0.737**	ns
	within	40			
17	between	3	0.5	**0.698**	ns
	within	40			
18	between	3	0.4	**0.780**	ns
	within	40			
19	between	3	0.7	**0.542**	ns
	within	40			
20	between	3	0.4	**0.750**	ns
	within	40			
21	between	3	0.7	**0.557**	ns
	within	40			
22	between	3	0.5	**0.709**	ns
	within	40			
23	between	3	0.7	**0.552**	ns
	within	38			
24	between	3	1.2	**0.321**	ns
	within	37			
25	between	3	0.6	**0.607**	ns
	within	36			
26	between	3	0.1	**0.974**	ns
	within	35			
27	between	3	0.7	**0.573**	ns
	within	35			
28	between	3	0.5	**0.708**	ns
	within	35			
29	between	3	0.8	**0.510**	ns
	within	35			
30	between	3	0.9	**0.474**	ns
	within	35			

TABLE 11.3-8: ANALYSES OF VARIANCE FOR THE VARIABLES JUVENILE AND MATURE WOOD BETWEEN AND WITHIN THINNING VARIANTS

df: degrees of freedom; F: F ratio; *p*: probability.

Variable	Source of variation	*df*	F	*p*	
juvenile	between	3	1.0	**0.419**	ns
	within	40			
mature	between	3	2.8	**0.054**	ns
	within	40			
without	between	1	45.3	**0.000**	***
	within	22			
moderate	between	1	27.7	**0.000**	***
	within	22			
heavy	between	1	54.6	**0.000**	***
	within	22			
extreme	between	1	20.4	**0.000**	***
	within	14			

TABLE 11.3-9: ANALYSES OF VARIANCE FOR THE VARIABLE JUVENILE AND MATURE WOOD WIDTH

df: degrees of freedom; F: F ratio; *p*: probability.

Variable	Source of variation	*df*	F	*p*	
Juvenile cm	between	3	23.2	**0.000**	***
	within	40			
Juvenile %	between	3	5.6	**0.002**	**
	within	40			
Mature cm	between	3	5.7	**0.002**	**
	within	40			

TABLE 11.3-10: ANALYSES OF VARIANCE FOR THE VARIABLE HARVEST AGE

df: degrees of freedom; F: F ratio; *p*: probability.

Variable	Source of variation	*df*	F	*p*	
10	between	3	0.7	**0.583**	ns
	within	40			
15	between	3	0.7	**0.552**	ns
	within	40			
20	between	3	1.1	**0.353**	ns
	within	40			
25	between	3	1.6	**0.206**	ns
	within	40			
30	between	3	1.8	**0.164**	ns
	within	40			
without	between	3	11.2	**0.000**	***
	within	55			
moderate	between	4	6.7	**0.000**	***
	within	55			
heavy	between	4	12.2	**0.000**	***
	within	55			
extreme	between	4	4.3	**0.007**	**
	within	35			

11.4 Log assortments

Table 11.4-1: Analyses of variance for the respective ages and V_{stand}

df: degrees of freedom; F: F ratio; *p*: probability.

Variable	Source of variation	*df*	F	*p*	
16 yrs $V_{stand.}$	between	3	16.81	**0.010**	*
	within	4			
18 yrs $V_{stand.}$	between	3	10.41	**0.023**	*
	within	4			
20 yrs $V_{stand.}$	between	3	7.08	**0.045**	*
	within	4			
30 yrs $V_{stand.}$	between	3	14.53	**0.013**	*
	within	4			

Table 11.4-2: Analyses of variance for the respective ages and V_{total}

df: degrees of freedom; F: F ratio; *p*: probability.

Variable	Source of variation	*df*	F	*p*	
18 yrs V_{total}	between	3	7.15	**0.044**	*
	within	4			
20 yrs V_{total}	between	3	7.35	**0.042**	*
	within	4			
22 yrs V_{total}	between	3	9,24	**0.029**	*
	within	4			
24 yrs V_{total}	between	3	8.66	**0.032**	*
	within	4			
26 yrs V_{total}	between	3	7.53	**0.040**	*
	within	4			
28 yrs V_{total}	between	3	7.49	**0.041**	*
	within	4			
30 yrs V_{total}	between	3	24.74	**0.005**	**
	within	4			

Table 11.4-3: Analyses of variance for the respective ages and $V_{>30unprun}$

df: degrees of freedom; F: F ratio; *p*: probability.

Variable	Source of variation	*df*	F	*p*	
16 yrs $V_{>30unpr.}$	between	3	69.09	**0.001**	**
	within	4			
18 yrs $V_{>30unpr.}$	between	3	72.66	**0.001**	**
	within	4			
20 yrs $V_{>30unpr.}$	between	3	38.92	**0.002**	**
	within	4			
22 yrs $V_{>30unpr.}$	between	3	50.91	**0.001**	**
	within	4			
24 yrs $V_{>30unpr.}$	between	3	45.54	**0.002**	**
	within	4			
26 yrs $V_{>30unpr.}$	between	3	29.27	**0.004**	**
	within	4			
28 yrs $V_{>30unpr.}$	between	3	23.81	**0.005**	**
	within	4			
30 yrs $V_{>30unpr.}$	between	3	32.51	**0.003**	**
	within	4			

Table 11.4-4: Analyses of variance for the respective ages and $V_{>30prun}$

df: degrees of freedom; F: F ratio; *p*: probability.

Variable	Source of variation	*df*	F	*p*	
16 yrs $V_{>30prun.}$	between	3	60.10	**0.001**	**
	within	4			
18 yrs $V_{>30prun.}$	between	3	56.13	**0.001**	**
	within	4			
20 yrs $V_{>30prun.}$	between	3	24.29	**0.005**	**
	within	4			
22 yrs $V_{>30prun.}$	between	3	23.74	**0.005**	**
	within	4			
24 yrs $V_{>30prun.}$	between	3	23.59	**0.005**	**
	within	4			
26 yrs $V_{>30prun.}$	between	3	14.80	**0.012**	*
	within	4			
28 yrs $V_{>30prun.}$	between	3	8.60	**0.032**	*
	within	4			
30 yrs $V_{>30prun.}$	between	3	19.94	**0.007**	**
	within	4			

11.5 Industrial yield

Table 11.5-1: Analyses of variance for the different variables

df: degrees of freedom; F: F ratio; *p*: probability.

Variable	Source of variation	*df*	F	*p*	
sawmill yield	between	6	47.6	**0.000**	***
	within	30			
sawmill conversion factor	between	6	29.9	**0.000**	***
	within	30			
peeled recovery rate	between	5	10.6	**0.000**	***
	within	49			
sliced veneer yield	between	6	18.1	**0.000**	***
	within	16			
sliced conversion factor	between	6	1.6	**0.201**	^{ns}
	within	16			

11.6 FINANCIAL PERFORMANCE

TABLE 11.6-1: ANALYSES OF VARI-ANCE FOR THE DIFFERENT VARIABLES

df: degrees of freedom; F: F ratio; *p*: probability.

Variable	Source of variation	*df*	F	*p*	
thinned gross revenue – current prices	between	2	1.5	**0.356**	ns
	within	3			
thinned gross revenue – no pruning premium	between	3	35.9	**0.002**	**
	within	4			
thinned gross revenue – new log assortments	between	3	34.1	**0.003**	**
	within	4			
gross revenue of the standing stock at age 30 years – current price	between	3	7.2	**0.043**	*
	within	4			
gross revenue of the standing stock at age 30 years – no pruning premium	between	3	6.8	**0.047**	*
	within	4			
gross revenue of the standing stock at age 30 years – new log assortments	between	3	8.7	**0.032**	*
	within	4			
total gross revenue at age 30 years – current prices	between	3	15.5	**0.011**	*
	within	4			
total gross revenue at age 30 years – no pruning premium	between	3	15.2	**0.012**	*
	within	4			
total gross revenue at age 30 years – new log assortments	between	3	15.6	**0.011**	*
	within	4			

TABLE 11.6-2: REVENUE (IN US$, CURRENT PRICES) PER LOG ASSORTMENT, UNPRUNED AND PRUNED, OBTAINED AT THE DIFFERENT THINNING PROCEDURES AND FINAL CUT

Total revenue per assortment in the 30-years rotation (Total^{1}). Total revenue for the unpruned (Total^{2}) and pruned (Total^{3}) assortments. Total revenue per intervention (Total^{4}). Proportion of assortments in relation to the total 30-years rotation revenue (%^{1}). Proportion of revenues of interventions in relation to the total 30-years rotation revenue (%^{2}). Harvest costs and net revenues per intervention. Assortments classified according to the small end diameter of each log (cm), with constant length of 2.5 metres.
5, 7, 10, 13, 15, 30 = year at which thinning or final cut took place.

Assortments		**WITHOUT**		**MODERATE**								**HEAVY**							**EXTREME**					
	cm	Total^{1}	*%^{1}*	5	7	10	13	15	30	Total^{1}	*%^{1}*	5	7	10	13	30	Total^{1}	*%^{1}*	5	10	13	30	Total^{1}	*%^{1}*
unpruned	10 - 19.9	2,728	*7*	553	876	686	1,102	973	982	5,171	*8*	880	551	866	1,267	823	4,387	*7*	1,761	200	245	240	2,446	*4*
	20 - 29.9	10,017	*25*			138	502	1,065	5,563	7,268	*11*			77	893	4,602	5,572	*8*		310	804	1,279	2,393	*4*
	30 - 39.9	6,769	*17*					200	12,498	12,698	*20*				191	13,420	13,610	*21*			1,571	4,940	6,511	*11*
	40 - 49.9	2,036	*5*						7,919	7,919	*13*					10,033	10,033	*15*			445	12,329	12,775	*22*
	50 - 59.9								1,202	1,202	*2*					1,496	1,496	*2*				8,213	8,213	*14*
	> 60																					537	537	*1*
	Total^{2}	21,550	*53*	553	876	824	1,604	2,237	28,164	34,258	*54*	880	551	944	2,351	30,374	35,099	*53*	1,761	509	3,065	27,539	32,875	*57*
pruned	20 - 29.9	3,645	*9*		47	1,031	1,198	1,706	493	4,475	*7*		123	1,107	2,291	147	3,668	*6*		875	94		969	*2*
	30 - 39.9	9,224	*23*				304	929	6,081	7,314	*12*				777	4,168	4,945	*8*		388	1,638	606	2,633	*5*
	40 - 49.9	4,645	*12*						12,234	12,234	*19*					14,593	14,593	*22*			2,104	2,933	5,037	*9*
	50 - 59.9	1,322	*3*						3,973	3,973	*6*					5,801	5,801	*9*				10,084	10,084	*17*
	> 60								980	980	*2*					1,684	1,684	*3*				6,582	6,582	*11*
	Total^{3}	18,836	*47*		47	1,031	1,502	2,635	23,760	28,975	*46*		123	1,107	3,067	26,392	30,690	*47*		1,263	3,837	20,205	25,305	*43*
	Total^{4}	40,386	*100*	553	923	1,855	3,106	4,872	51,924	63,233	*100*	880	674	2,051	5,418	56,766	65,789	*100*	1,761	1,773	6,902	47,744	58,180	*100*
	%^{2}	*100*		*1*	*1*	*3*	*5*	*8*	*82*	*100*		*1*	*1*	*3*	*8*	*86*	*100*		*3*	*3*	*12*	*82*	*100*	
Harvest costs		10,215		437	711	970	1,367	1,877	9,964	15,325		695	486	1,103	2,149	10,250	14,683		1,391	785	1,956	7,274	11,405	
Net revenue		30,540		116	212	884	1,739	2,995	42,234	48,181		185	188	948	3,269	46,802	51,393		371	988	4,946	40,422	46,727	

TABLE 11.6-3: REVENUES (IN US$, CURRENT PRICES) PER LOG ASSORTMENT, UNPRUNED AND PRUNED, OBTAINED AT THE FINAL CUT, CALCULATED FROM AGE 16-30 YEARS, IN 2 YEARS INTERVALS, FOR THE AREA WITHOUT THINNING AND MODERATE VARIANT

Total revenue for the unpruned (Total^1) and pruned (Total^2) assortments. Total gross revenue (Total^3). Assortments classified according to the small end diameter of each log (cm), with constant length of 2.5 m.
16, 18, 20...: year at which final cut took place.

	Assortments cm	WITHOUT								MODERATE							
		16	18	20	22	24	26	28	30	16	18	20	22	24	26	28	30
unpruned	10 - 19.9	6,032	5,776	5,369	4,693	4,746	4,028	3,194	2,728	1,373	1,327	1,248	1,197	1,202	1,102	1,050	982
	20 - 29.9	3,633	5,142	6,596	8,205	9,220	10,379	10,536	10,017	4,008	5,089	5,512	5,852	5,875	5,800	5,563	5,563
	30 - 39.9	410	1,007	1,612	2,308	3,264	4,036	4,816	6,769	1,348	2,872	4,847	7,426	9,103	10,944	11,326	12,498
	40 - 49.9				250	518	859	1,480	2,036		504	1,167	2,071	3,844	4,582	5,974	7,919
	50 - 59.9														376	389	1,202
	> 60																
	Total^1	10,075	11,925	13,577	15,456	17,748	19,302	20,027	21,550	6,729	9,792	12,774	16,546	20,024	22,804	24,303	28,164
pruned	20 - 29.9	6,709	6,939	7,050	6,988	6,974	6,529	5,429	3,645	3,196	2,244	1,949	1,355	1,047	867	733	493
	30 - 39.9	1,768	3,371	4,315	5,483	6,392	7,289	8,391	9,224	3,976	6,382	7,039	7,697	7,985	6,961	6,044	6,081
	40 - 49.9		436	1,191	2,291	2,556	3,323	3,780	4,645	1,033	2,296	3,960	6,668	7,006	9,953	12,346	12,234
	50 - 59.9						654	701	1,322			669	1,461	3,178	3,319	3,435	3,973
	> 60																980
	Total^2	8,477	10,746	12,555	14,761	15,922	17,794	18,300	18,836	8,205	10,922	13,617	17,182	19,216	21,100	22,558	23,760
	Total^3	18,552	22,670	26,133	30,217	33,670	37,096	38,327	40,386	14,934	20,714	26,391	33,727	39,240	43,904	46,860	51,924
	Harvest costs	6,697	7,624	8,340	9,060	9,891	10,346	10,187	10,215	4,135	5,225	6,190	7,368	8,237	8,875	9,155	9,964
	Net revenue	11,855	15,046	17,792	21,157	23,779	26,750	28.140	30,540	10,799	15,489	20,201	26,359	31,003	35,029	37,705	42,234

Table 11.6-4: Revenues (in US$, current prices) per log assortment, unpruned and pruned, obtained at the final cut, calculated from age 16-30 years, in 2 years intervals, for heavy and extreme variants

Total revenue for the unpruned (Total^1) and pruned (Total^2) assortments. Total gross revenue (Total^3). Assortments classified according to the small end diameter of each log (cm), with constant length of 2.5 m.
16, 18, 20...: year at which final cut took place.

	Assortments cm	HEAVY								EXTREME							
		16	18	20	22	24	26	28	30	16	18	20	22	24	26	28	30
unpruned	10 - 19.9	1,023	945	884	929	860	918	922	823	323	365	261	332	252	395	385	240
	20 - 29.9	4,159	4,815	5,016	4,800	4,818	4,957	4,794	4,602	1,582	1,476	1,373	1,385	1,348	1,217	1,064	1,279
	30 - 39.9	2,144	4,565	6,578	8,714	10,291	10,954	11,227	13,420	5,268	5,854	5,581	5,125	5,348	4,987	5,044	4,940
	40 - 49.9			1,183	2,970	4,254	5,763	7,072	10,033	2,051	4,896	7,622	11,236	12,507	14,472	15,095	12,329
	50 - 59.9						362	740	1,496		695	1,488	2,930	4,342	5,403	6,006	8,213
	> 60														501	1,493	537
	Total^1	7,326	10,325	13,660	17,413	20,222	22,954	24,754	30,374	9,224	13,285	16,325	21,008	23,796	26,974	29,087	27,539
pruned	20 - 29.9	2,110	1,103	654	292	258	269	242	147								
	30 - 39.9	5,830	7,074	7,636	7,867	6,636	5,973	6,201	4,168	2,461	968	362	186				606
	40 - 49.9	810	3,997	6,368	8,508	10,226	10,783	10,134	14,593	7,390	9,755	9,644	7,183	5,745	4,522	2,570	2,933
	50 - 59.9				1,334	2,520	4,612	5,194	5,801	1,628	3,833	5,369	8,693	10,744	12,092	13,607	10,084
	> 60								1,684			1,792	3,094	4,597	4,538	5,961	6,582
	Total^2	8,750	12,175	14,658	18,000	19,639	21,636	21,771	26,392	11,480	14,556	17,167	19,157	21,085	21,152	22,137	20,205
	Total^3	16,076	22,500	28,318	35,414	39,862	44,591	46,525	56,766	20,704	27,842	33,492	40,164	44,882	48,126	51,224	47,744
	Harvest costs	4,191	5,245	6,175	7,228	7,861	8,568	8,859	10,250	3,718	4,637	5,282	6,207	6,822	7,315	7,721	7,274
	Net revenue	11,885	17,254	22,143	28,186	32,000	36,023	37,666	46,802	16,985	23,204	28,210	33,957	38,059	40,811	43,503	40,422