Modelling the effect of stand density management and environmental variables on *Pinus patula* wood properties.

by

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Declaration

By submitting this dissertation electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

This dissertation includes two original papers published in peer-reviewed journals, one paper that is in review, and one unpublished paper currently in preparation for submission to an accredited scientific journal. The development and writing of the papers (published and unpublished) were the principal responsibility of myself and, for each of the cases where this is not the case, a declaration is included in the dissertation indicating the nature and extent of the contributions of co-authors.

Date: March 2020

Abstract

Modelling the effect of stand density management and environmental variables on *Pinus patula* wood properties.

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Approximately one million hectares of *Pinus patula* has been planted worldwide, mainly in southern and eastern Africa and accounts for roughly half of the total softwood plantation area in South Africa. Improved growth rates and shorter rotation ages of these forest resources have caused an increase in the proportion of juvenile wood and a decrease in the stiffness of lumber, which often does not comply with the requirements for structural use. The growing space of trees has been shown to influence wood properties and may be a useful management intervention to improve stiffness properties. The financial benefits of these short rotation systems also means that they are likely to persist into the future. An understanding of the properties of wood within the juvenile zone is therefore increasingly important.

The objectives of this study were thus (1), to examine the effect of tree spacing expressed as stand density, particularly at stand establishment, on the stiffness of wood and important wood properties which are known to influence wood stiffness and (2), to study the development of wood in young trees as affected by selected environmental factors.

The study was based on four experiments. In the first experiment wood increment cores were non-destructively removed from a total of 171 trees from four different planting density treatments from an 18-year old *Pinus patula* spacing trial. The wood density, microfibril angle (MFA) and ring width were measured using Silviscan3 technology. In a second experiment, two commercial *Pinus patula* stands which were subjected to different stand density management regimes, were destructively sampled and 37 trees were processed into lumber of which the modulus of elasticity (MOE) and modulus of rupture (MOR) were measured. In the third experiment, 46 trees from a spacing trial was also destructively sampled and processed into lumber of which MOE and MOR were measured. The last experiment was a controlled greenhouse potting trial where the temperature, water supply and leaf nitrogen/potassium ratio (N/K) were measured and compared to the MFA and density of 168 trees over their first/second year of growth.

Bending test results on lumber from trees from commercial stands showed that, compared to a number of stands with typical stand density regimes, only lumber processed from a higher stand density (1667 stems ha^{-1}) conformed to the requirements for structural use. The MOR values were however adequate across all management regimes. The MOE of lumber from a spacing trial showed that only the most closely spaced trees (2981 stems ha^{-1}) had lumber which conformed to requirements for structural grades. MFA, varied from roughly 30° at the pith to 7° at the bark, and along with wood density and knot characteristics, was able to explain over 70% of the variation in lumber MOE. The increase in lumber MOE with closer spacing was due to a combined effect of decreases and increases in both MFA and density respectively, and a restriction of the juvenile core.

MFA and density were both significantly influenced by tree spacing, decreasing and increasing with closely spaced trees respectively. The differences in growth rate due to tree spacing could not fully capture the effects of spacing, which had an independent effect on wood properties. Environmental variables also had a significant effect on growth and cell properties of *Pinus patula*. The stiffness of the young saplings was significantly influenced by leaf mass and by water supply and N/K. Based on these results it seems as if wood stiffness is linked to foliar biomass.

Stand density seems to have great potential as a management intervention to improve the cell and wood properties controlling the stiffness of South African-grown *Pinus patula* lumber at final harvest. Low levels of water supply and N/K can also increase the stiffness of wood within early cambial ages.

Uittreksel

Modellering van die effek van bestuur van vak-digtheid en omgewingsveranderlikes op *Pinus patula* houteienskappe.

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Ongeveer een miljoen hektaar *Pinus patula* is reeds wêreldwyd aangeplant, hoofsaaklik in Suid- en Oos-Afrika, en beslaan die helfte van die sagtehoutplantasie-area in Suid-Afrika. Verbeterde groeikoerse en korter rotasietydperke van hierdie boshulpbronne het ’n toename in die hoeveelheid jeughout en ’n afname in die styfheid van hout veroorsaak, wat dikwels nie aan die vereistes vir strukturele gebruik voldoen nie. Daar is bewyse dat die groeiruimte van bome die houteienskappe beïnvloed en dit kan ’n nuttige bestuurs-intervensie wees om styfheidseienskappe te verbeter. Die finansiële voordele van hierdie kort rotasiestelsels beteken ook dat dit waarskynlik in die toekoms sal voortduur. ’n Goeie begrip van die eienskappe van hout in die jeugsone word dus toenemend belangrik.

Die doelstellings van hierdie studie was dus (1) om die effek van boomspasiëring te ondersoek, veral by vak-vestiging, op die styfheid van hout en belangrike houteienskappe met ’n invloed op houtstyfheid en (2), om die ontwikkeling van hout in jong bome te bestudeer, wat beïnvloed word deur geselekteerde omgewingsfaktore.

Die studie is gebaseer op vier eksperimente. In die eerste eksperiment is inkrementboorsels uit ’n totaal van 171 bome verwyder uit vier verskillende plantdigtheidsbehandelings in ’n 18-jarige *Pinus patula*-spasiëringsproef. Die houtdigtheid, mikrofibrilhoek (MFA) en ringwydte is met Silviscan3-tegnologie gemeet. In ’n tweede eksperiment is twee kommersiële *Pinus patula*-vakke, wat aan verskillende vakdigtheid behandelings onderwerp is, vernietigend bemonster en 37 bome verwerk tot hout waarvan die modulus van elastisiteit (MOE) en die modulus van die skeuring (MOR) gemeet is. In die derde eksperiment is 46 bome uit ’n spasiëringproef ook vernietigend bemonster en verwerk tot hout waarvan MOE en MOR gemeet is. Die laaste eksperiment was ’n beheerde kweekhuisproef waar die temperatuur, watertoevoer en die blaar stikstof/kalium verhouding (N/K) gemeet is en vergelyk word met die MFA en digtheid van 168 bome gedurende hul eerste/tweede jaar van groei.

Die resultate van die buigtoets op hout van bome van kommersiële vakke het getoon dat, in vergelyking met ’n aantal vakke met tipiese vak-digtheidstelsels, slegs hout wat verwerk is van ’n hoër vakdigtheid aan die vereistes vir strukturele gebruik voldoen. Die MOR waardes was egter voldoende in alle bestuursregimes. Die MOE van hout uit ’n spasiëringsproef het getoon dat slegs die bome met die kleinste afstand tussen bome aan die vereistes vir strukturele gebruik voldoen. MFA, het gewissel van ongeveer 30° by die pit tot 7° by die bas, en tesame met die houtdigtheid en die kwas-kenmerke, kon meer as 70% van die variasie in die MOE van hout verklaar word. Die toename in die MOE van hout met ’n nouer spasiëring was te wyte aan ’n gesamentlike effek van afnames en toenames in onderskeidelik MFA en digtheid, en ’n beperking van die jeugkern.

MFA en digtheid is beide aansienlik beïnvloed deur die boomafstand, neem af en neem toe met kleiner spasiëring, onderskeidelik. Die verskille in groeitempo as gevolg van boomafstand kon nie die gevolge van die spasiëring ten volle vasvang nie, wat ’n onafhanklike uitwerking op die houteienskappe gehad het. Omgewingsveranderlikes het ook ’n beduidende effek op die groei en seleienskappe van *Pinus patula* gehad. Die styfheid van die jong boompies was beduidend beïnvloed deur blaarmassa en die watervoorsiening en N/K. Op grond van hierdie resultate lyk dit asof blaarfunksie die houtstyfheid beïnvloed.

Vakdigtheid blyk groot potensiaal te hê as bestuursintervensie om die sel- en houteienskappe te verbeter wat die styfheid van die Suid-Afrikaans-gekweekte *Pinus patula*-hout tydens die finale oes beheer. Lae vlakke van watervoorsiening en N/K kan ook die styfheid van hout binne die vroeë kambiaaltydperk verhoog.

Preface

"Nothing is so calculated to enlarge the mind and strengthen the intellect as the study of the Bible. No other study will so elevate the soul and give vigor to the faculties as the study of the living oracles."[1]

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[1] Ellen G. White, *Mind, Character, and Personality Vol 1*, Review and Herald Publishing, 1999, p.93.

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Dedications

In loving memory of Jo-Anne Erasmus

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Chapter 1

Introduction

Background

Wood is an important natural resource used for a variety of purposes, which include furniture, fuel, pulp and paper and construction. More and more wood is sourced from plantation forestry, which continues to expand significantly on a global scale, occupying an estimated 291 million ha by the year 2015, with the average annual rate of increase peaking at 5.3 million ha per year during the period 2000-2010 (FAO, 2016). In 1980, there were 18 million ha of forest plantations, compared to 44 million ha in 1990 and 187 million ha in 2000 (Carle et al., 2002). In South Africa, the total forest area stands at approximately 1.2 million ha with *Pinus patula* accounting for half (50.4%) of the total softwood plantation area in 2016 (DAFF, 2017). Approximately one million ha of *Pinus patula* have been planted worldwide, mainly in southern and eastern Africa (Dvorak et al., 2000).

Approximately 75% of all South African produced sawn softwood is categorised as structural lumber—making it the single most important product category for saw-log growers. These growers are faced with two crucial considerations: product specifications and financial feasibility. The latter typically takes preference and primarily drives the grower's long term planning which is usually to produce pruned (quality) sawlogs in such a way as to secure the best rate of return on investment and risk reductions (Griess et al., 2016). This can be achieved through maximizing stand volume productivity through interventions, such as tree breeding, site-species optimizing and fertilization (du Toit and Norris, 2012). Trees thus grow faster and are harvested earlier. Globally important species like *Pinus radiata* D. Don and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), as cited by Moore and Cown (2017), have seen significant reductions in rotation age in recent years. Similarly, the harvesting ages of locally grown pine species intended for saw-log production, which include *Pinus patula*, *Pinus elliottii*, *Pinus taeda* (loblolly pine) and *Pinus radiata*, have been reduced considerably (Crickmay and Associates, 2005).

One drawback of reaping the financial gains of faster growth has been made evident by numerous studies highlighting the increase of juvenile wood content at final harvest (Walker and Nakada, 1999; Malan, 2003; Moore et al., 2012; Schimleck et al., 2018). In many species, juvenile wood is typically characterised by high microfibril angle and low wood density (Moore and Cown, 2017)—properties, which display strong associations with wood stiffness (Cave and Walker, 1994; Xu and Walker, 2004; Wessels et al., 2015). Consequently studies around the world suggest that increased proportions of this type of wood will lead to a reduction in the mechanical properties of lumber (Kretschmann and Bendtsen, 1992; Burdzik, 2004; Dahlen et al., 2012). One study found that *P. patula* lumber from trees harvested below 20 years had stiffness values of about 25% less than required by national standards (Dowse and Wessels, 2013). Previous studies indicate that planting trees closer to one another may improve some mechanical properties of wood (Roth et al., 2007; Waghorn et al., 2007; Lasserre et al., 2008, 2009). A study by Lasserre et al. (2005) reported the gains attributable to genetics to be only 47% of that attainable through spacing trees more closely.

Previous research clearly indicates that the most influential part of a tree's bole, with respect to solid wood products, is the wood that is laid down by the cambium within the first few growth rings (Zobel and Sprague, 1998). These growth rings make up large proportions of the recovered product where the mature rings, with properties more preferable for the production of structural lumber, are less prevalent as they are mostly chipped away in the milling process. Lumber recovered in this region thus typically displays lowest mechanical properties, such as the modulus of elasticity Xu and Walker (2004); Vikram et al. (2011); Moore et al. (2012). Since the characteristic strength values of wood material are determined by the weakest portion of the strength distribution curve Madsen (1992), our understanding and prediction of the wood properties in this region is important. A current model of wood formation (Drew and Downes, 2015) showed better predictive power in mature wood compared to juvenile wood and highlights the need to improve our understanding within this region. In order to address the challenges of faster growth and consequent earlier harvesting of softwood saw-log plantations, the objectives of this study were as follows:

- to examine the effect of tree spacing, particularly at establishment, on the variation and improvement of lumber stiffness
- to examine the effect of initial tree spacing on the underlying properties of wood density and microfibril angle and their influence on lumber stiffness
- to study the effect of fertilization, water availability, and temperature on the development of wood formed during early cambial growth, specifically the effect on wood density and microfibril angle.

Although this study considered the objectives from a number of perspectives, examining a range of related properties, the ultimate focus was on wood stiffness.

Structure of thesis

This dissertation is in the format of a compilation of independent scientific articles, each addressing a particular topic within the broader scope of this study. Although written independently from each other, the articles were all related to some extent and hence there are some recurring themes and topics presented in subsequent chapters. The dissertation consists of an introduction (Chapter 1), followed by two published papers and two unpublished papers—one of which is currently in review. The second and third chapters have been built on the candidate's MSc work (Erasmus, 2016), but as reported in this dissertation, the analysis and reporting have entirely been reworked and new data, made available or generated, has also been added to the analysis. The fourth and fifth chapters were largely based on two new experiments conducted for this PhD project. The last section (Chapter 6) concludes the dissertation with a full summary of all research results. Differences in format and the terms used between chapters were as result of the journals they appear in or will be submitted to, for review. Consequently, there are some terms that may be used interchangeably. For example, planting spacing and initial spacing both refer to the spacing or stand density of trees at establishment. Appendix A contains the signed declarations by the candidate and co-authors regarding the nature and extent of the contribution of each author to each paper.

The study was based on four experiments. In the first, a *Pinus patula* spacing trial was sampled non-destructively. In the second experiment, two commercial *Pinus patula* stands, with different stand density management regimes, were destructively sampled and processed into lumber. Data on 17 different commercial compartments from a previous study by (Wessels et al., 2014) was also made available in this study. The third experiment was similar to the first one but in addition to the non-destructive tests, the spacing trial was destructively sampled and processed into lumber. The last experiment was a controlled greenhouse potting trial, where selected environmental factors were controlled and evaluated for their influence on wood properties of young *Pinus patula* trees. The following is a brief summary of the contribution of each papers' to the overall objectives of this study:

Chapter 2

Erasmus J, Kunneke A, Drew DM, Wessels CB. 2018. The effect of planting spacing on *Pinus patula* stem straightness, microfibril angle and wood density. Forestry: An International Journal of Forest Research 91.3 (2018): 247-258.

- This study examined the possibility of planting more trees, per unit area of land, at stand establishment, to improve the underlying properties, namely microfibril angle and wood density, controlling wood stiffness. These properties were examined non-destructively. The effect on the straightness of the tree stem was also measured since it is related to the economic feasibility of planting spacing.

Chapter 3
Erasmus J, Wessels CB. 2019. The effect of stand density management on *Pinus patula* lumber properties. European Journal of Forest Research (2019): 1-11.

- This study uses destructive methods to describe the within- and between-tree variation of the modulus of elasticity and other important lumber properties as influenced by stand density of *Pinus patula*.
- Data from a previous study on 17 commercial compartments situated on the Mpumalanga escarpment were used in this study in conjunction with the material harvested here.

Chapter 4
Erasmus J, Drew DM, Wessels CB. 2019. The flexural lumber properties of *Pinus patula* Schiede ex Schltdl. & Cham. improves with decreasing initial tree spacing. Annals of Forest Science. In review.

- The study made use of both destructive and non-destructive methods to evaluate the influence of tree spacing at establishment on wood properties at both the annual ring and sawn lumber levels. Two spacing trials were used in this investigation
- An important question in this study was concerned with whether difference in wood properties due to spacing could be accounted for by difference in tree growth.

Chapter 5
Erasmus J, Drew DM, du Toit B, Wessels CB. 2019. The effect of water availability, temperature, and NK ratio on selected wood properties of *Pinus patula*, *Pinus elliottii* X *caribaea*, and *Pinus patula* X *tecunumanii* saplings. Unpublished Manuscript

- This study focuses on the development of wood at early cambial ages using young *Pinus patula* material. Additionally, two other hybrid species were included in the study to assess differences in responses.

- Wood density, microfibril angle and the stiffness of wood were examined under the influence of fertilization and water supply. This study also uses a different method to the previous studies to relate temporal changes in environmental factors on the development of wood.

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Chapter 2

The effect of planting spacing on *Pinus patula* stem straightness, microfibril angle and wood density

Justin Erasmus · Anton Kunneke · David M. Drew · C. Brand Wessels [1]

Abstract Improved growth rates and shorter rotation ages have caused a reduction in the stiffness of structural lumber from South African-grown pine plantations. Microfibril angle (MFA) and wood density are known to be two wood properties that influence wood stiffness. Therefore, the objective of this study was to determine the effect of planting spacing of *Pinus patula* trees, on the MFA and wood density, as well as stem straightness. A total of 171 trees from four spacing treatments (403, 1097, 1808 and 2981 stems ha^{-1}) from an 18-year old experimental *P. patula* plantation located in Mpumalanga, South Africa, were analysed for wood density, MFA, and ring width. A sub-sample of 81 trees was scanned for tree form using a terrestrial laser scanner. A non-linear mixed-effects model using a power function was developed to model MFA and wood density as a function of ring number and ring width. Planting spacing had a highly significant effect on stem straightness with the most widely spaced trees having the worst mean stem straightness. However, the stem straightness did not increase consistently with increasing stems ha^{-1}. The dynamic modulus of elasticity of standing *P. patula* trees increased greatly with closer spacing—more so than any other species reported in literature. The mixed model showed that, after accounting for differences due to ring number and ring width, spacing treatment had a significant effect on both the initial MFA

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and its rate of change with age. For wood density, this remaining effect of spacing treatment was only displayed in its radial rate of change. Based on these results, it seems as if planting spacing has great potential as a management intervention to improve the mechanical wood properties and in certain cases also the stem straightness of South African-grown *P. patula* at final harvest.

Introduction

Of all sawn wood produced and sold in South Africa, ∼75 per cent is regarded as structural lumber (Crickmay and Associates, 2015), making it the single most important product category for local sawmills. The most important tree resource for these lumber processors is *Pinus patula*, which accounts for 52.2 per cent of the total softwood area in South Africa (DAFF, 2014). *Pinus patula* is also widely planted in other African and South American countries with an estimated worldwide total of one million hectares planted with this species in 1994 (Wright, 1994). A critical issue for *P. patula* structural lumber producers is that a large portion of their end products must conform to the minimum mechanical requirements for structural lumber. This has become more difficult in South Africa in recent years as changes to the plantation resources resulted in reduced mechanical properties of lumber (Burdzik, 2004; Dowse and Wessels, 2013).

As improvements in forest management and genetic material have increased growth rates, the harvesting age of South African-grown pine trees, mainly *Pinus patula*, *elliottii*, *taeda* and *radiata*, managed for saw-log production, has been reduced considerably from ∼28 years in 1983 to ∼23 years in 2003 (Crickmay et al., 2005). Since then, South African studies have shown a significant reduction in important mechanical properties of lumber, particularly the mean stiffness (modulus of elasticity, MOE) of visually graded lumber Burdzik (2004); Wessels et al. (2011); Dowse and Wessels (2013). Dowse and Wessels (2013) and Wessels et al. (2014) reported the mean MOE of lumber, processed from 16 to 20 year-old *P. patula* stands, to be ∼25 per cent less than required for the lowest and most produced structural grade in South Africa. Globally, reduced mechanical properties of fast growing trees have also become a growing concern as studies from other countries, using different species, have accordingly reported significant proportions of non-compliant structural products harvested at younger ages (Cown, 1992; Kretschmann and Bendtsen, 1992; Biblis and Brinker, 1993; Biblis, 2006). In light of these reports, the South African sawmilling industry needs to address the low MOE of *P. patula* and other softwood resources to continue the processing thereof into acceptable structural products.

The structure of wood cell walls largely determines the mechanical properties such as the MOE of wood (Barnett and Bonham, 2004; Tsoumis, 2009). Microfibril angle (MFA), the orientation of cellulose microfibrils in the secondary cell wall with respect to the longitudinal axis of tracheid cells, and wood density have been shown to be the two most influential properties for *Pinus radiata* (Cown et al., 1999; Evans and Ilic, 2001; Downes et al., 2002; Xu and Walker, 2004) and *P. patula* (Wessels et al., 2015a) wood stiffness. However, a poor relationship between MOE and wood density of *P. radiata* corewood has been reported in some studies (Burdon et al., 2001; Lasserre et al., 2009; Watt et al., 2010). Research by Cown et al. (1999) noted that wood density in *P. radiata* does become more influential with increasing cambial age. Some authors argued that MFA is the only property to account for large variations in radial MOE trends in fast grown softwoods with wood density acting only as a supporting property (Cave and Walker, 1994; Walker and Butterfield, 1996). In contrast, research relating the average MFA to the stiffness of fullsized lumber, instead of small clear specimens, has shown wood density to have a similar influence on lumber MOE (Wessels et al., 2015a), and in some cases even more so than MFA (Downes et al., 2002; Cown et al., 2004; Vikram et al., 2011).

Previous studies on several softwood species showed that planting spacing might influence the mechanical properties and volume recovery. Closely spaced plantations display positive effects on wood stiffness in *P. radiata* (Lasserre et al., 2005, 2008, 2009; Waghorn et al., 2007a; Moore et al., 2015; Wessels and Froneman, 2015) and in other species (Wang and Ko, 1998; Chuang and Wang, 2001; Ishiguri et al., 2005; Roth et al., 2007; Clark III et al., 2008; Moore et al., 2009; Amateis et al., 2013; Rais et al., 2014). The increase in stiffness with increasing stems ha^{-1} has frequently been attributed to the increase in the height diameter ratio (slenderness). Based on Euler's buckling theory, tall, slender trees in competitive environments will require wood that is higher in stiffness in order to resist buckling due to their increasing self-weight (Spatz and Bruechert, 2000; Watt et al., 2006; Waghorn and Watt, 2013; Merlo et al., 2014; Wessels et al., 2015b).

Planting spacing can also influence the straightness of trees (Macdonald and Hubert, 2002), which has economic consequences for log processors. Both the yield and quality of lumber is greatly affected by crooked stems (Cown et al., 1984; Monserud, 2003; Ivković et al., 2007; Lachenbruch et al., 2010) and some studies suggest value losses in the sawmill process of roughly 10 per cent due to poor stem straightness (Carino et al., 2006). Leaning stems and those with excessive sweep are known to cause compression wood (Timell, 1986; Krause and Plourde, 2008), which has been shown to reduce wood stiffness (Lindström et al., 2004; Sonderegger et al., 2008). The effect of planting spacing on stem straightness is, however, not always consistent. Trees in stands planted with narrow spacing have been shown to display better stem straightness, improving volume recovery (Malinauskas, 2003; Tong and Zhang, 2005; Belley et al., 2013; Froneman, 2014; Smith et al., 2014) although spacing effects on stem straightness were sometimes less clear (Egbäck et al., 2012; Liziniewicz et al., 2012). On the other hand, trees grown under suppressed conditions in closely spaced plantations may also display poor stem straightness (Theron and Bredenkamp, 2004).

The main objective of this study was to determine the effect that planting spacing has on the important properties of MFA and wood density of *P. patula* trees. At the same time, we also wanted to establish the effect of planting spacing on stem straightness. The results of the study would be useful in formulating future forest management regimes for *P. patula* grown in South Africa. To the authors best knowledge, this is the first study measuring the effect of planting spacing of *P. patula* on MFA and stem straightness.

Materials and methods

Experimental layout

This study was conducted using an 18 year-old *P. patula* spacing experiment located in the Mpumalanga escarpment on the Montrose plantation near the town of Barberton, South Africa (25.9037° S, 30.8729° E). This area has a mean annual rainfall of ~850mm and mean midday temperatures of ~17 °C (Barberton aviation weather station, Code: FABR, 25.7175° S, 30.9750° E, 681m ASL). The trees in this study were pruned at 5, 7 and 9 years after planting to 2, 3.5 and 5.5m respectively. The experiment followed a randomized complete block design consisting of four planting spacing levels of 403, 1097, 1808 and 2981 stems ha^{-1}, each replicated in two blocks. Each sampling plot had been planted with 49 seedlings in a 7 by 7 tree layout (variable area plots) but only the centre 25 trees were included in the study reported here as the outer trees were considered buffer rows. Out of a possible 200 trees, only 171 were still available for analysis due to mortality, indicated by the survival percentages of treatments in Table 1.

Table 1: Plot data and sample sizes

Planting spacing (stems ha^{-1})	Mean DBH* (cm)	Mean height* (m)	Survival (%)	Total stem volume (m^3 ha^{-1})	Sample size*
403	32.7 (34.1, 34.1)	23.3 (23.9, 24.9)	96	321	48 (22, 10)
1097	23.8 (22.8, 25.3)	21.5 (20.9, 22.8)	96	428	48 (24, 10)
1808	19.9 (21.5, 21.7)	20.6 (22.2, 21.2)	84	451	42 (19, 10)
2981	16.9 (17.3, 17.8)	20.3 (20.1, 21.4)	66	417	33 (16, 10)

*The first and second values in parenthesis indicate values of the sub-sampled trees for stem straightness (TLS measurements) and the removal of increment cores respectively.

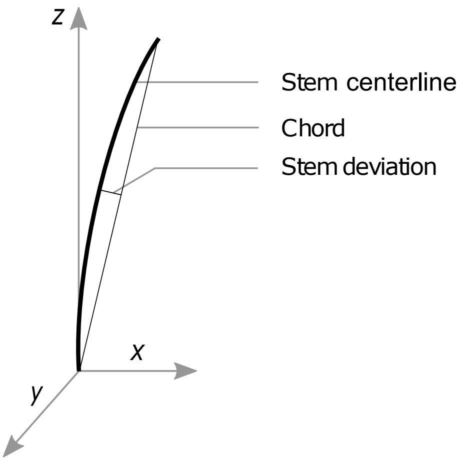

Figure 1: Illustration of the measurement of stem straightness

Measurements

The stem deviation (from perfect straightness) was measured up to 6m from tree base using data from a terrestrial laser scanning (TLS) system for one randomly chosen replication block. A Trimble FX phase shift scanner (Trimble Inc.) with angular resolution of 8 sec was used, which results in a sample step of 4 mm at a distance of 20 m. The scan setup used a minimum of four scans per plot. Of the 85 trees available in the chosen replication, a total of 81 were reconstructed from TLS scans and analysed for stem straightness. The other four trees were excluded from the analysis due to either limited scans, causing insufficient points in the point cloud for those trees, or forking below 6 m. The variation of these tree dimensions (manually measured on the 81 trees) from the full sample is indicated in Table 1. We defined stem straightness as the maximum deviation from the stem's centreline perpendicular to a straight line (chord) joining the two centre-points of the stem at the base and 6 m (Figure 1). The perpendicular deviations were derived through vector equations using three-dimensional coordinates of tree stems which were provided by the 3D Forest software package, version 0.31 (www.3dforest.eu). Stem straightness was then calculated from the set of perpendicular distances for each tree by selecting the maximum.

Basal area and the relative stand density (RD), according to Curtis (1982), was calculated for each spacing treatment. The diameter at breast height (DBH) and standing tree height were manually recorded for all trees (Table 1). The slenderness of trees was taken as the ratio of tree height to DBH. The dynamic MOE of standing trees was calculated from stress wave velocities at breast height obtained using the Fakopp Treesonic instrument (Fakopp Enterprise Bt.; Divos, 2010). From the wood density (ρ) assumed constant at 1000 kg m^{-3} (Wielinga et al., 2009), and the stress wave velocity (V), the MOE was then estimated from the following:

$$MOE = \rho V^2 \tag{1}$$

The probe generally penetrated ∼20 mm into the wood and thus effectively only recorded outerwood MOE and was not hindered by bark. Increment cores were taken at breast height (1.3 m above ground) from the northern side of 10 randomly chosen trees per spacing treatment—40 trees in total. Water in the increment cores was replaced by ethanol in three stages before the cores were dried to equilibrium moisture content. The MFA, wood density and ring widths of each sample were measured using the CSIRO Silviscan 3 apparatus (Evans, 1999) in Melbourne, Australia, at a radial resolution of 2 mm for MFA and 0.025 mm for wood density. Ring widths were defined by the distance between the maxima of wood density of successive rings in the radial wood density profile. In this study, the majority of annual rings had no latewood (LW) according to both interpretations of Mork's definition of LW cells (Denne, 1989)—which showed that this definition could not be used in our study. A wood density threshold of 500 kg m^{-3} was then chosen as a definition of LW percentage. This was based on values from literature (Koubaa et al., 2002) and overlaying wood density profiles with images of increment core samples; *P. patula* typically has distinctly visible darker bands of LW zones.

The growth of individual trees varied and therefore the width of the first year rings depended on when the height of a specific tree reached 1.3 m (which was the sampling height)—resulting in widely varying ring widths for the first year ring. Due to varying growth rates some trees only reached a height of 1.3 m after several growth seasons and therefore sometimes had fewer than 15 year rings at breast height. Cores also contained mostly earlywood for the last annual ring as trees were sampled just before winter. Therefore, in the statistical analysis only the 2nd to 13th annual rings were considered.

The mean width of rings, from pith to bark, and for each spacing treatment, were also overlaid with a cant sawing pattern and a 4 mm sawing kerf to simulate which annual rings will be present in a given board position. The mean wood properties for simulated board positions were then calculated from the rings demarcated by the sawing pattern.

It would have been preferable to destructively sample trees and measure the MOE of the lumber from these trees, but at the time of this study no *P. patula* spacing experiments were available for destructive testing and therefore the focus of this study was rather on the basic properties of MFA and wood density as well as stem straightness.

Statistical analysis

The R system for statistical computing (R Core Team, 2018) and Statistica (Dell Inc, 2016) were used for data analysis. Pearson correlations between the various individual tree dimensional variables and average wood properties were computed. The effect of planting spacing on DBH, tree height, stem straightness and dynamic MOE was tested using one-way analysis of variance (ANOVA) where Fischer's LSD post hoc tests were subsequently performed. Two non-linear mixed-effects models (Pinheiro and Bates, 2000), fitted with the R package "nlme" (Pinheiro et al., 2016), were developed to examine the effect of planting spacing on the pith-to-bark variation in wood density and MFA. The first model was the power function presented by Moore et al. (2015):

$$Y_{ijk} = (\alpha_i + a_{ij})\, RN_{ijk}{}^{(\beta_i + b_{ij})} + \epsilon_{ijk} \tag{2}$$

where Y_{ijk},RN_{ijk} and ϵ_{ijk} are the response variable (MFA or wood density), the ring number, and the residual error of the kth annual ring in the jth tree in the ith spacing treatment, respectively. The parameters α_i and β_i correspond to the initial value (ring 1) and the radial rate of change in the response variable, respectively, which could vary for the ith spacing treatment. The a_{ij} and b_{ij} terms are the random effects for the jth tree in the ith spacing treatment. Considering that planting spacing heavily affects ring width, an additional model incorporating ring width (cf. Auty et al., 2013) was also developed to test if planting spacing still had any effect on the estimated parameters after accounting for differences in ring number and ring width:

$$Y_{ijk} = (\alpha_{0,i} + a_{ij} + \alpha_{1,i}\, RW_{ijk})\, RN_{ijk}{}^{(\beta_{0,i} + \beta_{1,i}\, RW_{ijk})} + \epsilon_{ijk} \tag{3}$$

All parameters were thus adjusted for RW_{ijk}, the ring width of the kth annual ring in the jth tree in the ith spacing treatment, by the $\alpha_{1,i}$ and $\beta_{1,i}$ parameters which could also vary with the ith spacing treatment. Because only rings 2-13 were considered, the 2nd annual ring was designated as ring number 1 for this analysis. Likelihood ratio tests and Akaike's information criterion, AIC Akaike (1974), were used to evaluate the significance of including each term in both models—random effects, fixed effects and the effect of spacing treatment. Heteroscedasticity was modelled as a power function of ring number (Auty et al., 2013) while the random effect parameters were considered to account for correlations among residuals (Moore et al., 2015). Subsequently, annual ring widths, modelled as an exponential function of cambial age (parameters not shown), were used to predict the radial profiles of wood properties given by equation (3), for each spacing treatment (Auty et al., 2017).

Results

Stem straightness

Planting spacing had a highly significant effect ($P < 0.001$) on the average stem straightness (Figure 2A and Table 2). However, the trend across spacing treatments was inconsistent. The most widely spaced treatment (403 stems ha^{-1}) had the least straight stems with a mean deviation of 83 mm. Stem straightness for trees from the 1097 stems ha^{-1} treatment was significantly ($P < 0.001$) greater than the 403 stems ha^{-1} treatment and displayed the lowest mean stem deviation of 41 mm. There were no significant differences in the mean stem straightness between the two most closely spaced treatments.

Table 2: Stand-level characteristics for each spacing treatment

Planting spacing (stems ha^{-1})	Stem straightness (mm)*	Slenderness	MOE (MPa)*	Basal area (m^2 ha^{-1})	Relative stand density
403	83.1 (18.8)	0.73	10150 (620)	33.4	5.8
1097	40.7 (7.3)	0.92	12739 (624)	48.2	9.8
1808	70.4 (10.0)	1.06	14607 (1202)	50.0	11.1
2981	55.5 (15.0)	1.23	15044 (893)	46.3	11.1

*Values in parenthesis are ± SE.

DBH, height, slenderness and site occupancy

Planting spacing had a highly significant effect ($P < 0.001$) on DBH as shown in Figure 2B. As expected, the mean DBH decreased with increasing stems ha^{-1}—in total, DBH reduced by 48 per cent from the widest to closest spacing (Table 1). Planting spacing had a highly significant effect ($P < 0.001$) on mean tree height—tree height decreased by 8 per cent from 403 stems ha^{-1} to 1097 stems ha^{-1}. There was a further non-significant decrease in mean tree height of only 6 per cent between 1097 stems ha^{-1} and 2981 stems ha^{-1}. The mean slenderness for each spacing treatment can be seen in Table 2 and Figure 2D. The effect of planting spacing on slenderness was highly significant ($P < 0.001$), increasing by 68 per cent from 403 to 2981 stems ha^{-1}. Both RD and basal area followed an increasing trend from 403 to 1808 stems ha^{-1}, above which RD remained constant while basal area then decreased (Table 2). The most notable increases were between 403 and 1097 stems ha^{-1}.

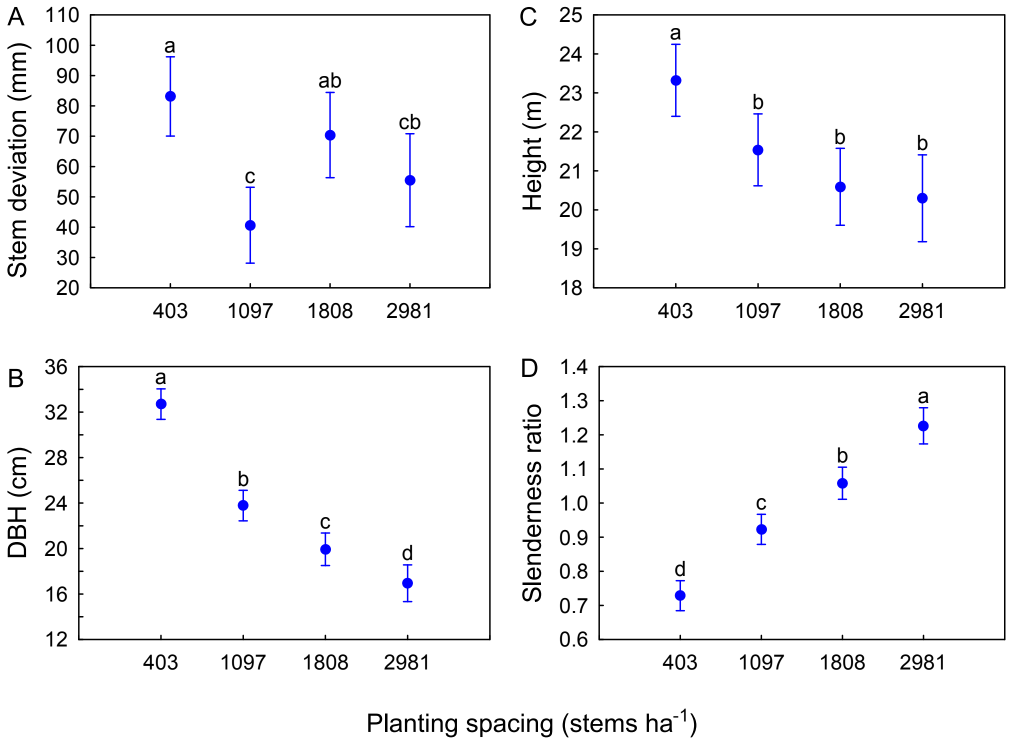

Figure 2: Means and 95 per cent confidence intervals for stem straightness (A), DBH (B), height (C) and slenderness ratio (D) for each spacing treatment. Different letters denote significant differences at $P < 0.05$.

Dynamic MOE

Spacing treatment had a highly significant effect ($P < 0.001$) on the dynamic MOE (Table 2). The mean MOE increased by 48 per cent from 403 to 2981 stems ha^{-1}—a mean rate of increase (Δ MOE/Δ planting spacing) of 1.9 MPa ha stems^{-1} (Figure 3). Differences in means were the greatest between 403 and 1097 stems ha^{-1} and thereafter, displaying smaller differences between the more closely spaced treatments showing an asymptotic type response.

Microfibril angle

The mean MFA per annual ring across all spacing treatments decreased from 31° to 7° between the 2nd and the 13th year rings (Figure 4A). As expected, MFA displayed a clear decreasing trend with increasing ring number (cambial age). For a given annual ring, the overall trend in MFA was a decreasing angle from 403 stems ha^{-1} to the closer spacing treatments. The mean MFA for the 403 stems ha^{-1} treatment decreased to about the 11th annual ring before it reached a constant level of ~12°, while in the more closely spaced treatments, MFA rapidly decreased

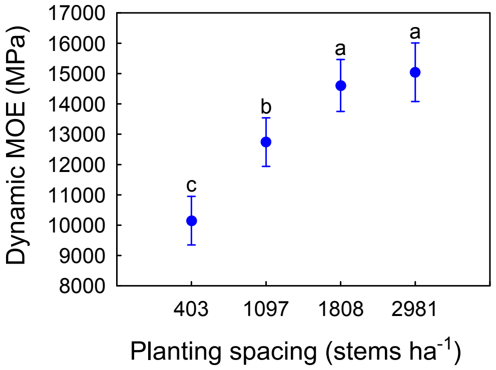

Figure 3: Means and 95 per cent confidence intervals for MOE for each spacing treatment. Different letters denote significant differences at P $<$ 0.05.

up to the seventh and eighth annual ring before stabilizing. As a result, the mean MFA decreased by 5°, on average, for the first nine rings from 403 to 1097 stems ha^{-1}. There was also a 5° decrease from 1097 to 1808 stems ha^{-1} near the pith (the second to fourth annual ring) for equivalent annual rings while the MFA values for treatments 1808 and 2981 stems ha^{-1} were similar at all annual rings. The model given by equation (2) (parameters not shown, AIC = 2415), showed that only α_i was significantly influenced by spacing ($P < 0.001$). The α term was significantly greater for 403 and 1097 stems ha^{-1} compared with the other treatments.

When ring width was included, spacing treatment had a significant ($P < 0.001$) effect on all parameters of the model given by equation (3), which had a considerably better fit to the data (lower AIC value of 2244) (Table 3). Modelled MFA was greater for the 403 and 1097 stems ha^{-1} treatments compared with the other two treatments up to ring 6 (Figure 5A). The rate of decline was clearly lower for the 403 stems ha^{-1} treatment compared with the other treatments, although this gradient was not mediated through neither $\beta_{1,i}$ or $\beta_{0,i}$ (non-significant) but determined by ring width through the α_1 term. Modelled MFA was negatively influenced by ring width due to the significant $\alpha_{1,i}$ term for the 1097 stems ha^{-1} treatment and the $\beta_{1,i}$ term for the 1808 stems ha^{-1} treatment (Table 3). The $\alpha_{0,i}$ and $\beta_{0,i}$ parameters differed significantly, even after ring width had been taken into account. The $\alpha_{0,i}$ parameter for the 1097 stems ha^{-1} was significantly greater than for the other treatments, while its $\beta_{0,i}$ parameter was the only significantly different value relative to 403 stems ha^{-1}.

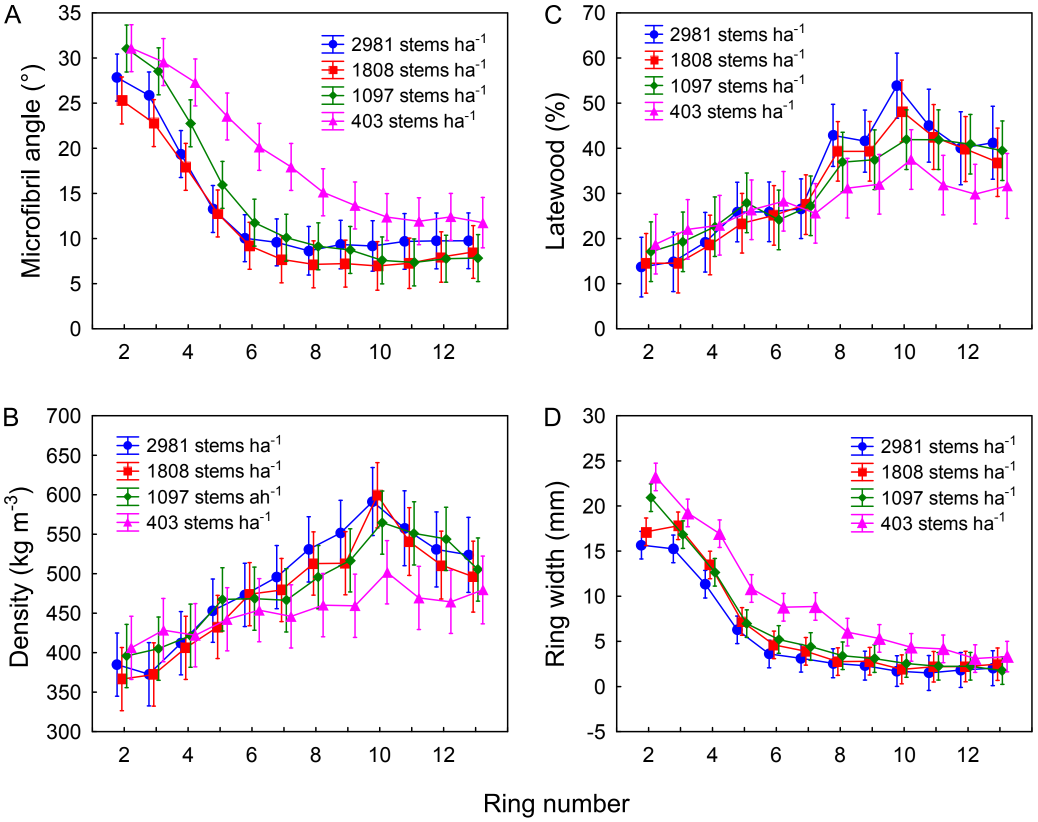

Figure 4: Variation in microfibril angle (A), wood density (B), latewood percentage (C) and ring width (D) at different spacing treatments and rings from pith. Vertical bars denote 95 per cent confidence intervals.

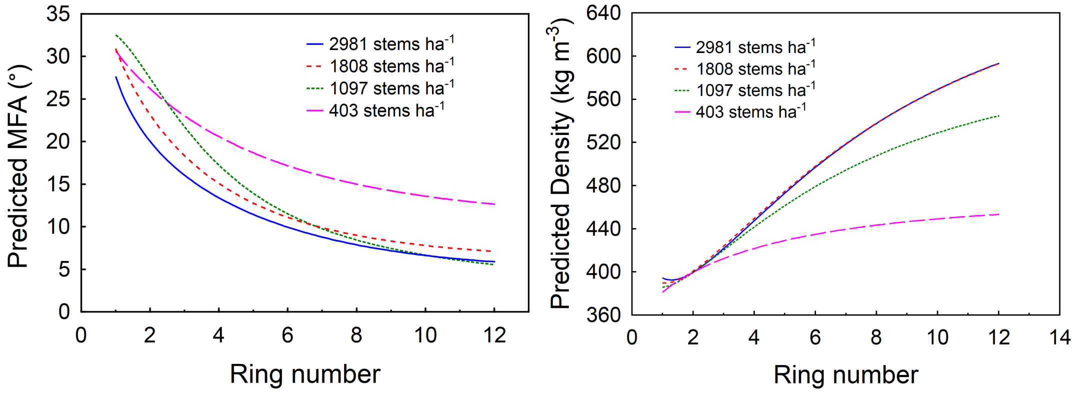

Figure 5: Variation in predicted microfibril angle (A) and wood density (B) from equation (3) at different spacing treatments and rings from pith.

Table 3: Parameter estimates, standard errors, *P*-values and standard deviations for the random effect estimates of equation (3). Estimates for the fixed parameters show their values and intercept (Int., i.e. 403 stems ha^{-1}), and values for the other treatments relative to the intercept (i.e. the change in estimate from 403 stems ha^{-1}). The α_0 and α_1 parameters for wood density are the only fixed parameters (single value for all treatments).

Parameters	MFA				Wood Density			
	Estimate	SE	t-value	p-value	Estimate	SE	t-value	p-value
(Int./Fixed)	13.965	2.812	4.966	<0.001	431.8	13.556	31.854	<0.001
α_0, 1097	24.495	3.616	6.774	<0.001				
α_0, 1808	-9.844	3.063	-3.213	0.001				
α_0, 2981	-4.650	3.475	-1.338	0.182				
(Int./Fixed)	0.713	0.119	6.014	<0.001	-2.164	0.624	-3.467	<0.001
α_1, 1097	-0.992	0.144	-6.895	<0.001				
α_1, 1808	0.502	0.124	4.030	<0.001				
α_1, 2981	0.541	0.162	3.330	<0.001				
(Int.)	-0.086	0.068	-1.270	0.205	0.023	0.015	1.526	0.128
β_0, 1097	-0.715	0.073	-9.807	<0.001	0.077	0.012	6.357	<0.001
β_0, 1808	0.145	0.083	1.739	0.083	0.115	0.013	9.003	<0.001
β_0, 2981	-0.060	0.100	-0.603	0.547	0.115	0.013	9.099	<0.001
(Int.)	0.001	0.003	0.316	0.753	0.001	0.001	0.446	0.656
β_1, 1097	0.030	0.004	8.021	<0.001	-0.006	0.002	-3.031	0.003
β_1, 1801	-0.014	0.004	-3.199	0.002	-0.01	0.002	-4.429	<0.001
β_1, 2981	-0.001	0.006	-0.069	0.945	-0.012	0.002	-5.433	<0.001
Random parameters	Std. Dev.				Std. Dev.			
- tree	3.098				37.584			
- residual	0.661				24.486			

Wood density

Wood density varied from ~370 kg m^{-3} close to the pith to ~600 kg m^{-3} at ring 10 (Figure 4B). The general trend was an increase in wood density with increasing cambial age up until the 10th annual ring after which it then began to decline. No gradient change was observed in ring width after the 10th annual ring but a similar observation was displayed in the latewood percentage (Figure 4C). There were no clear differences in the wood density between spacing treatments within the first six annual rings, after which the general trend for equivalent annual rings was an increase in wood density with increasing stems ha^{-1}. These differences were most pronounced between 403 stems ha^{-1} and the other treatments. The model parameters (equation (2)) (AIC = 4941) were significantly different between wide and closer spacing treatments, both α_i and β_i, showing that the variation of wood density was affected by planting spacing.

The model for wood density given by equation (3) (AIC = 4867) (Table 3, Figure 5B) showed that spacing treatment did not significantly influence the initial density of wood ($\alpha_{0,i}$). Ring width, however, did not emerge as being a significant contributor to differences in initial wood density between different spacing treatments ($\alpha_{1,i}$). Both components of the radial rate of change in wood density ($\beta_{0,i}$ and $\beta_{1,i}$) was significantly influenced by spacing treatment. This was evident as ring width differed between treatments especially near the pith, while wood density displayed no clear differences in the same region. The rate parameter $\beta_{0,i}$, for a given ring width, increased significantly with increased stems ha^{-1} while ring width also had an increasingly negative influence on modelled wood density in closer spacings ($\beta_{1,i}$, Table 3). Accordingly, the predicted wood density between treatments were similar near the pith, but the incline rate clearly increased from 403 stems ha^{-1} to 1808 and 2981 stems ha^{-1} (Figure 5B). The modelled wood density curves for 1808 and 2981 stems ha^{-1} were nearly completely overlapping (Figure 5B).

Relationship between properties

Correlations between measured properties were reported in Table 4. Slenderness displayed insignificant correlations with wood density, LW percentage and tree height (despite being a function of tree diameter and tree height) but was strongly related to DBH (r = 0.86). Although slenderness also correlated significantly to MOE, a weak relationship was still displayed (r = 0.42 or r^2 = 0.18). MFA was the property with the highest Pearson correlation with MOE (r = -0.66) which weakened somewhat when only considering the outer 20 mm of increment cores. Wood density and LW percentage both correlated significantly with ring width, with an especially high correlation coefficient between wood density and LW percentage (r = 0.89).

Table 4: Pearson correlation coefficients between the mean tree variables and wood properties measured or calculated from all 40 increment cores

Variable	DBH	Height	Slenderness	Ring	Density	LW %	MFA	MOE*
DBH	1	**0.65**	**-0.86**	**0.8**	-0.26	-0.19	**0.49**	**-0.51**
Height		1	-0.24	**0.58**	0.01	0.05	0.3	-0.19
Slenderness			1	**-0.63**	0.28	0.23	**-0.39**	**0.42**
Ring width				1	**-0.43**	**-0.36**	**0.48**	**-0.42**
Density					1	**0.95**	-0.11	0.20 (0.24)
LW %						1	-0.03	0.05
MFA							1	-0.66 (-0.43)
MOE								1

*Values in parentheses indicate correlations between MOE and the mean wood properties for the last 20mm of increment cores; bold correlations are significant at $P < 0.05$.

Simulated lumber properties

The pith boards of the 2981 stems ha^{-1} treatment had a mean MFA of 19.3° compared with 30.3° for 403 stems ha^{-1}—a 57 per cent increase (Figure 6). Wood density showed a similar trend of increasing with board position and stems ha^{-1} except for the wood density of the pith boards for 403 stems ha^{-1}, which was quite high due to the high wood density values of the first three rings from the pith for this treatment. The 403 stems ha^{-1} treatment had trees with greater diameters and displayed the capacity to produce additional boards, but in terms of MFA and wood density, its best board (second from the pith), was still worse than the first boards next to the pith of 2981 stems ha^{-1}.

Discussion

It was expected that the closely spaced treatments would result in straighter trees as some studies have found that decreased planting spacing and competition for sunlight and other growth resources from evenly planted neighbouring trees can help direct growth straight upwards (Woods et al., 1992; Smith et al., 2014). This was partly supported by the finding in our study that the 403 stems ha^{-1} treatment had the least straight stems. However, an inconsistent trend points to some opposing effects. Part of the reason for this might be that certain soil nutrient deficiencies has been shown to result in stem deformity (Birk, 1991; Turvey et al., 1992). Severe competition between densely planted trees might therefore result in nutrient deficiencies for individual trees. The high RD of both 1808 and 2981 stems ha^{-1} is close to the defined level of imminent mortality of 12 for South African pines (Kotze and du Toit, 2012) indicating severe competition which could possibly have led to nutrient deficiencies for some trees. We hypothesize that another reason for decreases in stem straightness at closer spacing might be the high mortality rate (Table 1), which can cause uneven openings in the canopy. Poor stem straightness might result from the tree positioning itself towards openings in the canopy. The low survival rates in the two most closely spaced treatments (Table 1) supports this hypothesis.

Another factor that should be considered in future studies, but which did not play a role in this study, is the influence of thinning. Treatments with higher stand densities did not always result in straighter stems, but when thinning is performed, they provide the opportunity to remove more trees with poor stem straightness earlier in the life of the trees—thereby removing competition for better shaped trees to grow faster (Macdonald and Hubert, 2002). Planting spacing should thus be considered in combination with possible thinning regimes when evaluating tree form at final harvest. Stem straightness has a big influence on sawmill volume recovery and processing efficiency (Carino et al., 2006; Hamner et al., 2007; Yerbury

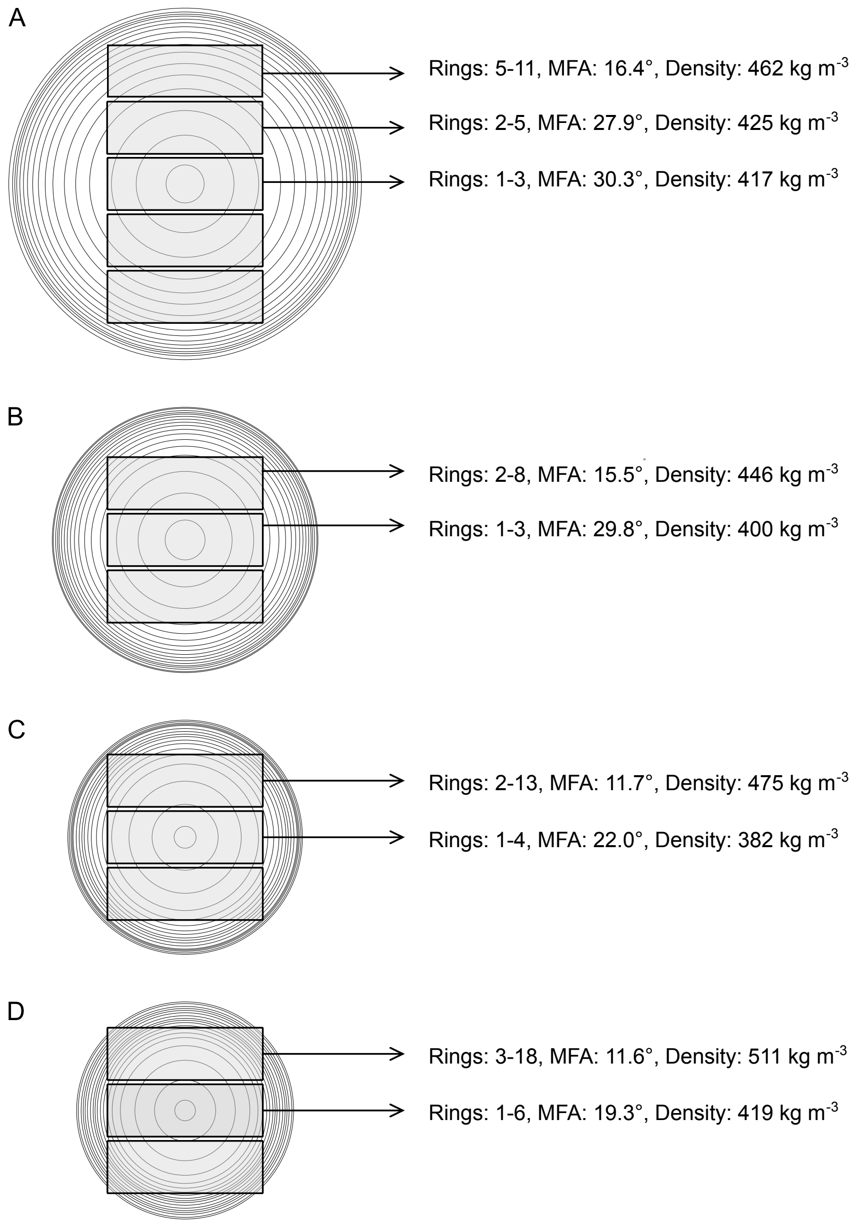

Figure 6: The mean ring widths for 403 stems ha^{-1} (A), 1097 stems ha^{-1} (B), 1808 stems ha^{-1} (C) and 2981 stems ha^{-1} (D), overlaid with a 40 x 120 mm cant sawing strategy drawn to scale including a saw kerf of 4 mm. Maximum and minimum rings are indicated for each board position with their mean MFA and wood density.

and Cooper, 2017) and future work should focus on a better understanding of the influence of growing space, manipulated through both planting spacing and thinning, on stem straightness of *P. patula*.

In terms of wood properties, the overall effect of growing space was much clearer. The strong positive influence of planting spacing on the dynamic MOE (Figure 3) was higher than that found in studies on any other softwood species. In studies by Waghorn et al. (2007a,b) and Lasserre et al. (2005) on *P. radiata*, Roth et al. (2007) on *Pinus taeda* and Froneman (2014) on *Pinus elliottii*, the mean dynamic MOE gradients varied between 0.8 and 1.2 MPa ha stem^{-1} increases in stems ha^{-1}, which was roughly 50 per cent lower than found in this study (1.8 MPa ha stem^{-1}). However, the range of planting spacing in our study was greater than that of the other studies with the exception of Froneman (2014).

At the individual tree level, the poor relationship between MOE and slenderness was contrary to the results of various other studies that found a comparatively good linear relationship. Results by Watt et al. (2006b, 2009), Waghorn et al. (2007b) and Lasserre et al. (2009) on *P. radiata* found slenderness to explain 49–71 per cent of the variation in tree dynamic MOE. Interestingly, Lasserre et al. (2008) found stem slenderness to seemingly account for variation in tree MOE as a previously significant effect of planting spacing became non-significant once adjustments were made for differences in slenderness (adding slenderness as a covariate), suggesting tree slenderness to be the main mechanism through which closely spaced trees improve wood stiffness. Contrastingly, Roth et al. (2007) found the effect of planting spacing on the MOE of young *P. taeda* to remain significant after adjustments for stem slenderness, with the authors suggesting environmental and genetic factors to control the outerwood dynamic MOE through mechanisms other than stem form. Similarly, it seems as if the increased MOE with increasing stems ha^{-1} from this study was not only mediated through tree slenderness.

MFA differences observed in our study were similar to results of previous studies displaying reduced MFA with closer spacing at either establishment (Lasserre et al., 2009; Watt et al., 2011) or after thinnings (Moore et al., 2015; Auty et al., 2017), although our study covered a wider range of tree spacing. In general, our study found a positive influence of growth rate on MFA, similar to various other studies (Lindström et al., 1998; Sarén et al., 2004; Auty et al., 2013). Furthermore, a residual effect of planting spacing on the variation of wood properties over and above cambial age and ring width was also evident. This highlights the limitations associated with the common use of ring width (growth rate) as a proxy for spacing since it may not fully capture cause and effect (Zobel, 1992; Auty et al., 2017). It remains unclear why a tree would exhibit lower MFA when planted more densely and growth (or ring width) is reduced, if not due mainly to slenderness and growth rate differences. Other explanations for the apparent differences in wood properties with tree spacing may include the ratio of live crown length to tree height (Kuprevicius et al., 2013).

The lower MFA near the pith with increasing stems ha^{-1} in this study (Figures 4A and 5A), is an important finding. This inner region of the stem forms part of the boards which usually display the worst MOE in logs of *P. patula* (Wessels et al., 2014), and other species (Xu and Walker, 2004; Vikram et al., 2011; Moore et al., 2012, 2013; Rais et al., 2014; Wessels and Froneman, 2015). The generally high MFA values near the pith is part of the reason for the lower stiffness of pith boards, as saplings with small diameters require more flexibility to prevent fracture of the stem when subjected to wind loading (Barnett and Bonham, 2004; Burgert, 2006). This is one theory that could also possibly explain why MFA generally improved with increasing stems ha^{-1}. Closely planted trees should result in less wind exposure (Green et al., 1995) which has been shown to decrease taper while increasing wood stiffness (Gardiner et al., 1997; Spatz and Bruechert, 2000; Bascuñán et al., 2006; Brüchert and Gardiner, 2006). The decrease of 5° in MFA, on average, from 403 to 1097 stems ha^{-1} and from 1097 to 1808 stems ha^{-1} (only for some rings) could potentially be of significant value to structural lumber producers. For *P. radiata*, a 5° improvement in corewood has been suggested to be enough to represent an increase in wood stiffness of up to 50 per cent (Walker and Butterfield, 1996).

In a study by Wessels et al. (2015a) it was shown that the mean wood density, MFA and ring width, calculated from year rings could be used to successfully predict the stiffness of boards. Ring width is an important property since it affects the geometry of sawing and subsequently the individual lumber properties. Therefore, although the improved MFA from 1097 to 1808 stems ha^{-1} was restricted to only the first few rings, these growth rings will occupy a significant proportion of volume within pith boards as the growth rate is typically greatest at the pith (Figure 6). Furthermore, in trees harvested at a young age, pith boards constitute a large percentage of the total recovered product. Rings closer to the bark, with better mechanical properties, are unfortunately less prevalent as they are mostly chipped away in the sawmilling process. It must be noted that for some increment cores, pith eccentricity and compression wood may have had a negative influence on the accuracy of some ring width and wood property measurements respectively.

It was noted that the earlier the apparent onset of competition commenced in a stand of trees, the sooner the MFA began to stabilize. The point where maturewood begins is often defined as the radial position where wood properties have stabilized—usually after a transition zone (Cown, 1992; Zobel and Buijtenen, 2012). When only considering MFA, it seems as if this transition then occurs earlier for plantations with increased stems ha^{-1}. On the other hand, it was also apparent that the radial MFA and wood density gradients decreased with decreasing stems ha^{-1} (Figure 4A and B), which has also previously been reported (Malan et al., 1997; Moore et al., 2015). In terms of wood quality, a low MFA gradient is usually considered a positive trait that will guard against uneven shrinkage which leads to warping of lumber products (Huang et al., 2003; Malan, 2010).

An interesting result was the decline in wood density after the 10th annual ring (Figure 4B). Distinct shifts in wood density profiles have previously been reported (Moore et al., 2015). However, this decline was consistent for all the spacing treatments and was only mirrored in LW percentage, suggesting that it was probably a function of growing conditions not related to spacing (Cregg et al., 1988; Filipescu et al., 2014).

Conclusions

In summary, the narrow spacing treatments (1808 and 2981 stems ha^{-1}) gave three distinct advantages in terms of wood properties compared with the wide spacing treatments (403 stems ha^{-1}): First, the absolute mean MFA values of the more closely spaced treatments were significantly lower for rings close to the pith. Second, based on MFA, the juvenile core seems to be restricted to the first seven or eight year rings from the pith, whereas for the 403 stems ha^{-1} treatment, the juvenile core transition only started at rings 10 or 11. Third, due to suppressed growth, the centre boards of narrow spacings will contain more mature rings than that of the 403 stems ha^{-1}. Combined, this resulted in improved MFA properties at similar board positions for closer spacings which, excluding the pith boards, was also the case for wood density. Comprehensive sawing and lumber testing studies will be required to evaluate the effect of planting spacing on final product properties. After accounting for differences due to ring number and ring age, spacing treatment had a significant effect on both the initial MFA and its rate of change with age. For wood density, this remaining effect of spacing treatment was only displayed in its radial rate of change.

The results of this study showed that increased stems ha^{-1} has the potential to improve the underlying wood properties controlling lumber stiffness. It might be possible to reap the benefits of closely spaced plantations to control wood properties during juvenile growth and then thin a stand to inhibit mortality and potentially improve the average stem form. The sample size in this study was limited and so additional studies are required to reinforce these results. Future work should also include destructive sampling of trees and processing into lumber to evaluate the effect of planting spacing on the actual final product. Stem straightness at the final harvest could possibly also be improved using narrow spacing and thinning but results were not conclusive. More work is required to understand the effect of planting spacing on stem straightness as well as the possible effect of thinning.

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Chapter 3

The effect of stand density management on *Pinus patula* lumber properties

Justin Erasmus · C. Brand Wessels[1]

Absrtact Rapid growth rates and the accompanying reduced rotation ages of forest plantations have resulted in increased proportions of juvenile wood. Growing space markedly influences growth rate and may be manipulated by stand density management. The objective of this study was to evaluate the effect of stand density on the modulus of elasticity (MOE), modulus of rupture (MOR) and other selected properties of young (16-20 years) South African-grown *Pinus patula* lumber. Thirty-seven trees from two commercial stands were processed into 71 logs, cant-sawn into lumber, and tested for MOE, MOR, wood density, and distortion. The first stand was planted at 1334 stems ha^{-1} and thinned to 827 stems ha^{-1} at age 11. The second stand was planted at 1667 stems ha^{-1} and was unthinned. Lumber from a previous study on 17 different commercial stands from more conventional (lower) stand density management regimes were also analysed using linear mixed-effects models. Only lumber from the 1667 stems ha^{-1} stand conformed to the requirements for structural use, and had a considerably higher mean MOE of 8967 MPa compared to 7134 MPa for the 1334/827 stems ha^{-1} stand and 5556 MPa for the more conventional stands. MOR values were adequate for all stands. Unlike previous studies on other species, slenderness did not seem to have a profound effect on the MOE of the lumber from these *Pinus patula* trees. Stand density management therefore has the potential to increase lumber stiffness of *Pinus patula* and should be considered as a forest management intervention for wood quality improvement by saw log growers in South Africa.

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Introduction

Plantation forestry continues to expand significantly on a global scale, occupying an estimated 140 million ha in the year 2005, with an average annual rate of increase of 2.8 million ha per year during the period 2000-2005 (FAO, 2005). In 1980, there were 18 million ha of forest plantations, compared to 44 million ha in 1990 and 187 million ha in 2000 (Carle et al., 2002). In South Africa, the total area of intensively managed forest plantations stands at approximately 1.2 million ha with *Pinus patula* accounting for half (50.4%) of the total softwood plantation area in 2016 (DAFF, 2017). Approximately one million hectares of *P. patula* has been planted worldwide, mainly in southern and eastern Africa (Dvorak et al., 2000).

Afforestation in South Africa is presently constrained by a lack of suitable and available land (Zwolinski and Bayley, 2001; Louw, 2006). The total afforested area has declined from approximately 1.5 to 1.2 million ha during the period 1996-2016 (Godsmark, 2017). At the same time, the strategy of softwood plantation management has shifted towards accelerated tree growth through tree breeding and intensive silvicultural practices in order to supply the country's growing need for lumber and to reduce the cost per unit of lumber produced (Malan, 2003; du Toit et al., 2010; Wessels et al., 2014). The rapid growth enables forest companies to adopt shortened rotations; reducing the time between successive yields of merchantable log classes. Furthermore, investing in such a system reduces the risk of damage due to fire or insects (Griess et al., 2016).

Saw logs entering the market from these fast-growing resources are likely to contain a considerable proportion of juvenile wood (Walker and Nakada, 1999). This wood type is usually considered inferior to that of mature wood, mainly due to its characteristically high variability in virtually all properties—a feature that affects the performance of structural lumber (Kennedy, 1995; Xu and Walker, 2004; Malan, 2010). It is certainly recognized worldwide that such intensively managed systems have secured financial benefits at the expense of product quality and consequently utilization (Cown, 1992; Zobel and Sprague, 1998; Larson et al., 2001; Moore and Cown, 2017). Burdzik Burdzik (2004) performed an in-grade testing study of visually graded S5 lumber (the lowest South African structural grade) from four sawmills and reported that all of the mills produced graded lumber which did not conform to the bending strength or stiffness requirements of SANS 10163-1 (2003). Recent studies reinforce concerns that the wood material of various young South African saw-log resources has changed, affecting wood stiffness negatively (Wessels et al., 2011, 2014; Dowse and Wessels, 2013). This is also true for other international species (Biblis, 2006; Dahlen et al., 2012). The stiffness or modulus of elasticity (MOE), a measure of the relationship between stress and strain, is one of the most important mechanical properties for users of structural lumber (Moore, 2012; Wessels and Petersen, 2015), which is the main product category (±70% of sawn wood) for local sawmills (Crickmay and Associates, 2015). In order to grade and sell structural lumber, it is imperative that an acceptable percentage of lumber conforms to the requirements of grade characteristic values.

The ideal would be to produce good quality wood while maintaining shorter rotations. Increasing the stand density may be advantageous in that regard, having displayed the potential to improve mechanical properties of various species either at establishment or after subsequent thinning (Lasserre et al., 2005; Roth et al., 2007; Waghorn et al., 2007a; Clark III et al., 2008; Moore et al., 2009; Antony et al., 2012; Rais et al., 2014). South African studies on locally grown softwoods support the positive influence of higher stand densities at establishment, improving the wood stiffness of *Pinus radiata* (Wessels and Froneman, 2015) and *Pinus elliottii* sawn lumber (Froneman and Wessels, 2018). However, the results of these studies are highly species and site specific and need verification beyond these parameters. Overall, high stand densities may be a useful management technique for growers and processors of saw logs focused on producing structural lumber. Moreover, the subsequent reduction in growth rate incurred at the individual tree level may not necessarily have an adverse effect on volume production per unit forest area and may even increase it, depending on site conditions and rotation age (van Laar, 1978; Carter et al., 1986).

A recent study proved the positive relationship between planting density and the basic properties of wood density (WD) and microfibril angle of *P. patula* (Erasmus et al., 2018). In that study, however, destructive testing of trees and assessment of sawn lumber properties was not possible. Due to a lack of available *P. patula* spacing trials for destructive testing at the time of this study, commercial stands with large differences in the competitive environment of individual trees were utilised for a comparative study on mechanical lumber properties. The main objective of the study was therefore to evaluate the effect of increased inter-tree competition of *P. patula* stands on the sawn lumber mechanical and other selected properties. Results from this study may assist in developing plantation management regimes aimed at cultivating trees with improved wood properties.

Materials and methods

Experimental layout

The study used material from two commercial stands of 17- and 18-year-old *P. patula* located in the Mpumalanga province of South Africa. Although local difference may have existed, both sites were selected from land types that had the same characteristics; mean annual temperatures of 16.2 °C, a mean annual precipitation of 887.7 mm and clay loam soil with average depths of 366 mm. Both sites were classified as moderately steep crestal terrain with stony shallow shale and quartzite soils tonguing into weathered rock (also classified as Glenrosa soil). The selected stands were in proximity (approximately 2 km apart) and were planted at 1334 stems ha^{-1} (stand S; Montrose plantation) and 1667 stems ha^{-1} (stand T; Montrose plantation). Stand S was thinned to 827 stems ha^{-1} at 11 years of age while stand T was left unthinned and had a stand density of 1560 stems ha^{-1} at the time of sampling (Table 1). Both stands were pruned during the fifth, seventh and ninth year to a height of 2, 3.5 and 5.5 m, respectively. The seed for both stands was first generation bulk seed orchard mix from Zimbabwe.

Table 1: General data for sample trees and stands for both this study (stands S and T) and an earlier study (stands A-R) by Wessels et al. (2014)

Stand	Initial stems ha-1	Remaining stems.ha-1*	Thinning ages (yrs)	Final stems ha-1	Age (yrs)	Site Index 20	Number of trees sampled	Mean DBH (cm)	Mean Tree length (m)	Mean Slenderness
S	1334	827	11	827	18	20.2	20	29	23.8	0.82
T	1667	1560	-	1560	17	20.1	17	27.4	19.8	0.72
A	1372	653 / 459 / 275	2008/11/18	275	17	23.9	10	36	20.9	0.59
B	1372	645 / 409 / 288	8/13/17	288	19	23.2	10	33.8	21.8	0.64
C	1372	720 / 451 / 275	10/16/20	275	16	22.6	10	26.2	18.4	0.71
D	1372	579 / 395 / 275	10/13/17	275	17	26.5	10	32.7	22.3	0.69
E	1111	611 / 340	10/15	340	17	21.7	10	30.2	18.4	0.61
F	1372	650 / 423 / 312	9/14/17	312	20	20.9	10	32.3	20.1	0.61
G	1372	657 / 458 / 230	8/15/19	230	19	26.3	10	31.9	23	0.75
H	1372	588 / 417 / 258	10/13/18	258	17	24.8	10	27.6	20.8	0.76
I	1372	650 / 397 / 148	8/13/17	148	19	25.8	10	36.5	23.8	0.66
J	1372	631 / 381 / 237	8/13/19.5	237	19	25.7	10	37.4	23.8	0.64
K	1372	622 / 401 / 275	7/13/17	275	16	21.6	10	29.1	18	0.63
L	1372	680 / 497 / 284	8/11/16	284	20	29.6	10	34	27	0.8
M	985	585 / 306	11/18	306	17	24.3	10	31.4	20.6	0.66
N	816	395 / 275	15/18	275	19	17.9	10	26.9	16.4	0.63
O	816	397	14	397	16	23.3	10	27.8	19	0.7
P	1372	642 / 425 / 275	8/14/18	275	18	25.6	10	29.4	22.8	0.79
R	1372	595 / 435 / 278	8/13/18	278	19	26.1	10	33.4	24	0.73

*Remaining stems ha-1 corresponds to the thinning event

Results from 17 other stands of similar age, and planting densities between 816 and 1372 stems ha^{-1}, from a previous study on the MOE of *P. patula* lumber from the same area (Wessels et al., 2014) were also available for comparison purposes (Table 1). These stands were mostly thinned earlier than stands S and T, and were regularly thinned so that trees rarely reached a very competitive growth environment (see Table 1). The seed for 16 of these 17 stands were second generation

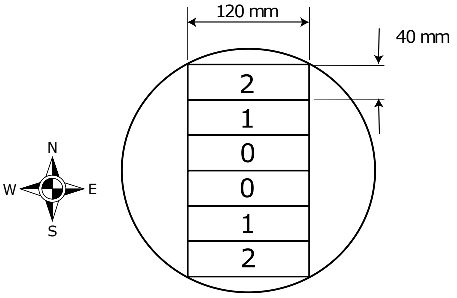

Figure 1: The cant sawing pattern used when processing lumber

seed from the company's (Safcol) own seed orchards situated at Mac-Mac in the Mpumalanga area. Seed for stand C was from another South African company (Mondi Ltd.). For comparative purposes stand S can be considered a stand with a high level of inter-tree competition throughout its life, stand T (which was thinned late) had a lower level of inter-tree competition, whereas stands A-R had very low levels of inter-tree competition due to lower planting densities and regular thinning. Stands A-R were selected specifically to include the maximum possible site variation in the Mpumalanga escarpment area. It is therefore unlikely that stands S and T, also situated in this area, will have site characteristics falling completely outside the range covered by sites A-R. Interested readers are referred to previous studies that used the same sample material (stands A-R) but had different objectives dealing with a variety of site, growth and wood property factors (Louw and Scholes, 2002; Kipuputwa et al., 2010). The studies concerned with wood property variation (Dowse and Wessels, 2013; Wessels et al., 2015b) paid little interest in stand density management at the time; different sampling strategies were used which limited a combined data analysis with stands S and T.

Measurements (stand S and T)

The diameter at breast height (DBH) was measured on the standing sample trees while tree length was measured after felling. Only trees with DBH greater than 23 cm were included in the study. Six out of the 26 trees in stand S, and 12 out of the 29 trees in stand T were smaller than 23 cm. The reason for this was to ensure a minimum small end-diameter of around 16 cm for saw logs—smaller logs could not be processed into sawn boards. This also mirrors industrial practice where smaller logs are processed into either poles or chips for pulp. The slenderness for each tree was simply calculated as the ratio of tree length (m) and DBH (cm).

Two 2.4 m logs were harvested, where possible, directly above a height of 1.3 m and 5.5 m, from each tree—producing 71 logs which were then processed into 260 boards. Log end-templates, similar to that described by Smith et al. (2003), were applied to log ends in order to track any given board after processing using a cant sawing pattern (Fig. 1). All lumber had cross-sectional wet dimensions of 40 x 120 mm. Boards were kiln-dried to a target moisture content of 12%. The range of rings present in a given board was counted by reconstructing logs using the templates. It was also possible to locate the last latewood produced and therefore the mean, maximum and minimum cambial age (CA) and tree age could be determined for each board. The ring width, defined as the perpendicular distance from the start of earlywood to the end of latewood, was also measured using high resolution digital (scaled) images of board ends and the image analysis software, ImageJ (Abramoff et al., 2004).

WD, moisture content and the distortion (twist, bow and spring) of each board were measured according to SANS 1783-2 (2013). Four-point bending tests were performed according to the guidelines set out in SANS 6122 (2014) using an Instron tensile/bending apparatus. The MOE was calculated using a 4-point setup between the loads 400 and 2200 N. The load range was slightly adjusted for instances where load -deflection curves were not linear. All tests done on lumber were conducted with the same equipment used by Wessels et al. (2014).

Statistical analysis

The R system for statistical computing (R Core Team, 2018) was used for all data analysis. The hierarchical structure of the data warranted the application of linear mixed-effects models (Lindstrom and Bates, 1990; Pinheiro and Bates, 2000) where a nested structure was assumed for the random effects ($\sim N(0, \sigma^2)$) of tree, log position and board position. Only fixed and random effects that contributed significantly to the models, determined through Chi-square based likelihood ratio tests (at $\alpha = 0.05$ level of significance) and Akaike's information criterion (AIC Akaike, 1974), were retained. Lower AIC values are typically preferred. Each of stands A-R had insufficient MOE and MOR data to be included in a formal test of significance that compares all stands (A-T), and thus were excluded from all models fitted with MOE and MOR as dependent variables. In such cases, only the general trends of stands A-R are reported to assist in interpreting the effect of stand competitive environment. Likewise, lumber distortion for all stands were also informally compared due to the generally low values and different measuring units between the two studies for twist. The following model was formulated to examine the variation of lumber properties:

$$Y_{ijklm} = \mu + S_i + L_k + B_l + (SL)_{ik} + (LB)_{kl} + (SB)_{ik} + \alpha_{ij} + \alpha_{ijk} + \alpha_{ijkl} + \epsilon_{ijklm} \quad (1)$$

where Y_{ijklm} is the MOE, MOR or WD of an individual board; μ is the grand mean; S_i, L_k and B_l are the fixed effects of the i^{th} stand, the k^{th} log and the l^{th}

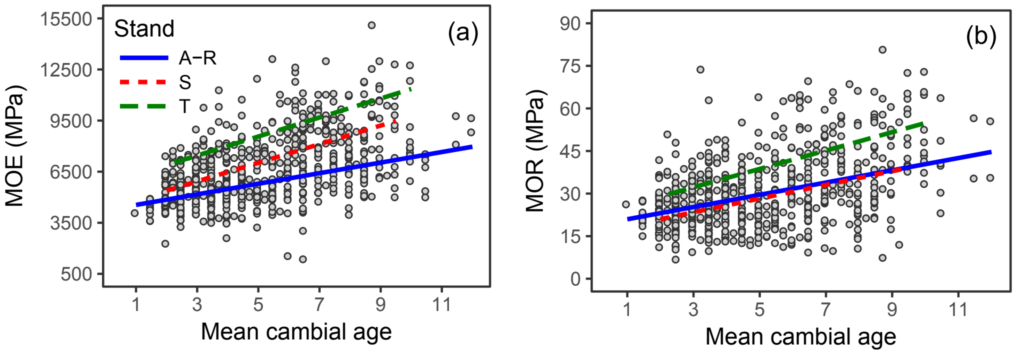

Figure 2: The radial variation of MOE (a) and MOR (b) across mean cambial ages for different stands

board position respectively; $(SL)_{ik}$, $(LB)_{kl}$ and $(SB)_{ik}$ are the interaction terms for the respective levels of factors S_i, L_k and B_l; α_{ij}, α_{ijk} and α_{ijkl} are the random effects at the tree, log and board position levels respectively. Multiple-comparisons (Fischer's LSD test) between factor-level means were made with a pairwise significance threshold of $\alpha = 0.05$.

Results

Bending stiffness (MOE)

The MOE for boards varied from 1407 to 15150 MPa and displayed a significant and positive relationship with CA ($R^2 = 0.27$, $p < 0.001$) (Fig. 2). For a given CA, MOE was greatest for stand T, followed by stand S, with stands A-R having the lowest MOE. Differences between stand S and stands A-R increased with CA due to the lower radial gradient of MOE for stands A-R. There was no significant effect of the interaction between board position and stand ($p = 0.3944$). The mean MOE of the pith boards of stand T was similar to that of the outer boards of stand S while the outer boards of stand T had a mean MOE significantly greater than the rest (Fig. 3a). As expected, MOE increased with board position (Fig. 3a and 4a). For stand S, the mean MOE of boards from the bottom logs was significantly lower than that of the top logs, whereas there was no difference due to log position for stand T (Fig. 3b). Differences in MOE between board position 0 and 1 increased from the top log to the bottom (Fig. 3c). Overall, the mean and 5th percentile MOE of stands A-R were both below the values required for grade S5 lumber (Table 2). These values were also much lower than that of stand S, which were 20% and 28% lower than that of stand T respectively. Stand T was the only stand to comply with MOE requirements for grade S5 (Table 2).

Table 2: Mean and 5th percentile (in perenthesis) values of properties measured on lumber

Property	Stand	Board position			All**	Required/ limit*
		0	1	2		
MOE	A-R	5126	5915	6862	5556 (3877)	7800 (4630)
	S	5948	8146		7134 (4214)	
	T	7760	9940		8967 (5832)	
MOR	A-R	26	29	38	30 (15.0)	11.5
	S	23	33.2		29 (12.9)	
	T	23	33.2		41 (13.1)	
Density	A-R	415	424	445	424	360
	S	413	425		435	
	T	463	511		490	
Twist***	A-R	17.9	12	8.7	13.7	10 (mm m^{-1})
	S	1.8	1.7		1.7	4-5 (°)
	T	2.1	1.9		2	4-5 (°)
Spring	A-R	2.7	2.5	2.3	2.6	15
	S	0.7	0.6		0.6	
	T	1	0.7		0.8	
Bow	A-R	2	2.4	2	2.2	10
	S	1.7	1.5		1.6	
	T	2	1.4		1.7	
Ring width	A-R	12.7	10.4	8.1	10.8	
	S	10.2	6.9		8.4	
	T	8.9	6.7		7.7	
Max CA	A-R	5.7	8	10.8	7.5	
	S	5.7	10.6		8.3	
	T	6.8	11.1		9.2	
Max real age	A-R	-	-	-	-	
	S	7	12			
	T	9	14			

*The required values and limits for structural use (S5) according to SANS 1783-2 and SANS 10163-1.

**Values here may include additional board position.

***Twist was measured in mm m^1 for stands A-R and in degrees for stands S and T.

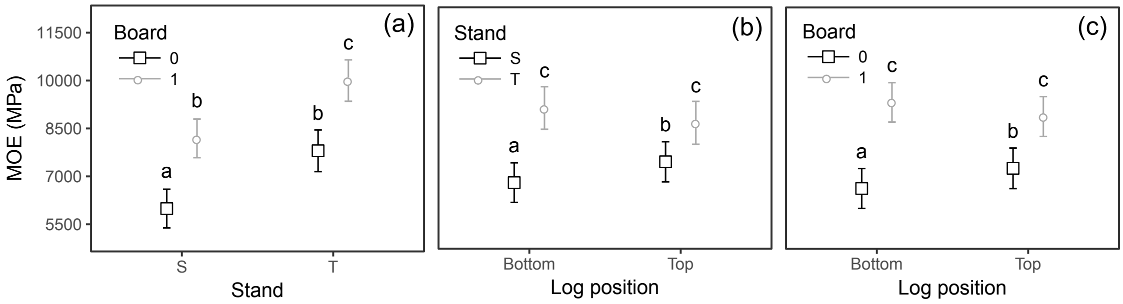

Figure 3: Means and 95% confidence intervals of MOE for the interactions between stand and board position (a), stand and log position (b), and board and log position (c). Different letters denote significant differences.

Bending strength (MOR)

Fig. 4b depicts the variation of MOR which followed the same overall trends of MOE (with the exception of stands N and O which decreased from board 0 to 1), and displayed a moderate association with MOE ($R^2 = 0.55$, $p < 0.001$) which increased markedly when only considering stands S and T ($R^2 = 0.70$). There was no significant effect of the interaction between board position and stand ($p = 0.4428$). Like MOE, the absolute change in MOR from board position 0 to 1 was also greater for stands S and T when compared with stands A-R (Fig. 4). Similar to MOE, the mean MOR of the pith boards of stand T was the same as that of the outer boards of stand S (Fig. 5a). The same trends for MOR, as for MOE, were observed in terms of the effect of board and log position (Fig. 5). The 5th percentile MOR for stands A-R was 15 MPa which was above the characteristic value for grade S5 and close to the requirement for the next structural grade S7 (15.8 MPa, Table 2). Similarly, the 5th percentile bending strength for stands S and T were higher than required. The mean MOR of stand S was 29% lower than that of stand T (Table 2).

Wood density

WD followed the same overall pattern of variation as both MOE and MOR, in terms of variation between stands, and increases with board position (Fig. 6). There was no significant effect of the interactions between stand and log position ($p = 0.179$) and between log and board position ($p = 0.3219$). A highly significant interaction between stand and board position ($p < 0.0001$) meant that the differences in WD between board positions increased from stands A-R to stands S and T (Fig. 6). It is interesting to note that the stands with the highest WD boards from A-S (stand S and C) had outer boards of similar WD to the pith boards of stand T (not indicated in Fig. 6). The mean WD for board position 1 of stand T was

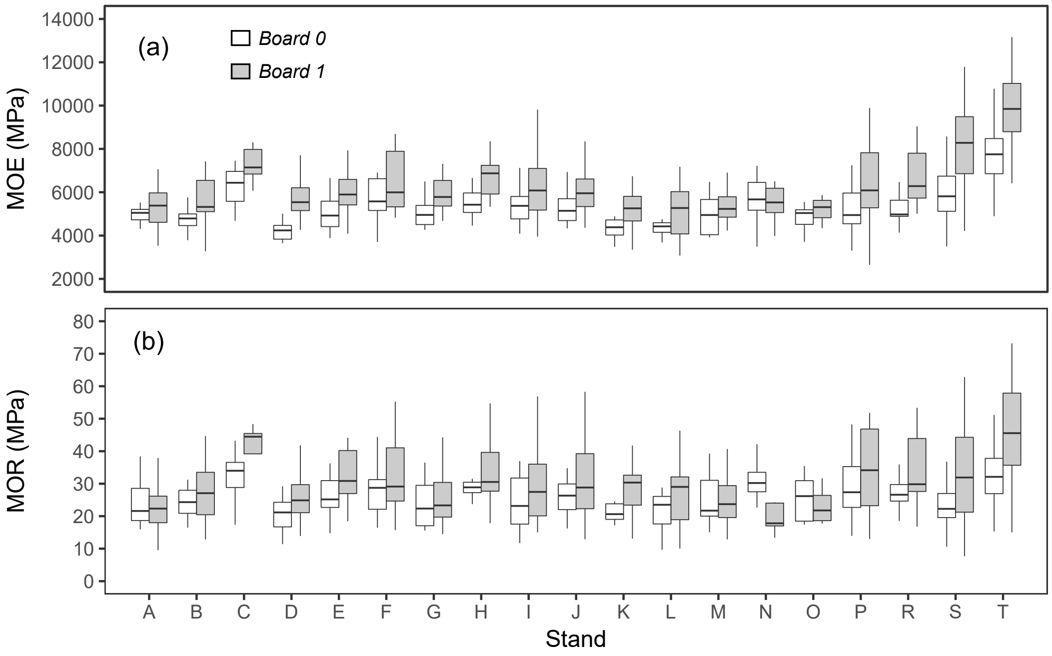

Figure 4: Boxplots of MOE (a) and MOR (B) for each stand

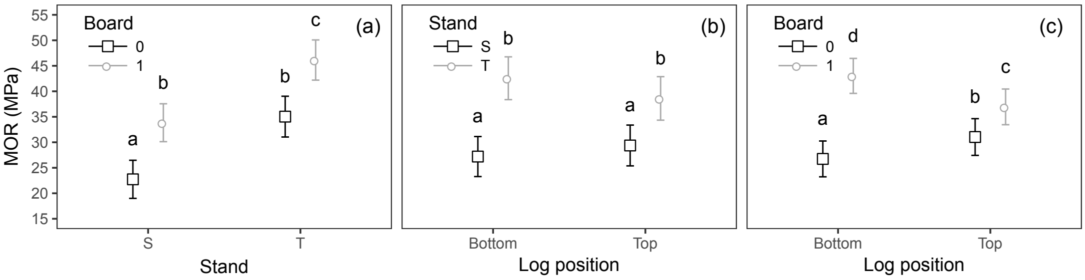

Figure 5: Means and 95% confidence intervals of MOR for the interactions between stand and board position (a), stand and log position (b), and board and log position (c). Different letters denote significant differences.

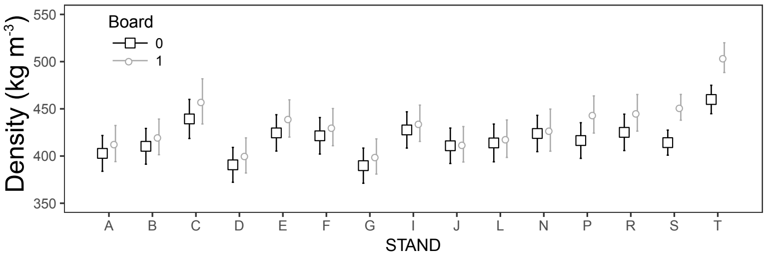

Figure 6: Means and 95% confidence intervals of WD for the interactions between stand and board position.

significantly greater than all other factor level combinations. Log position had a significant effect on WD ($p = 0.0139$) where WD for the top logs (427 kg m^{-3}) was significantly lower than for the bottom logs (433 kg m^{-3}). All stands met the minimum requirements for grade S5 (Table 2). Furthermore, Stands S and T were even sufficient for grades S7 (425 kg m^{-3}) and S10 (475 kg m^{-3}) respectively.

Distortion (bow, spring and twist)

The average bow and spring in all stands were well below the limits for structural use (Table 1). The twist was also relatively low for stands S and T but was higher than the limits for stands A-R. Take note that twist was measured differently in the study involving stands A-R to the measurement used for stands S and T. For stands A-R , twist decreased with board position [significantly according to Wessels et al. (2014), Table 1]. For stands A-R, only board position 2 had a mean twist below the limit and therefore more than half of the lumber was rejected based on this property in the study of Wessels et al. (2014).

Ring width and cambial age

As expected, the mean ring width reduced with increasing stand density (Table 2). The maximum CA therefore increased from stands A-R to stand S to stand T in the case of board 1. For board 0, only stand T had higher maximum CA and stands S and A-R had the same maximum cambial age. In general, the maximum CA at equivalent board positions therefore generally increased with inter-tree competition due to decreased radial growth.

Discussion

Based on a previous study on the positive effect of planting density on the dynamic MOE of *P. patula* (Erasmus et al., 2018), it was expected that stand T would have lumber with a higher mean MOE than stand S. However, the magnitude of the difference was unexpected compared to the differences between stands A-R (Figure 4), which had a mean MOE that was inadequate for structural lumber (Table 2). The mean MOE of stand T (8967 MPa) was 61% higher than that of stand A-R and 26% higher than that of stand S. It is clear that MOR is sufficient for this resource across the studied spacing range and that MOE is the limiting property as only stand T had sufficient MOE for structural use. Note that the planting density of stand T was considerably higher than the norm for *P. patula* saw-log plantations in South Africa, which is more similar to that of stands A-R. In addition, the thinning age of 11 years for stand S, considering the planting density, was later than the norm for *P. patula* from this area. If the magnitude of this improvement in mechanical properties could be ascribed exclusively to stand density, it will mean that stand density management could independently serve as an excellent method to manage lumber stiffness and strength of fast growing *P. patula* in South Africa.

Most properties of juvenile wood display moderate to high inheritance, including the age of transition to mature wood (Zobel and Jett, 2012; Moore and Cown, 2017), which means that the results of this study need to be interpreted in light of the differences in genetic material if the influence of stand density is to be correctly understood. Although genetics may have had some influence on the differences observed in MOE between the three groups of seed, it does not explain the large difference observed between stands S and T, which were both planted from seed of the same source. The differences in site quality may also have caused some of the variation in MOE, although there were some sites (i.e., stands A, B, S and T) that had similar soil types and were close in proximity, but had markedly different mean MOE (Fig. 4), and were planted with different stand densities and genetic material. Stands S and T were also close to each other with similar soil and site quality (Table 1) and still had a large difference in MOE. Of all stands A-R, three (stands C, D and H) had a similar planting density and first thinning age as stand S (Table 1). Of these three, stand C was comparable to stand S in terms of MOE, despite differences in genetic material. Furthermore, at the time when the seeds were procured, fast growth and good stem form were the main criteria in these breeding programs according to the forest manager and it is unlikely that wood quality would have been included as a selection criterion. It is therefore highly likely that the relative high stand density of stand T was the main reason for the significantly higher mean MOE of this stand.

Higher stand densities, combined with late or no thinning, may influence the mechanical properties of lumber through the improvement of wood properties of individual rings and the displacement thereof (Erasmus et al., 2018). Firstly, the slower radial growth of stand S compared with the average of stands A-R ensured that the older year rings were restricted to boards adjacent to the pith boards (Table 2). It is a well-established fact that microfibril angle (the orientation of cellulose microfibrils, MFA) and WD are more favourable, with respect to wood stiffness, at higher CA for *P. patula* (Wessels et al., 2015a), and many other species (Moore and Cown, 2017). A given board with a higher mean CA will therefore result in improved mean MFA and WD values, which increases the stiffness of lumber (Downes et al., 2002; Vikram et al., 2011). Secondly, the properties of individual rings probably also improved considering that the outermost boards of stand S and stands A-R had similar mature rings (max CA) but markedly different MOE (Table 2). In addition, the effect of increasing the board position from 0 to 1 for stand S was similar to increasing the stand density for the pith boards. This is despite an increase in max CA of 5 from board 0 to 1 for stand S and an increase of only 1 from stand S to stand T for pith boards. Conversely, WD displayed the opposite trend, increasing more with stand density than with board position. According to the radial variation of MFA for some of stands A-R, uniform values commence at around the 8th ring (Wessels et al., 2015a). Given the max CA in Table 2, roughly 65% of the boards for these stands therefore contained juvenile wood, compared to just over 50% for stand S. The relationship between MOE and WD and MOR and WD was relatively strong compared to other studies (Johansson, 2003; Dowse and Wessels, 2013) and, along with MFA, were probably the main reasons why stand T had better mechanical properties (see also Fig. 4 and 6). Combined, these features ensured that even though additional boards were recovered from greater diameter trees for stands A-R, the strongest boards were still inferior to that of stands S and T (Table 2).

An interesting question in this study was related to the relative influence of thinning age and intensity on MOE. The maximum real age of board 0 for stand S was below its thinning age (Table 2). This implies that the MOE of board position 0 for stand S was not influenced by thinning. Although the maximum real age was not available for stands A-R, the fact that the maximum CA of A-R was the same as for stand S (Table 2) and the earliest thinning age for A-R was 7 years (Table 1) imply that the pith boards for A-R was probably also not influenced by thinning. Comparing the mean MOE of board 0 from stand S with board 0 of stands A-R, one can observe that several stands had similar or even higher mean MOE for board 0 (i.e. stands C, F, H, I, J, and N)—see Fig. 4. By contrast, the mean MOE of board position 1 of stand S was far higher than board 1 of any stand from A-R. We would argue that the intensive thinning regimes of stands A-R are the most likely reason for the big differences between the MOE of board 1 of stand S through the effect of thinning on both growth rate and possibly WD and MFA. A more comprehensive research study on annual rings will however be required to answer this question conclusively. Research on Sikta spruce showed a significant effect of early respacing (thinning) intensity on MFA and WD, independent of radial position and growth rate (Auty et al., 2017), and ultimately on the MOE of lumber (Moore et al., 2009).

A trade-off of improved wood properties with higher stand densities is a reduction in radial uniformity (Malan et al., 1997; Fujimoto and Koga, 2010; Watt et al., 2011; Erasmus et al., 2018). This was evident given the sharp increase in the WD of boards from stands S and T compared to stands A-R (Figure 6 and Table 2). This occurrence is considered undesirable (Malan 2003) and, in terms of MFA, is one reason why distortion of lumber, particularly bow, in the juvenile core may occur due to uneven shrinkage (Huang et al., 2003). However, bow and spring was to some extent lower in stands S and T while the twist was only high in stands A-R, which were processed from a different mill. Drying practices may therefore have contributed to differences observed between stands. The low magnitude of distortion between stands S and T suggests that it does not need to be considered in terms of management decisions on stand density.

Explanations for changes in the radial wood property patterns include the age of cambial initials and their location with respect to the live crown, which are discussed in detail by Lachenbruch et al. (2011). Considering previous research on the effect of tree spacing on ring-level properties of *P. patula* (Erasmus et al., 2018), like Zobel and Sprague (1998), we are of the opinion that cambial age is the major determinant of juvenile wood duration.

Many studies attribute observed increases in stiffness with stand density to mechanisms related to tree slenderness of *Pinus radiata* (Watt et al., 2006; Waghorn et al., 2007b; Lasserre et al., 2009). Slenderness was the lowest in stands A-R but decreased from stand S to stand T, which presents a very interesting and unexpected result. The aforementioned studies argue that higher slenderness increases instability, which induces higher stiffness wood to maintain structural integrity. Relatively good relationships between dynamic MOE and individual tree slenderness were obtained ($r > 0.70$) in these studies. Similar results were also found for *P. taeda* (Roth et al., 2007; Antony et al., 2012). Roth et al. (2007) suggested that genetic and environmental factors also modulate stiffness of *P. taeda* through mechanisms other than tree size and form. Similarly, it is clear that the differences in *P. patula* lumber stiffness observed between stands S and T were not related to slenderness. Another explanation for higher stiffness is that closely spaced trees are more protected and will experience less wind loads (Green et al., 1995; Lasserre et al., 2005), which reduces wood stiffness (Spatz and Bruechert, 2000; Bascuñán et al., 2006). This was certainly also possible in the case of stand S, specifically after the thinning, and especially for stands A-R.

Another factor that played a role in this study is that of height in the stem. The significant decrease in WD from the bottom to the top logs is supported by a previous study on some of stands A-R that showed WD to be lower at 6 m compared to 1.3 m above ground (Wessels et al., 2015a). The differences in MOE and MOR is probably due to the effect of pruning on the bottom log. Pruning at the height of the bottom log occurred from year 7; the tree ages of the outer boards varied roughly between 7-13 years on average (Table 2), which means that the outer boards from the bottom log will be mostly knot-free. The knots cause grain deviation which is the actual causal factor for mechanical weakness related to knots (Walker, 1993). Although the length of the logs did not allow for defect-placement and may have diluted the effect of knots, according to (Madsen, 1992), it is a better reflection of the random knot placement in actual lumber constructions (Wessels et al., 2014). Lastly, and as alluded to previously, another hypothesis that could have been instrumental in the effect of prunning is that the depth of the live crown was reduced. Larson (1969) demonstrated that the presence of auxins produced by the live crown promotes the production of wood with juvenile characteristics. Accordingly, It is thought that the reduction in auxins caused by an increased distance to the live crown causes the development of mature wood. The extent of such an effect is questioned when mature wood is observed in older open-grown trees, even when the live crown extends to the ground (Zobel and Sprague, 1998).

Conclusion

Based on the results of this study it seems as if stand density management has the potential to improve the stiffness and bending strength of *P. patula* lumber considerably. However, the study used commercial stands from different sites (but close to each other) which did not have identical growth conditions and management interventions. In this study, it was found that tree height and slenderness had no effect on the MOE of the lumber from stands S and T—contradicting results from several other studies on different species. In order to gain a better understanding of the environmental influence such as competition on the stem form and mechanical and physical properties of *P. patula* wood, a better understanding of the tree as a biomechanical system will be an advantage. Future work should consider detailed mechanical analysis of the shape of stems and loads on tree stems planted at different densities (over time) which should enable a better understanding of the mechanical requirements of a tree stem and the subsequent properties of wood formed during its growth.

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Chapter 4

The flexural lumber properties of *Pinus patula* Schiede ex Schltdl. & Cham. improves with decreasing initial tree spacing

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Abstract

Key message **An increase in the stiffness of sawn wood with a decrease in initial tree spacing was confirmed for *Pinus patula* Schiede ex Schltdl. & Cham. The underlying properties of microfibril angle, wood density and knot frequency explained 72% of the variation in lumber stiffness. Tree spacing influenced wood properties over and above differences due to growth rate.**

Context Rapid growth rates and educed harvesting ages of South African-grown pine plantations have caused a reduction in the stiffness of structural lumber, which accounts for about 75 per cent of all sawn wood. Microfibril angle and wood density are known to influence wood stiffness.

Aims The objective of this study was to evaluate the effect of slower growth rates, caused by narrow tree spacing, on the suitability *Pinus patula* Schiede ex Schltdl. & Cham. wood for structural lumber.

Methods An 18 and 19 year-old *Pinus patula* spacing experiment with four levels of initial tree spacing (1.83 m × 1.83 m, 2.35 m × 2.35 m, 3.02 m × 3.02 m and 4.98 m × 4.98 m) was sampled. Linear and non-linear mixed-effects models were developed to examine the effect of tree spacing on the quality of wood and lumber

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as defined by the modulus of elasticity, modulus of rupture and knot frequency of 208 lumber pieces, and the ring-level microfibril angle and wood density of 86 radial strips.

Results Wood and lumber quality improved with decreasing spacing and only the narrowest spacing had lumber that conformed to the requirements of the lowest South African structural grade. Microfibril angle, wood density and knot frequency explained 72% of the variation of lumber stiffness. After accounting for ring width differences (annual growth rate), there remained a significant effect of initial spacing on the parameters of models predicting microfibril angle and wood density.

Conclusions If higher strength grades are desired for *Pinus patula* lumber then wide initial spacing is discouraged.

Introduction

The selection of appropriate spacing between trees is an important tactical decision made in support of forest management strategies. The resulting growing space available is one of the major factors influencing full realization of the genetic potential of trees in terms of growth (Zobel and Talbert, 1984). The delayed onset of competition, caused by sufficient growing space, positively influences tree growth and vigour, which results in greater stem taper, lower living crowns with larger branch sizes, and a reduced risk of mortality (Savill et al., 1997; Harrington et al., 2009; Gadow and Kotze, 2014; Ashton and Kelty, 2018). Tree spacing is also the most powerful management tool available to influence the physical properties of wood raw material and their within-tree variability (Larson et al., 2001; Macdonald and Hubert, 2002; Schimleck et al., 2018). Control over tree spacing may be exercised at stand establishment/regeneration (initial spacing) or throughout the rotation at various developmental stages of the stand through respacing (pre-commercial) or thinning (Cameron, 2002).

Globally, the commercial management of softwood plantations has generally moved towards regimes that secure larger volume growth in the shortest possible time, typically favouring wider tree spacing (Hein et al., 2007; Kotze and du Toit, 2012; West, 2014). This strategic adaptation towards optimized stand volume productivity is guided by management objectives, which classically aim to grow large trees at the lowest cost possible, while maximizing financial return. In South Africa, constraints in the form of land availability, water legislation and conservation demands pose further challenges (Zwolinski and Bayley, 2001; Louw, 2006). These factors have made South African forestry highly productive (ranked 19th in the world by industrial roundwood production by 2012) despite a forest cover of only about 1.2 million ha (Jürgensen et al., 2014). Between the years 1960-2016, plantation production increased by 38% while the afforested area simultaneously increased by only 5% (Godsmark, 2017). Under such aggressive management, trees consequently grow much faster, and merchantable volumes are realized sooner.

Considering the age dependency of mechanical properties, the main consequence of increased productivity on wood quality is largely considered to be an increase in juvenile wood proportions at final harvest (Larson et al., 2001; Malan, 2010). This wood type is characterised by high microfibril angle (MFA) and low wood density (WD) (Moore and Cown, 2017), which negatively influences wood stiffness (Cave and Walker, 1994; Burdon et al., 2004; Xu and Walker, 2004; Vikram et al., 2011; Wessels et al., 2015a). Lumber processed mostly from this wood material is then likely to decrease the percentage of lumber graded to higher strength classes, which are normally classified according to stiffness. Several studies over the last few decades have confirmed the negative effects of increased juvenile proportions on lumber strength (modulus of rupture, MOR) and stiffness (modulus of elasticity, MOE) and in some cases lumber distortion (Kretschmann and Bendtsen, 1992; Burdzik, 2004; Biblis, 2006; Dahlen et al., 2012; Dowse and Wessels, 2013). The MOE of structural lumber produced in South Africa has been reported at 25% less than the lowest structural grade S5 (Dowse and Wessels, 2013) which, in terms of MOE, is comparable to the second lowest European strength class C16 (CEN, 2016).

In response to wood quality concerns, initial research in South Africa has focussed on establishing the current resource characteristics and variation of mechanical and physical properties of wood, as well as the non-destructive prediction thereof (Wessels et al., 2011, 2014, 2015a,b; Dowse and Wessels, 2013; Muller et al., 2017). These studies clearly indicate that the nature of wood material from modern plantations has changed. In South Africa, the focus continues to shift towards understanding wood property variation in response to silviculture (Malan, 2012), particularly initial spacing (Wessels and Froneman, 2015; Erasmus et al., 2018; Froneman and Wessels, 2018), with increased emphasis on an end-product perspective. Although numerous spacing trials have been established in the country (Gadow and Kotze, 2014), the main focus has largely been on studying growth and form (Malan et al., 1997). More work is required to elucidate the influence of spacing on wood properties.

An initial experiment evaluating the effect of initial spacing on the MFA and WD of *Pinus patula* wood was completed, using increment cores from standing trees (non-destructive) of a spacing trial, and was reported in Erasmus et al. (2018). In the current study, an additional spacing trial was destructively sampled and processed into sawn lumber. Data from both spacing trials (destructive and non-destructive) were utilized in the current study where the objective was threefold: First, to investigate the effect of initial spacing on the physical and mechanical lumber properties of *P. patula*, particularly lumber MOE. Second, to assess the influence of MFA, WD, and knot properties on lumber MOE. Third, we also aimed to examine the effects of changes in growth rate, as mediated through initial spacing, on the within-tree variation of MFA and WD. The results of this study would assist in formulating forest management regimes that consider wood quality of *P. patula* in addition to growth and yield, since this species is the dominant conifer in South Africa and accounts for about half the softwood area in the country (DAFF, 2019).

Materials and methods

Experimental site and design

This study was conducted using an 18 and 19 year-old *P. patula* spacing experiment, both located in the Mpumalanga escarpment near the town of Barberton, South Africa (25.7175° S, 30.9750° E and 25.7665° S, 31.2395° E respectively). The 18 year-old (Montrose) experimental trial, reported in a previous study (Erasmus et al., 2018), is situated roughly 30 km from the 19 year-old (Highlands) experimental trial. This area has a mean annual rainfall of about 850 mm and mean midday temperatures of about 17 °C. All trees in this study were pruned at five, seven and nine years after planting to a height of 2, 3.5 and 5.5 m respectively. Each spacing experiment followed a randomised complete block design consisting of four square initial spacing levels, each replicated in two blocks (Table 1). For brevity, we hereafter simply refer to each spacing level by the shortest distance between trees i.e. 1.83 m, 2.35 m, 3.02 m and 4.98 m. Each sampling plot had been planted with 49 seedlings in a 7 × 7 tree-layout (variable area plots) but only the centre 25 trees were considered in the study reported here as the outer trees were considered buffer rows.

Sampling and measurements

Relative stand density, a measure of site occupancy, was calculated according to Curtis (1982) and the diameter at breast height (DBH) and standing tree height were manually recorded for all trees. The top height was taken as the mean of the 20% thickest trees per spacing treatment (Sharma et al., 2002). The slenderness of a tree was taken as the ratio of tree height (adjusted by -1.3m in order to coincide with breast height) to DBH. Additional data of the Highlands trial was available, measured or calculated. This included the measurements of DBH and height for each year throughout the duration of the experiment. A regression-supported sampling was also used to estimate the total mass of the branches of three to four randomly selected trees per spacing treatment. A minimum of 23 branches (one random branch per whorl), distributed over the full length of the bole were weighed (branch wood, bark and foliage combined). The basal diameter was measured on all branches for these trees (2611 branches in total). The logarithmic form of the

Table 1: Summary of measured and calculated variables across tree spacing.

Description		Spacing (m^2)				Limits / requirements*
		4.98	3.02	2.35	1.83	
Tree-level: Montrose and Highlands trials	Planting density (stems ha^{-1})	403	1097	1808	2981	
	Survival (%)	97	91	75	57	
	Basal Area (m^2 ha^{-1})	36.3	50.2	51.3	45.3	
	Relative Stand Density	6.2	10	10.9	10.6	
	Total stem volume (m^3 ha^{-1})	349	463	471	409	
	Mean DBH (cm)	33.9	24.9	21.3	18	
	Mean Height (m)	23.5	22.3	21.4	20.7	
	Mean Slenderness	0.67	0.86	0.97	1.11	
	Top height (m)	24.6	23.8	24	22.8	
	Quadratic mean DBH (cm)	34.4	25.3	21.9	18.4	
Tree-level: Highlands trial	Mean live crown height (m)	15.2	17.9	18	17	
	Mean live crown length ratio	0.37	0.26	0.21	0.27	
	Mean crown mass (kg)	399	102	115	38	
	Mean branch diameter (mm)	26.2	20.3	21.4	16.2	
	Mean branch count	278	176	112	156	
Board-level: Highlands trial	Sample size (logs)	11	12	12	11	
	Sample size (boards)	74	56	39	39	
	Mean MOE (MPa)	6445	7613	7119	8537	7800
	5th perc. MOE (MPa)	3992	4923	5129	5342	4630
	5th perc. MOR (MPa)	11.9	15.7	16.6	22.2	11.5
	Mean knot frequency	7.1	7.9	8.3	9.1	
	Mean max knot size (mm)	14.6	10.6	11.7	7.4	
	WD (kg/m3)	445	464	447	467	360
	Bow (mm/m)	1.88	1.75	1.95	1.36	10
	Twist (°)	2.08	2.84	3.28	3.46	5
	Spring (mm)	1.74	2.5	2.64	1.69	15
	Mean RW SilviScan (mm)	11.5	8.8	8.7	6.4	
	Mean MFA SilviScan (°)	21.9	16.2	16.9	14.1	
	Mean WD SilviScan (kg m^{-3})	418	458	460	491	
Ring-level: Montrose and Highlands trials	sample size (trees/radial strips)	20	22	22	20	
	RW (mm)	9.4	6.8	6	5.5	
	MFA (°)	18.5	13.6	13.1	12.4	
	WD (kg m-3)	443	491	502	507	
	LW (%)	26.2	31.5	31	32.4	

*Limits and required values according to SANS 1783-2 (2013) and SANS 10163-1(2003) respectively.

power law model, with branch basal diameter as the independent variable, was used to estimate model coefficients and then predict branch mass for all branches not weighed, according to the method described by Seifert and Seifert (2014). Dead branches were measured and estimated separately. Crown mass was calculated as the total branch biomass (Table 1). The height of the live crown base was measured and the ratio of live crown length to the tree height was calculated (four to fifteen trees per treatment). The varying sample size here was due to undistinguishable live crowns caused by fire damage to some branches.

Material preparation and testing

Radial strips were processed from samples removed at 1.3 m above ground for randomly selected trees of both trials for the measurements of MFA and WD using the CSIRO Silviscan 3 apparatus (Evans, 1999) in Melbourne, Australia, at a radial resolution of 2 mm and 0.025 mm respectively (Table 1). Compression wood, by means of visual inspection, was avoided when processing strips. Latewood percentage (LW) was calculate using a threshold of 500 kg m^{-3}, adjusted according to darker latewood bands of rings.

For the Highlands trial only, 11-12 trees per spacing treatment were randomly selected and a 2.4 m saw log was removed directly above a height of 1.3 m for each tree (Table 1). The logs were processed using a cant sawing pattern, yielding 208 boards with cross-sectional wet dimensions of 40 x 120 mm (Fig. 1). Boards were kiln-dried to a target moisture content of 12%. Templates on the ends of logs enabled the tracking of each board processed from a given log. The range of rings present in a given board was counted by reconstructing logs using the templates. Therefore, we could assign a mean ring-level MFA and WD value to each board, as well as the change in MFA from the minimum to maximum MFA according to the annual rings of the corresponding radial strip. All boards containing pith tissue were marked as "Board 0"—also referred to as pith boards in this study (Fig. 1). Due to the small sample size, board 3 was excluded from data analysis. WD, moisture content and distortion (twist, bow and spring) of each board were measured according to SANS 1783-1 (2013). Four-point bending tests were performed according to the guidelines set out in SANS 6122 (2014) using an Instron tensile/bending apparatus. The MOE was calculated between the loads 400 and 2200 N. The maximum knot diameter and total number of knots (knot frequency) in the maximum stressed area, i.e. centre third of the span, were assessed for each board (Table 1).

Data analysis

The R system for statistical computing (R Core Team, 2018) was used for all data analysis. The hierarchical structure of the data warranted the application of linear

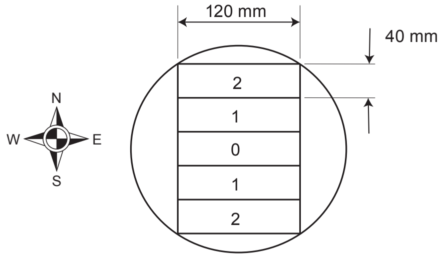

Figure 1: The sawing pattern used to process logs. Board positions are indicated from 0 (pith-board) to 2 (outer board).

and non-linear mixed-effects models (Lindstrom and Bates, 1990; Pinheiro and Bates, 2000). Following the experimental design, a nested structure was considered for all the random effects ($\sim N(0, \sigma^2)$) of block, plot, tree and radial position, before model simplification. All fixed and random effects were evaluated with Chi-squared based likelihood ratio tests and Akaike's information criterion, AIC (Akaike, 1974). Multiple-comparisons (Fischer's LSD test) between factor-level means of lumber and wood properties were made with a pairwise significance threshold of $\alpha = 0.05$. Fit indices (R^2) were calculated on the fixed part of models, as well as after the inclusion of each random effect, according to the equations given by Parresol (1999). Model performance was assessed with the mean absolute error $|E|$ and root mean square error (RMSE). Only full annual rings were considered for data analysis.

The following model was used to analyse the variation of lumber MOE, MOR and WD as caused by spacing treatment and radial position from the pith:

$$Y_{ijkl} = \mu + \tau_i + r_k + (\tau r)_{ik} + b_{ij} + b_{ijk} + \epsilon_{ijkl} \tag{1}$$

where Y_{ijkl} is the MOE, MOR and WD of an individual board; μ is the grand mean of the response variable; τ_i is the fixed effect of the i^{th} spacing treatment; r_k is the fixed effect of the k^{th} radial position; $(\tau r)_{ik}$ is the spacing treatment and radial position interaction effect; b_{ij} and b_{ijk} are the random effects at the tree and board position level and ϵ_{ijkl} is the within-group error. Analysis of covariance was also carried out to examine the influence of wood properties on lumber MOE (Highlands only) using the following model:

$$Y_{ijk} = \beta_0 + b_i + b_{ij} + \beta_1 MFA_{ij} + \beta_2 WD_{ij} + \beta_3 \log(K_{ijk}) + \epsilon_{ijk} \tag{2}$$

where Y_{ijk} is the MOE of lumber; β_0, β_1, β_2 and β_3 are parameters to be estimated from the data and MFA_{ij}, WD_{ij} and K_{ijk} are the MFA, WD and knot frequency of each board; b_i is the random effect of the ith tree; b_{ij} is the random effect of the j^{th}

radial position within the i^{th} tree. Sensitivity analysis was done on the fixed part of the model to determine the relative "influence" of varying independent parameters, one at a time, on MOE (Pannell, 1997). In Eq. 2, a particular variable was changed from the observed 5th to the 95th percentile while holding the remaining variables constant at their observed means. The absolute change in MOE, predicted by Eq. 2, was then recorded as a percentage of the total change in MOE for all variables.

Various exponential and logistic model parameterizations were screened to determine the most appropriate model for simulating the pith-to-bark behaviour of ring-level MFA and WD. The modified three-parameter logistic model (Eq. 3), presented by Jordan et al. (2005), proved to be the best fit for MFA:

$$Y_{ij} = \frac{\alpha_0}{1 + e^{-\alpha_1 CA_{ij}}} + \alpha_2 + a_{2i} + \epsilon_{ij} \tag{3}$$

$$Y_{ij} = \frac{\alpha_0}{1 + e^{-\alpha_1 CA_{ij}}} + \alpha_2 + \alpha_3 RW_{ij} + a_{2i} + \epsilon_{ij} \tag{4}$$

where Y_{ij}, CA_{ij} and ϵ_{ij} are the MFA, cambial age (ring number from pith; starting at ring 2), and the residual error of the j^{th} annual ring in the i^{th} tree; $(\alpha_0/2 + \alpha_2)$, α_1 and α_2 corresponds to the initial MFA (y-intercept), the rate parameter, and the lower asymptote respectively, which could all vary with spacing; a_{2i} is the random effect for the i^{th} tree. Since changes in wood properties due to silvicultural events are typically accompanied with responses in tree growth, we additionally wanted to see if there remained an effect of spacing over and above CA_{ij} and ring width (RW_{ij}). The α_2 parameter was therefore changed to a linear function of RW_{ij} (Eq. 4). Radial MFA profiles were then simulated (Eq. 4) by using mean ring width values per annual ring and spacing, which were predicted by Eq. 3 with RW_{ij} as the dependent variable (parameters not shown) (Auty et al., 2017).

Alternative parameterizations of the same models proved to be the best fit in modelling WD:

$$Y_{ij} = \frac{\alpha_0 + a_{0i}}{1 + e^{-\alpha_1 CA_{ij}}} + \alpha_2 + \epsilon_{ij} \tag{5}$$

$$Y_{ij} = \frac{\alpha_0 + \alpha_3 RW_{ij} + a_{0i}}{1 + e^{-\alpha_1 CA_{ij}}} + \alpha_2 + \epsilon_{ij} \tag{6}$$

where Y_{ij} is the WD of the j^{th} annual ring in the ith tree; α_0 is the maximum (asymptotic) WD value; α_1 is the rate parameter; $(\alpha_0/2 + \alpha_2)$ is the initial WD value. Equation 5 allows the α_0 parameter to vary randomly instead, while Eq. 6

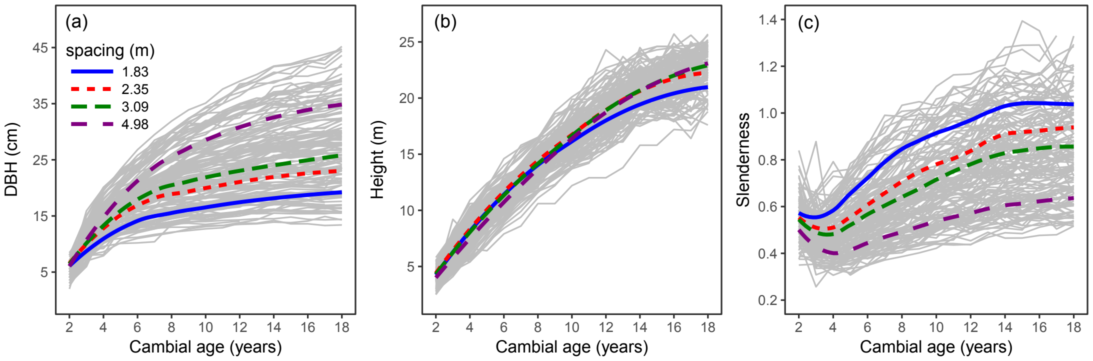

Figure 2: The variation of (a) DBH, (b) Height and (c) slenderness after reaching 1.3 m, for the Highlands trial only, fitted with a locally-weighted smoothing function to all observations (grey lines) for each spacing.

adjusts the same parameter for RW_{ij}. This had the effect of adjusting the asymptotic mature wood values and increasing the effect of RW_{ij} with CA_{ij}. Slenderness was also added to the models, in place of RW, for both MFA and WD (Highlands trial only), but RW proved to contribute more to the explanation of wood property variation.

Results

Stand Characteristics

Tree survival rates and site occupancy are indicated in Table 1. DBH increased with spacing for all ages. Differences also increased with age, especially between the two widest spacing treatments (Fig 2a). Tree height remained relatively similar for all ages up until ages of about 10 after which the change in height decreased for 1.83 m (Fig. 2b). After an initial decrease, slenderness gradually increased and was consistently greater with decreasing spacing (Fig. 2c). The rate of change in slenderness was slightly sharper with closer spacing. Crown development in terms of mass was far greater in the wider spacing (Table 1) due to both larger diameters and greater number of branches. Crown size generally reduced with closer spacing (Table 1).

Board-level MOE and MOR

Individual board MOE varied from 2243 to 13601 MPa and the mean MOE increased with closer spacing with the exception of a relatively small decrease from 3.02 m to 2.35 m (Table 1). There was a significant linear relationship between MOE and mean CA ($R^2 = 0.5$; $p < 0.001$). Differences in MOE between board

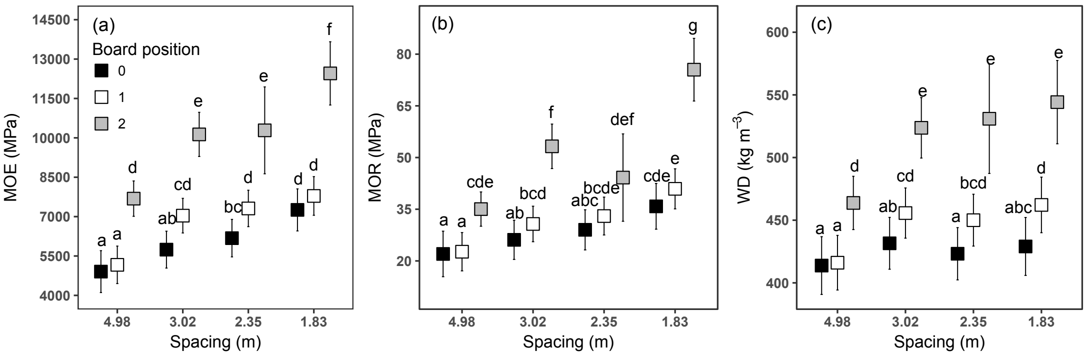

Figure 3: Means and 95% confidence intervals of (a) MOE, (b) MOR and (c) WD at different spacing and board position. Different letters denote significant differences.

1 and 2 increased with decreasing spacing (except from 3.02 m to 2.35 m, Fig. 3a). MOE for board 2 of the narrowest spacing was significantly greater than that of the 3.02 m and 2.35 m spacing, which in turn were significantly greater than that of the widest spacing. MOE for board 2 of the widest spacing displayed no significant difference to that of board 1 of the 3.02 m and 2.35 m spacing, and even with board 0 for the closest spacing. Only board 2 for spacing of 3.02 m and closer had mean values greater than 7800 MPa and consequently, only the 1.83 m spacing conformed to the S5 mean MOE standard (Table 1). The widest spacing was the only treatment that failed to fulfil the required fifth percentile MOE (Table 1). MOE variation could be moderately explained by both the mean MFA ($R^2 = 0.64$; $p < 0.001$) and WD of lumber ($R^2 = 0.56$; $p < 0.001$) individually. However, WD had the greatest effect on MOE in the model given by Eq. 2, followed by knot frequency and lastly mean MFA (Table 2). The model was able to explain 72% of the variation in MOE (92% with random effects) (Table 3).

Table 2: Sensitivity analysis of the fixed effects of Eq. 2

Parameter	coefficient	Sensitivity analysis				
Intercept	3623.758	mean	5th	95th	change	%
WD	16.35	452.44	393.31	543.81	2460.24	0.39
MFA	-84.47	19.68	8.46	29.89	-1810	0.29
Log (Knots)	-1031.79	2.07	1.1	3.04	-2007.8	0.32

MOR varied from 2.9 to 86.3 MPa and was best explained by MOE ($R^2 = 0.73$). Therefore, the variation of MOR across spacing and board position generally followed the same patterns as MOE. MOR for the outermost boards of the closest spacing was significantly greater than the rest (Fig 3b). Board 2 for the widest spacing displayed no significant difference to board 1 for the second widest spacing and even board 0 of the two narrowest spacings. Overall, the fifth percentile MOR was sufficient to comply with the characteristic bending strength of grade S5 lumber, and the 2.35 and 1.83m spacing treatments even complied with grade S7 requirements (15.8 MPa).

Table 3: Summary of all model statistics

level	Model	Property	AIC	Log-likelihood	R^2			Model errors	
					Fixed	Tree	Radial position	|E|	*RMSE*
Board	eq. 1	MOE	3049	-1510	0.67	0.81	0.85	943	1221
	eq. 2	MOE	3114	-1550	0.72	0.83	0.92	874	1140
	eq. 1	MOR	1395	-683	0.53	0.65	-	9	11
	eq. 1	WD	1732	-851	0.49	0.83	0.88	27	34
Ring	eq. 3	MFA	6154	-3065	0.77	0.87	-	3.2	4.1
	eq. 4	MFA	5985	-2977	0.8	0.89	-	3	3.8
	eq. 5	WD	13058	-6517	0.51	0.75	-	52.6	69
	eq. 6	WD	13022	-6498	0.52	0.76	-	51.4	67.9

Board-level WD and distortion

The WD of boards varied from 356 to 638 kg m^{-3} and had a moderate relationship with mean CA ($R^2 = 0.53$) and MOE ($R^2 = 0.51$) but displayed a weaker relationship with MOR ($R^2 = 0.35$). Compared to MOE and MOR, a similar pattern of variation of WD is observed (Fig 3c). Board 2 for the three closest spacing treatments were significantly greater than that of the widest spacing, which was not significantly different to board 1 for the other spacing treatments. All spacing treatments conformed to the S5 standard for WD at the board level (Table 1).

Spacing had no clear effect on values of bow and spring but twist decreased notably with spacing (Table 1). Twist also consistently decreased from 4.4° to 1.6° from board 0 to 2. The association between lumber distortion and mean MFA as well as the MFA gradient of boards were all very weak and below $R^2 = 0.03$. Overall, the mean lumber distortion values in this study was lower than the limits for structural use (Table 1).

Ring-level MFA and WD

The mean MFA per treatment varied between approximately 8° and 32°, displaying a decreasing non-linear trend with CA (Fig. 4a). Values for 4.98 m was, on

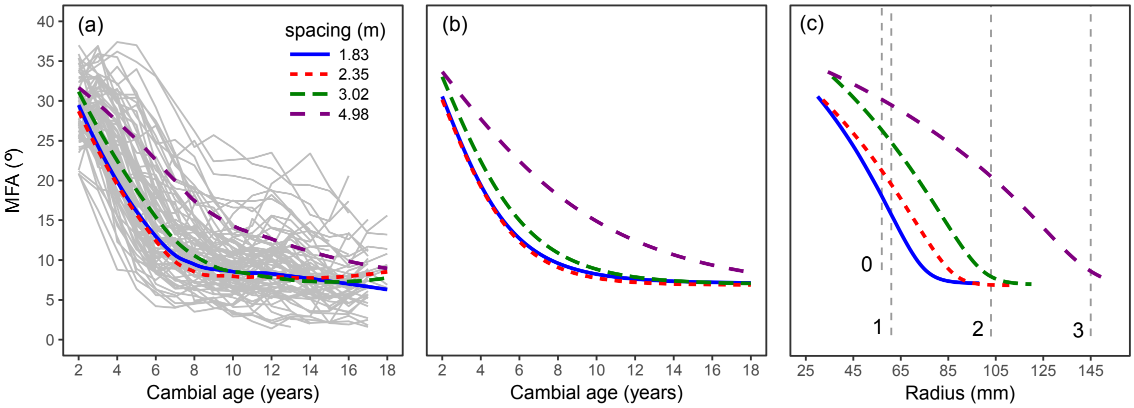

Figure 4: Radial profiles of observed (a) and predicted (a and b) MFA with each spacing level fitted with (a) locally-weighted smoothing functions ("loess") to all observations (grey lines), (b) Eq. 4 and (c) Eq. 4 plotted on a radius scale. Grey vertical lines represents the maximum radial distance (in all directions) bounded by a given board position (see Fig. 1).

average, 4.9° greater than for 3.02 m. Compared to the rest, the 4.98 m spacing clearly exhibited a lower radial MFA gradient which began to stabilize after age 10 , which was roughly three rings more than for any other spacing. MFA for the three other spacing treatments were relatively similar at equivalent rings. Results from Eq. (3) confirmed these observations. Both the α_0 and α_2 parameters decreased significantly with reduced spacing (Fig. 5a and b). The lower asymptote (α_2) did not differ significantly with spacing.

Equation (4) proved to be the best fitting model, explaining 79 per cent (89 per cent with random effects) of MFA radial variation (Table 3). MFA was strongly associated with RW ($R^2 = 0.74$). The RW coefficient (α_3) was significantly less for the widest spacing compared to the rest (Table 4). There remained a significant effect of spacing on the α_0 and α_1 parameters over and above the effect of CA and ring width. Overall, modelled MFA for the 4.98 m spacing treatment clearly displayed the slowest radial rate of decline (Fig. 4b). Up to about CA 10, the second widest spacing was also consistently greater than the two closest spacing treatments. When plotting the Modelled MFA against tree radius, differences between the widest spacing and the rest increased more markedly due to the combined effects of RW and annual MFA increases with increased spacing (Fig. 4c).

The mean WD per treatment increased steadily from pith to bark, varying roughly between 340 and 580 kg m^{-3} (Fig. 6a), was closely associated with LW ($R2 = 0.77$). WD in the 4.98 m spacing also displayed no clear indication of reaching a stable value towards the bark compared to the other treatments, which began to stabilise at around the 10th annual ring. Accordingly, Eq. (5) showed that the widest spacing had the highest and lowest α_0 and α_2 parameters respectively (Fig.

Table 4: Model parameters of Eq. 4 for MFA and Eq. 6 for WD. Estimates for the fixed effects are given by their intercept (Int., i.e. 4.98 m) and the values for the other treatments are relative to the intercept (i.e. the change in estimate from 4.98 m)

Fixed effects	MFA				WD			
	Estimate	SE	t-value	p-value	Estimate	SE	t-value	p-value
α_0 (Int.)	38.5	2.91	13.25	$<$0.001	465.41	27.1	17.15	$<$0.001
$\alpha_{0,3.02}$	-18.05	4.78	-3.78	$<$0.001	-34.85	22.8	-1.53	0.126
$\alpha_{0,2.35}$	-22.14	5.05	-4.38	$<$0.001	-68.35	22.7	-3.01	0.003
$\alpha_{0,1.83}$	-21.47	4.96	-4.33	$<$0.001	-44.83	23.4	-1.91	0.056
α_1 (Int.)	-0.18	0.01	-13.61	$<$0.001	0.06	0.01	6.81	$<$0.001
$\alpha_{1,3.02}$	-0.16	0.04	-3.88	$<$0.001	0.11	0.02	5.12	$<$0.001
$\alpha_{1,2.35}$	-0.25	0.06	-4.09	$<$0.001	0.21	0.03	6.35	$<$0.001
$\alpha_{1,1.83}$	-0.18	0.06	-3.09	0.002	0.16	0.03	5.65	$<$0.001
α_2 (Fixed)	5.41	0.38	14.2	$<$0.001	191.35	17.2	11.11	$<$0.001
α_3 (Int./Fixed)	0.39	0.07	5.58	$<$0.001	-4.75	0.85	-5.57	$<$0.001
$\alpha_{3,3.02}$	0.38	0.11	3.31	0.001				
$\alpha_{3,2.35}$	0.33	0.12	2.85	0.004				
$\alpha_{3,1.83}$	0.44	0.13	3.3	0.001				

5c and d). A better depiction of the overall effect of spacing can be seen in Fig. 6b, given by Eq. (6) (explaining 52% of the variation, Table 3), which confirms the main difference being the lower WD gradient for the widest spacing. WD was moderately associated with RW ($R^2 = 0.43$). Spacing also had a significant effect on model parameters over and above RW and CA (Table 4). Predicted WD, based on distance from pith, is indicated in Fig. 6c where differences between spacing increased.

Discussion

Influence of initial spacing on grade recovery

Results of this study contribute clear findings to the body of literature dealing with the generally positive effects of closer spacing on mechanical properties of lumber processed from several species (Johansson, 1992; Brazier and Mobbs, 1993; Clark et al., 1994; Moore et al., 2009; Amateis et al., 2013; Rais et al., 2014; Froneman and Wessels, 2018). For *P. patula*, it is clear that as initial spacing increases, conformance to minimum structural requirements is limited by lumber MOE. This has also been proven true for South African-grown *Pinus radiata* (Wessels and Froneman, 2015) and *Pinus elliottii* (Froneman and Wessels, 2018). The contrary has

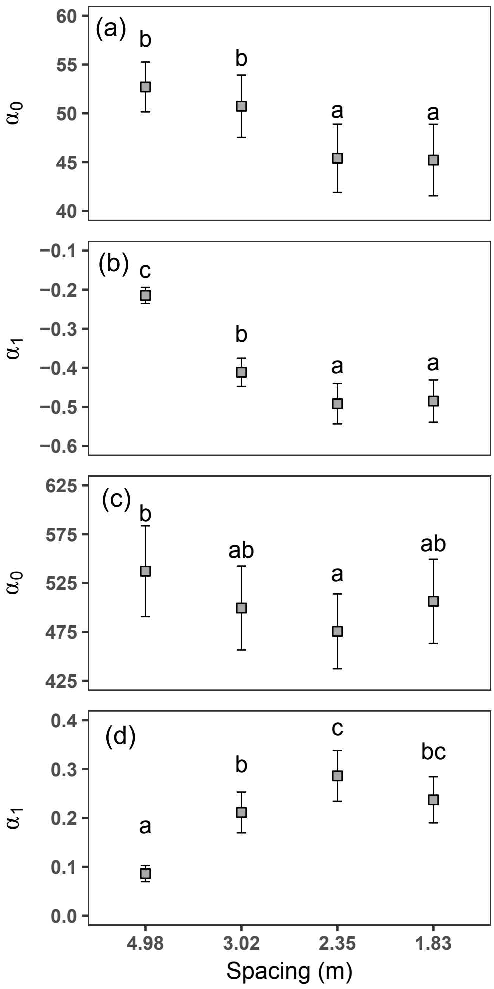

Figure 5: Parameter estimates and 95% confidence intervals of Eq. (3) for MFA (a and b) and Eq. (5) for WD (c and d). Different letters denote significant differences.

been shown for conifers on much longer rotations where the MOR restricts conformance with wider spacing (Moore et al., 2009). However, results are dependent on stand conditions and are best applicable to corresponding site- and species-specific management regimes.

In addition to strength and stiffness, acceptably low levels of lumber distortion are also required by end-users which, in the case of the distortion type twist, has been reported as problematic for *P. patula* resources (Dowse and Wessels, 2013; Wessels et al., 2014). The variation of twist was consistent with previous research which show a reduction in distortion from the juvenile core to the outer mature wood (Brazier and Mobbs, 1993; Moore et al., 2009). Twist did increase notably with spacing however, but varied less compared to the aforementioned studies on

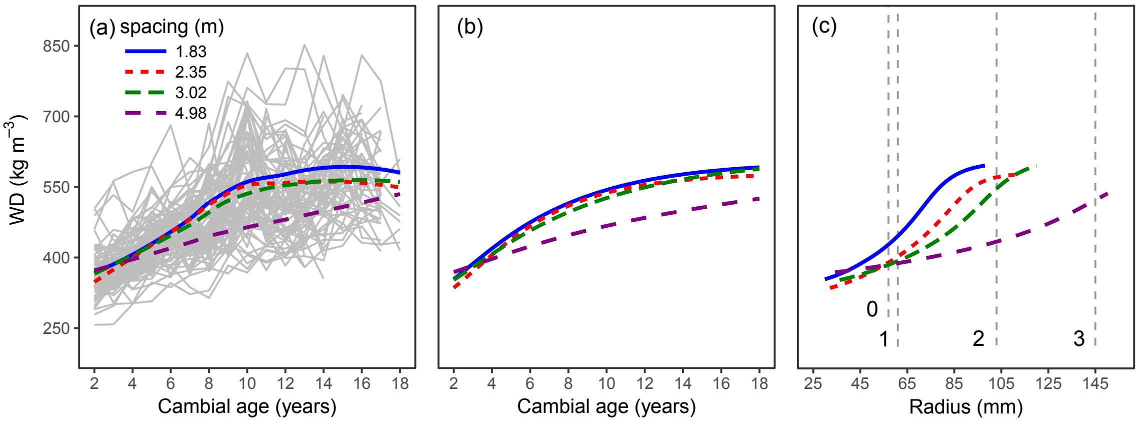

Figure 6: Radial profiles of observed (a) and predicted (a and b) WD with each spacing level fitted with (a) locally-weighted smoothing functions ("loess") to all observations (grey lines), (b) Eq. 6 and (c) Eq. 6 plotted on a radius scale. Grey vertical lines represents the maximum radial distance (in all directions) bounded by a given board position (see Fig. 1).

P. patula, which used different spacing ranges.

Mechanisms through which initial spacing influences lumber properties

In the study reported here, we showed that MFA correlated well with MOE and was the best individual predictor thereof, which supports previous studies (Cave and Walker, 1994; Walker and Butterfield, 1996). This was despite the complexity in determining exactly which rings are present in boards, given that only a single radial strip was used to relate ring-level properties to boards and ignoring circumferential and longitudinal variation. Collectively however, MOE was slightly more sensitive to knot frequency and especially WD. This result differs somewhat from a previous study on *P. patula* (Wessels et al., 2015a), perhaps due to the lower spacing range, but consistent with other studies using different resources (Downes et al., 2002; Vikram et al., 2011).

Ring-level MFA and WD both displayed a relatively rapid initial gradient, improving favourably from the pith with gradients tending to react more sharply with reduced spacing. This feature has been recognized in previous studies on *P. patula* (Malan et al., 1997) and other species (Fujimoto and Koga, 2010; Watt et al., 2011; Moore et al., 2015). As a result, ring-level properties reach more uniform values at earlier CA. Considering that wood developed prior to this point fulfils the definition of juvenile wood according to Zobel and Sprague (1998), it then follows that the juvenile core is restricted in age with closer spacing. This effect is due to a restriction on crown development rather that a direct effect of spacing (Larson et al., 2001) (see Table 1). Additionally, this had the added effect of improving the average MFA, WD and LW (Table 1). Furthermore, the growth rate is markedly slower closer to the pith for closer spacing; therefore, increasing differences in wood properties between spacing at equivalent radii, which was especially the case for MFA closer to the pith (Fig. 4 and 6). This observation was also reflected at the board level where the MOE was generally higher at the same board position. Note that the smaller difference between board 0 and 1, compared to the rest, contributes to the explanation of the comparable lumber properties between these board positions (Fig. 4c and 6c).

The increase in differences of wood properties at higher radii elucidates the significant interaction between spacing and board position on mechanical and physical lumber properties. The practical implications are that the difference in mechanical properties between inner and outer boards are greater for closer spacing which is considered undesirable in terms of processing efficiency (Malan, 2010). Moreover, individual boards themselves will have sharper MFA and WD gradients, which could lead to uneven shrinkage or distortion (Walker and Nakada, 1999; Huang et al., 2003). This occurrence was not evident in the results reported here. However, the fact that the mean twist of boards increased with closer spacing lends some support to this view. Sawing patterns that increases the ring count of wood with sharp MFA gradients may be influential in this regard (Tsoumis, 2009). Overall, the magnitude of the increase of twist with spacing in this study is however of little practical importance as it was well within the limits for structural lumber.

Tree developmental effects on wood quality

With reference to the work reviewed by Zobel and Buijtenen (1989), Malan et al. (1997) concluded that the relationship between growth rate and WD is extremely complex given the varying interaction with environment and genetic material. The same author added that, given a quantity of photosynthetic substances produced by the crown, a fast growing tree will not always prioritise cell production over cell material. Furthermore, Larson et al. (2001) argued that the effect of RW on WD is an artefact of the inherent age dependency of WD and that the effect of juvenile growth rate, for a given CA, may be negligible. There was some evidence in this study to partially support this view as ring width differed markedly with spacing while WD remained relatively similar near the pith. However, after accounting for CA, there was an effect of RW, which increased at higher CA. The residual effect of initial spacing in this study also suggests that there are additional causal factors that control differences in wood properties across spacing treatments, which requires further investigation. An explanation argued by Auty et al. (2017) is that wood density in widely spaced trees may tend towards a minimum value regardless of radial growth. From a wood property modelling perspective, it is important to consider the limitations associated with the use of growth rate as a proxy for spacing given that the effects of spacing beyond growth rate are typically considered negligible.

There is consensus between many authors that the rapid initial decline in MFA is associated with mechanical constraints related to tree slenderness (Spatz and Bruechert, 2000; Watt et al., 2006; Lachenbruch et al., 2011; Waghorn and Watt, 2013; Wessels et al., 2015b). Saplings with small diameters produce higher MFA, which endows trees with considerable flexibility of the stem, acting as a safeguard against external forces. As the tree grows, a decrease in flexibility is beneficial to support its increasing weight. Slenderness in this study did not however contribute more than RW to the explanation of MFA or WD which, in this case, appears to result more from intrinsic gene expression manipulated by other spacing factors, rather than extrinsic controls related solely to slenderness (Lachenbruch et al., 2011). Within the first four rings at breast height, both slenderness and MFA decreased, thereafter slenderness increases representing a possible adaptation to a different developmental stage. Watt and Kirschbaum (2011) argue that part of the reason for slender stems is less tree sway caused by reduced wind in the canopy (Green et al., 1995) and increased collisions by neighbouring trees (Milne, 1991) within the canopy of high stand densities as canopy closure begins earlier for closer spacing (Kotze and du Toit, 2012). This allows a tree to secure greater height at a given diameter. Alternative models explaining the decreased MFA and increased stiffness are cell hydraulic aspects and crown development (Domec and Gartner, 2002; Kuprevicius et al., 2013). In addition, although the closely spaced trees were much slender, they had considerably less crown mass to support (Table 1).

Commercial implementation of closer spacing

From a wood quality perspective, this study in conjunction with many previous investigations seems to encourage a management regime with a stand density that is higher than currently deployed commercially. There has of yet, however, been limited response from South African and other southern hemisphere forest owners to such findings. This could be because forestry planners rarely incorporate the financial effect of better quality lumber in their planning scenarios and that very little work has been performed to quantify the economic benefits of such management scenarios for the full sawn lumber value chain. Note that not only did the mechanical properties improve in this study, but the volume per ha also improved up to a spacing of 3.52 m due to a better site-occupancy earlier in the rotation (Savill et al., 1997). This is despite the extra lumber recovered (Fig. 4c and 6c) for the widest spacing. The economic value of forest stands are thus not due solely to volume gains (Moore et al., 2018). Lumber graded to higher strength classes may therefore be possible without compromising on financial returns. It is recognized however that there will be several offsetting factors i.e. higher establishment costs, lower sawmill volume recovery, harvesting costs of smaller diameter trees, and transportation costs. Ultimately, a response from forest management will likely be initiated if a comprehensive economic evaluation of the value chain (including wood quality effects) can show similar or better returns than current management regimes. Alternatively, it could be that a desire to incorporate lumber in highly stressed applications further down the value chain will eventually drive engineers to demand an increase in mechanical properties (Moore, 2012). Further pressure from local mills is also likely as the price of graded lumber reaches import parity (Crickmay and Associates, 2013).

Conclusion

The advantages of closer spacing can be summarized as follows: First, at equivalent CA, mean WD and MFA is improved. Second, suppressed radial growth ensures that more mature rings are prevalent closer to the pith further improving wood properties at similar distances from the pith. Third, lumber in the closer spacing will have better mean MFA and WD values. These advantages results in mechanical board properties improving with closer spacing. The sharp wood property gradients did not result in significantly increased lumber distortion.

Overall, it appears that if higher strength grades are desired then low initial spacing is discouraged. The underlying properties that control wood stiffness during juvenile growth may be improved with closer initial spacing before possible later thinning to reduce mortality and stimulate volume growth. Subsequent studies on *P. patula* should include further investigation into the mechanisms controlling MFA and WD. Future work is required on further understanding the development of annual wood properties, particularly WD and MFA, as well how they are affected by thinning. Economic evaluation of management regimes with closer spacing (over the full sawn value chai) including the positive effect of better lumber grades, should be performed to better understand the potential of commercial implementation of such regimes.

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Chapter 5

The effect of water supply and Nitrogen/Potassium ratio on selected wood properties of *Pinus patula*, *Pinus elliottii* x *caribaea*, and *Pinus patula* x *tecunumanii* saplings

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Abstract

Microfibril angle and wood density are two important properties, which influence the mechanical properties of wood. A better understanding of how these properties vary within early cambial ages is increasingly important in fast growing commercial forests. The objective of this study was thus to evaluate the microfibril angle, density and stiffness of wood under the influence of periodic or developing drought in association with varied levels of nitrogen (N) and potassium (K) in young *Pinus patula*, *Pinus patula* x *tecunumanii*, and *Pinus elliotti*i x *caribaea*. Two levels of the ratio of N/K (Nitrogen : Phosphorus : Potassium ratios of 3:1:5 and 4:1:1) and three levels of water supply (100 ml, 500 ml and periodically alternating between the two) was replicated into two blocks of six plots each using a complete randomized block design with split plots to accommodate the different species. The diameter at the base of the saplings was measured weekly for one year and three months. The microfibril angle and density radial profiles at the stem base were re-scaled onto a temporal axis using measures of stem growth overtime (mm). The stiffness

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was evaluated by flexure of a destructively sampled section of the stem. The two factor levels did not significantly influence the average MFA of trees, but there was some evidence of temporal sensitivity of both density and MFA to drought periods. Temperature was also significantly correlated with monthly averages of wood density. Water supply and the ratio of nutrients significantly influenced wood stiffness, which was significantly correlated with leaf mass. The results provide some evidence that early cambial growth and the resulting wood properties, are sensitive to water availability and periods of water stress and that the growth within this region due to the ratio of nitrogen and potassium is not detrimental to either density or microfibril angle. The effects of water stress and nutrient effects on wood stiffness appeared to be mediated through the mass of leaves.

Introduction

The phenotypical attributes of wood quality, with respect to a specific end-use purpose, are the result of the interaction of a tree's genotype and the environment, within which it grows (Larson, 1969). Intensive forest management aims to create the kind of environment that promotes rapid growth, ultimately permitting shorter rotation ages (Moore and Cown, 2017). Between the years 1983-2003, the mean harvesting age of South African saw-log plantations of *Pinus patula* Schiede ex Schltdl. & Cham., the dominant conifer in the country, had reduced by 5 years (Crickmay et al., 2005). Given the financial benefits thereof, these management systems are likely to persist into the future (Carle and Holmgren, 2008). Taking into consideration the inherent age dependency of wood properties (Lachenbruch et al., 2011), the supply of raw material with increased proportions of young, juvenile wood will consequently also continue. This type of wood is highly variable in its properties and less predictable in its performance, posing a prominent challenge to the wood processing industry (Bowyer et al., 2003; Malan, 2010). The need to understand the mechanisms controlling quality components in this wood type is therefore increasingly important.

The production of wood begins with the division of cambial initials, followed by cell expansion, wall thickening and cell lignification (Tsoumis, 2009). When these developmental processes are affected by changes in environmental factors, such as water availability and temperature, the cambium may respond with the formation of wood having altered characteristics of properties such as wood density (WD) and microfibril angle (MFA) (Drew et al., 2009). A study by Lundgren (2004) showed irrigation to significantly explain both WD and MFA variation in Norway Spruce (*Picea abies* L. Karst.), where MFA increased with water availability. Wimmer et al. (2002) reported an increase in MFA in *Eucalyptus nitens* with a release of water stress, while an increase in WD with drought stress was displayed for Norway spruce (Bouriaud et al., 2005). Gonzalez-Benecke et al. (2010) found that irrigated trees of young loblolly pine (*Pinus taeda* L.), compared to rainfed trees, had a longer growing season with an increased latewood portion and consequently increased whole-ring WD.

Fertilization also stimulates growth and vigour and may therefore influence wood quality. A review by Zobel and Sprague (1998) on different species showed that, with some exceptions, juvenile WD generally decreased with fertilization and that the zone of juvenile wood increased. Downes et al. (2002) and Mäkinen et al. (2002) showed that fertilization can increase MFA and WD in radiata pine (*Pinus radiata* D. Don) and Norway spruce, respectively. Citing several studies, Bowyer et al. (2003) summarized that while losses in average WD due to fertilization amounted to about 6-10 percent in mature trees, little to no impact on WD existed in trees still within the juvenile stage. According to Malan (2012b), nitrogen (N) tends to increase the percentage of earlywood (which decreases ring WD), while a study by Wessels et al. (2015b) reported that *P. patula* trees characterized by low and high levels of potassium (K) and N respectively, tended to produce wood with better stiffness properties. The effect of the ratio of N to K (N/K) on the development of wood properties may therefore be a fruitful area of future research and was investigated in this study.

From a biomechanical perspective, mechanical constraints are also imposed on the growth and yield of trees (Niklas, 1993). It is proposed that as trees approach a theoretical critical height—the height at which a stem can no longer support its own weight against gravity—wood properties may be regulated to prevent such mechanical failure (Watt et al., 2006b; Waghorn and Watt, 2013). Differences between self- and nonself-supporting trees are illustrated by Jaouen et al. (2007). As the tree grows, it is also necessary to have sufficiently stiff wood to resist external forces, such as wind loading (Fournier et al., 2013). Studies have shown a reduction in wood stiffness of different species when exposed to wind or mechanical perturbation (Pruyn et al., 2000; Bascuñán et al., 2006). Telewski (1989) showed that MFA was affected by flexure of stems in young Fraser fir (*Abies fraseri* (Pursh) Poir.). The MFA closest to the pith is typically the most problematic (with respect to wood stiffness) (Moore and Cown, 2017), emphasizing the importance of understanding the mechanisms controlling its development in this part of the tree.

In this study, we focussed on the link between temporal changes in environmental factors and associated changes in properties of wood formed under those conditions. The objective was to evaluate the effects of periodic or developing drought in association with varied levels of N and K on wood properties in young *P. patula*, which was the main species used in this study considering the strong dependence of the industry. However, they are threatened by susceptibility to diseases in nursery saplings (Hongwane et al., 2018) and hence we introduced two important hybrid pine species, viz. *Pinus patula* x *tecunumanii* Low Elevation (*P.*

pat x *tec*) and *Pinus elliottii* x *caribaea* var. *hondurensis* (*P. ell* x *car*) to compare responses in wood development.

Materials and methods

Experimental description

The experimental work was conducted in a greenhouse tunnel on the campus of the University of Stellenbosch, South Africa. Over the course of the experiment (one year and nine months), daily temperatures in the tunnel ranged from approximately 11 to 40 °C. The pot experiment was established using a factorial arrangement of treatments in a complete randomized block design; two levels of soil fertility and three levels of water supply replicated into two blocks (Figure 1). Either a high (N 20.7%, P 5.2% and K 5.2% by weight) or low (N 14.3%, P 4.8% and K 23.9% by weight) N/K ratio of granulated fertilizer was supplied at 10g per month to each tree. In November 2016 each tree was planted into a 40 litre plastic nursery bag which was filled with a 20 litre mixture of sand (25%) and bark compost (75%). Fertilizer was applied from December 2016 up until mid-experiment when it was discontinued due to concerns that some tree mortality might have occurred due to fertilizer burn. Up until September 2017, when the experiment measurements started and the smallest stem diameters were greater than roughly 5 mm, water supply was kept constant using an overhead sprinkler irrigation system. Thereafter, water was supplied using a drip irrigation system at three treatment levels viz. 100 ml daily (droughted), 500 ml daily (no stress expected), and a level that alternates between 100 and 500 ml daily (to create a cyclical response). The timing of alternating the irrigation was arbitrary, looking for signs of water stress and using a simple handheld soil moisture meter.

Each treatment combination plot (the mth plot in Figure 1) was also split into three subplots to superimpose three species within the experiment: *P. patula* seedlings (open pollinated, single family) and cuttings of both *P. pat* x *tec* and *P. ell* x *car*. The cuttings were sourced from the Sappi Ltd. Pty seed orchard. Each subplot consisted of six trees (216 trees in total at the start of the experiment. Manual weed control was maintained for all trees throughout the duration of the experiment. For a given species, the young trees had approximately the same mean stem thickness at the base between treatment levels of water supply and N/K at the start of the experiment (Figure 2). To allow for any temperature and sunlight gradient within the tunnel, the plots were divided into a row of two blocks that ran parallel to these potential gradients. The temperature was also logged continuously.

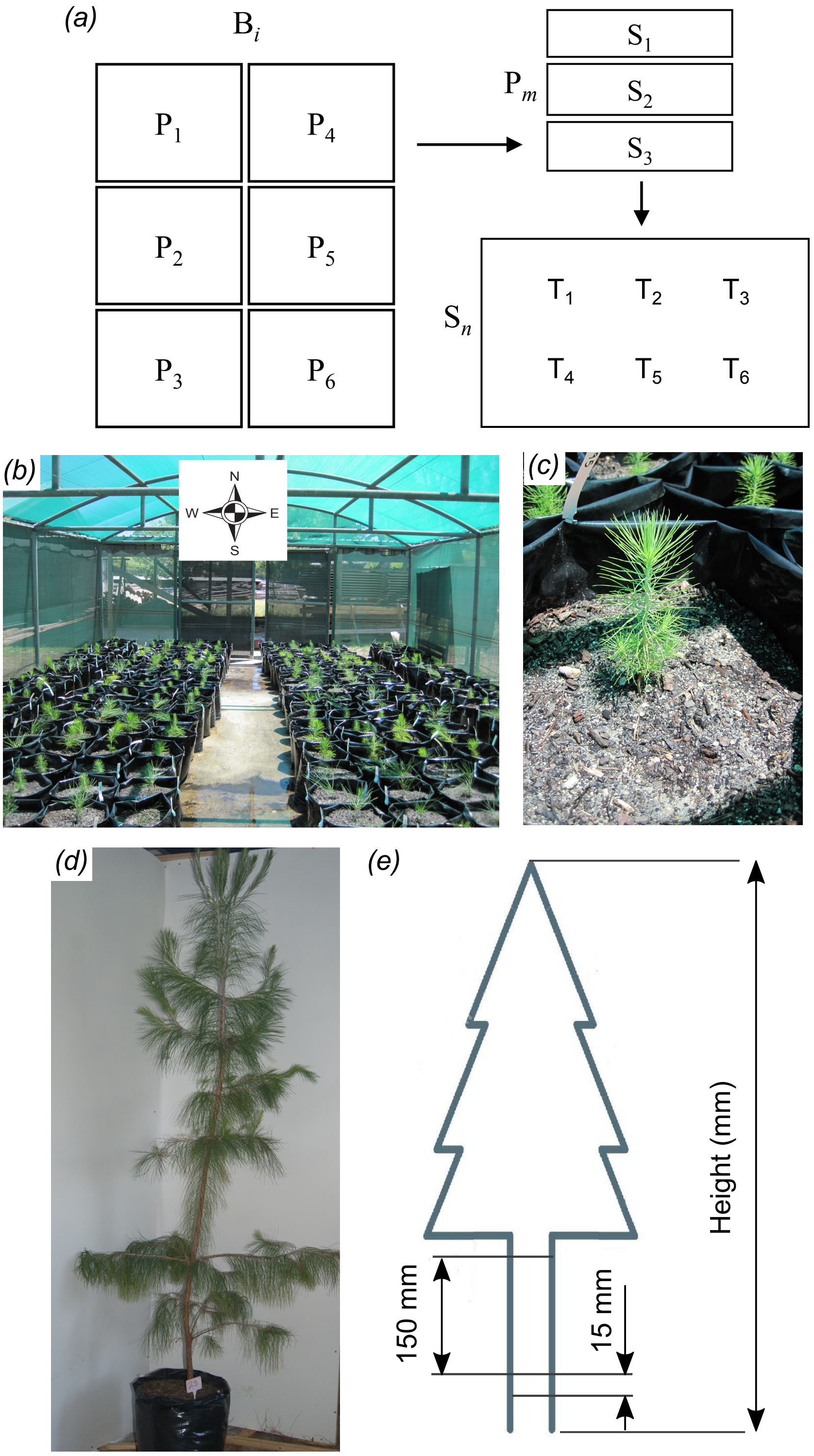

Figure 1: An illustration of the experimental design for six trees within the nth subplot (S_n) within the mth plot (P_m) within the ith block (B_i) (a) where the saplings were arranged into two blocks (b). Differences in trees between the start and end of the experiment are illustrated in (c) and (d). A diagram of the sampling procedure for the 15 mm Silviscan disc and the 150 mm MOE sample are illustrated in (e).

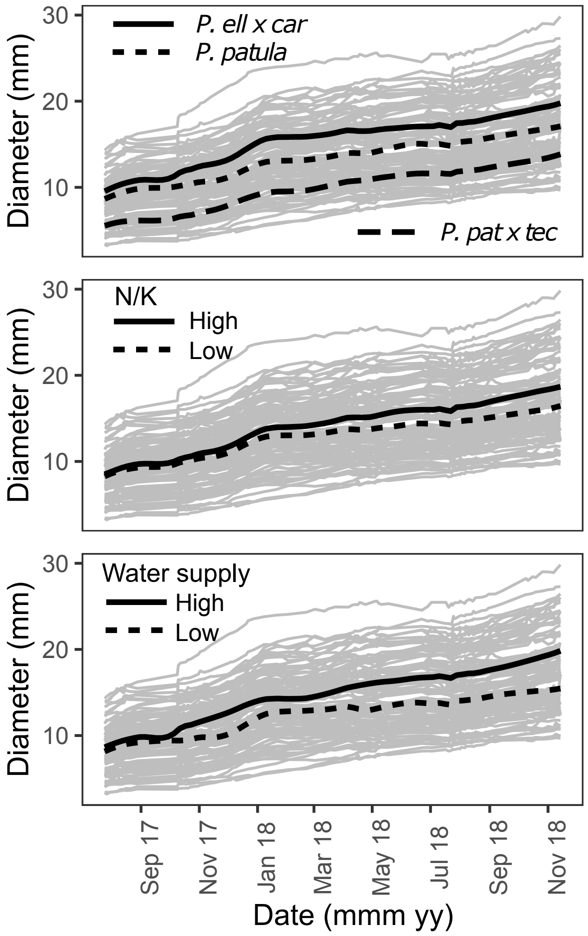

Figure 2: The variation of diameter growth over time grouped by species (top), N/K (middle), and water supply (bottom).

Tree growth

Stem growth was estimated by measuring diameter at a fixed point near the base, once a week using a digital veneer calliper (Mitutoyu Corporation) with a resolution of 0.01 mm. The stems were also pruned to constant height to clear a section for measurements which started six months after establishment and lasted for one year and three months. At the end of the experiment, the saplings were destructively sampled and the mass of the leaves, branches and roots were measured. The height and consequently the slenderness (height/diameter) were measured at the beginning and end of the experiment.

Sampling

Out of the 216 trees planted, only 168 were available for analysis due to mortality, mostly occurring within the *P. pat* x *tec* group (Table 1). At mid- and post-experiment, the needle-like leaves were sampled for chemical analysis where a small portion of the youngest fully developed foliage from each tree was sampled together for each sub-plot as a single value (effectively 2 values per sub-plot per block). The nutrient content was examined against adequate levels of nutrient concentration—the point above which growth yields are not expected to change significantly (above 10% of maximum yield) with any change in concentration levels up to toxic values (Smith and Loneragan, 1997). The reference levels of nutrient concentrations were given by Boardman et al. (1997). The nutrient content was obtained by multiplying the concentration levels with the dry needle mass. The leaves were dried at 65 °C for 24-48 hrs. The leaf area was also measured and divided by the dry mass of leaves to obtain the specific leaf area (SLA) at the end of the experiment. The roots were oven dried to a constant mass.

Table 1: Sample size (n) and average diameters for all trees for each factor level.

Factors		Treatments				
		N/K		Water supply		
		High	Low	High	Low	Alternating
Sample size (n)	*P. patula*	31	36	21	23	23
	P. ell x *car*	31	33	19	23	22
	P. pat x *tec*	20	17	14	8	15
	Total	82	86	54	54	60
Average diameter (mm)	*P. patula*	18.9	16.1	20.3	14.7	17.5
	P. ell x *car*	22.2	19.9	23.1	17.9	22.5
	P. pat x *tec*	14.3	13.1	16.3	11	12.9
	Average	18.5	16.4	19.9	14.5	17.6

A 15 mm disc was sampled from the position at which diameter measurements were made (Figure 1). The discs were sterilized and water in the wood was replaced with ethanol during several stages, after which discs were air-dried—this was done to prevent excessive cracking and cell collapse. WD (10 μm resolution), microfibril angle (MFA) and tracheid sizes (200 μm resolution) were measured along pith-to-bark wood strips using the CSIRO SilviScan apparatus in Melbourne, Australia (Evans, 1999).

A 150mm long section of the stem above the sampled disc (Figure 1) was subjected to 3-point bending after having been saturated with water and, using the principles of an elastic curve, the MOE was calculated from the following formula (Hibbeler, 2008):

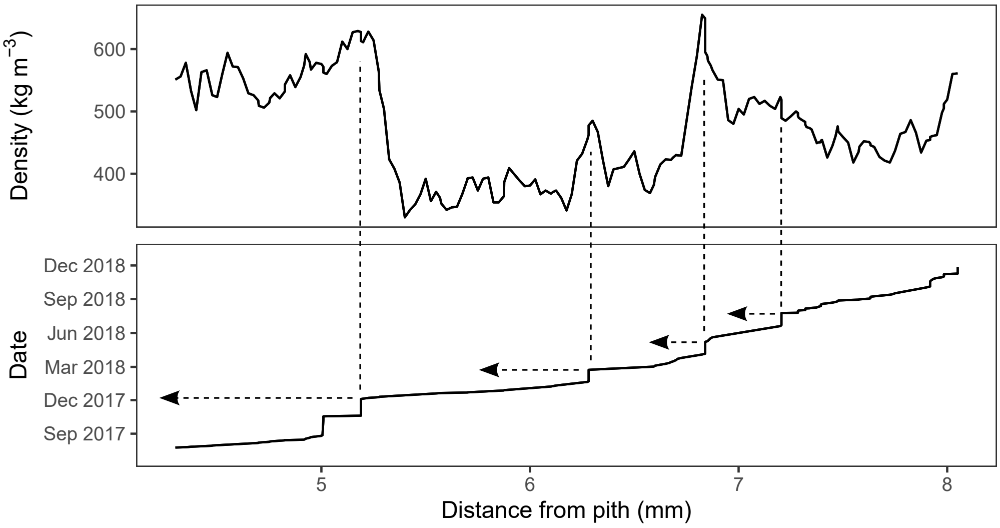

Figure 3: An example tree where the approximate date of the formation of portions of wood, and their properties, are related to a common axis.

$$MOE = \frac{PL^3}{48ID} \tag{1}$$

Where P is the change in the applied force from the beginning to the end of the elastic region, L is the test span (100 mm), I is the moment of inertia of the cylindrical-like test specimen, and D is the corresponding change in deflection. This sample was also oven dried to a constant weight, which was used to calculate the oven dry WD.

Rescaling

An important aspect of the study was to be able to determine when portions of wood were formed. To achieve this, the common "scale" of measurements of stem growth over time (mm) and the distance from the pith (mm) of measured wood properties were related using one randomly chosen replication (Figure 3). This was undertaken according to the methods described and discussed by Drew and Downes (2009). The stem radius measured manually was corrected for the bark thickness of each tree and assuming a constant rate of bark and phloem production. Xylem was considered non-compressible and when shrinkage was observed it was assumed to be a period of zero growth of xylem (i.e. no wood formed). Average daily rates of tracheid production were calculated by dividing the average daily stem growth for each month for each tree by the average radial diameter of the cells formed over that month (Drew et al., 2009).

Data analysis

Analysis of the data was conducted in R (R Core Team, 2018). Linear mixed-effects models were used to account for the hierarchical structure of the data (Lindstrom and Bates, 1990; Pinheiro and Bates, 2000). A nested structure was considered for all the random effects ($\sim N(0, \sigma^2)$) of plot and subplot before model simplification. All fixed (main and interaction terms) and random effects were evaluated with Chi-squared based likelihood ratio tests and Akaike's information criterion, AIC (Akaike, 1974). Not all properties were evaluated with significance tests. However, general trends were used to help assist in interpreting treatment effects. The low sample size for *P. pat* x *tec* meant that it was excluded from statistical analysis. The final model to evaluate tree properties was formulated as follows:

$$Y_{ijklmno} = \mu + B_i + N_j + W_k + S_l + b_{im} + b_{imn} + \epsilon_{ijklmno} \tag{2}$$

where $Y_{ijklmno}$ is the MOE, Diameter, WD (oven dry) or MFA of an individual tree; μ is the grand mean; B_i, N_j, W_k and S_l are the fixed effects of block, N/K, water supply and species; b_{im} is the random effect of plot m in block i; b_{imn} is the random effect of sub-plot n in plot m; $\epsilon_{ijklmno}$ is the residual error. When evaluating equation (2) with MOE, WD and MFA as dependent variables, tree diameter was added as a covariate to test if differences in growth could account for changes in the response variables between factor levels. The alternating water supply level was dropped from a combined statistical analysis and was analysed individually and visually for the onset and release of water stress. Nutrient concentrations and contents were related to the sub-plot level averages of wood and tree characteristics.

Results

Tree growth and development

At the end of the experiment, average stem diameter for *P. patula* was significantly smaller than *P. ell* x *car* (Table 2, Figure 4) and, as indicated in Figure 2, was generally lower throughout the term. For a given date, the diameter of *P. pat* x *tec* was about 3 and 6 mm less, on average, than *P. patula* and *P. ell* x *car* respectively. Both *P. patula* and *P. ell* x *car* had significantly greater diameters in plots with a higher N/K and water supply (Table 2, Figure 4). There was a notable growth response in diameter following and increase in water supply and reduced growth rates with lower water supply, as indicated in Figure 5. Within the period November-December 2017, there were some issues with the irrigation system; all levels received maximum water supply, which explains the similar increase in growth across all levels of water supply.

Table 2: Significance of factors when included in equation (2). Bold values are significant at $p < 0.05$

Dependent variable	Factors	p-value	p-value*
Diameter	Block	**0.0242**	
	Species	**0.0001**	
	Water supply	**0.0004**	
	N/K	**0.0159**	
MOE	Block	0.571	
	Species x Water supply	**0.0208**	**0.0058**
	N/K	**0.0017**	0.0832
	Diameter		$<$ **0.0001**
MFA	Block	0.3254	
	Species	$<$ **0.0001**	
	Water supply	0.117	
	N/K	0.1521	
	Diameter		0.4093
WD	Block	0.7592	
	Species x Water supply	**0.0151**	0.0839
	N/K	0.3248	
	Diameter		$<$ **0.0001**

*Adjusted when diameter was included.

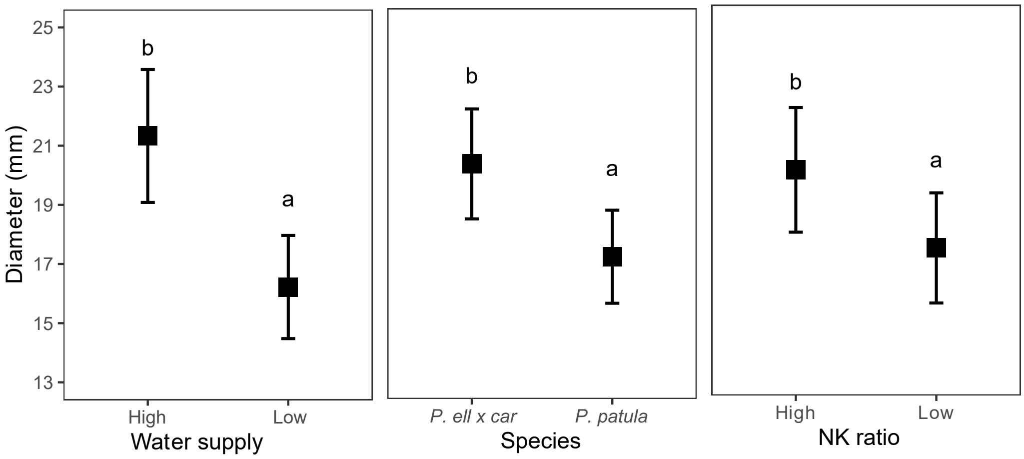

Figure 4: The means and confidence intervals for diameter from equation (2), grouped by water supply (a), species (b) and N/K (c).

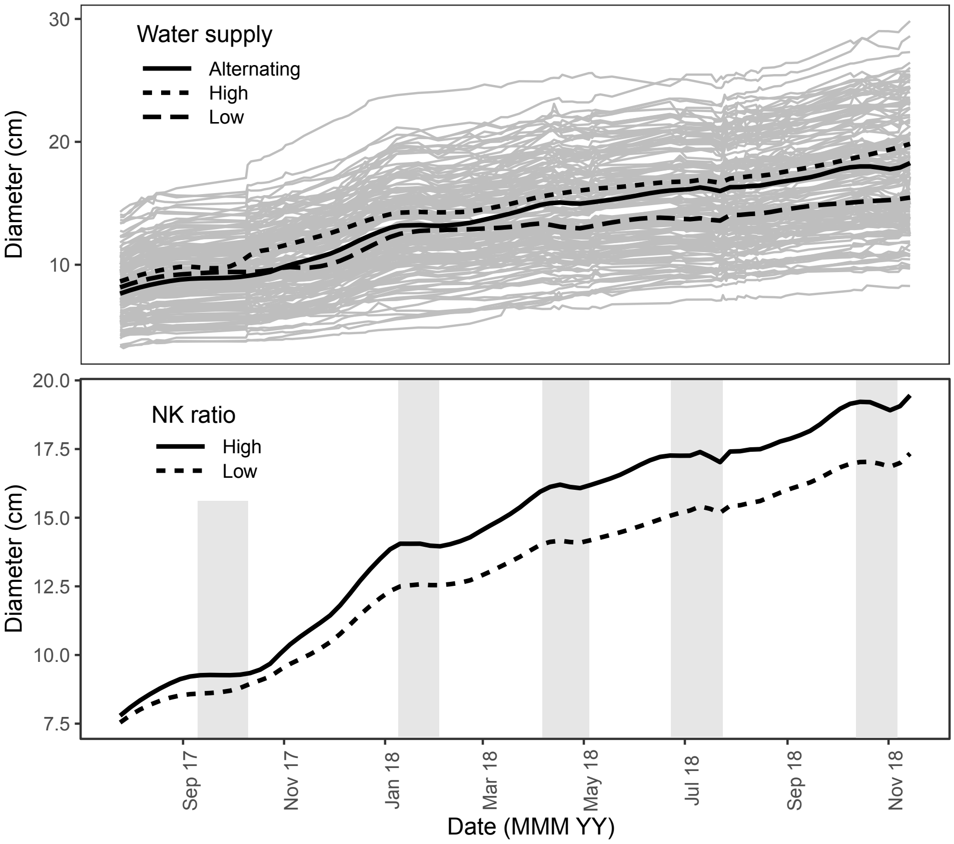

Figure 5: The variation of basal diameter over time grouped by water supply (top). Shaded areas (bottom) represent periods where water supply, for the treatment level receiving alternating levels of water supply, grouped by N/K, was consistently at the minimum level.

There was also a significant effect of block on diameters with an average difference of about 3 mm (Table 2). Temperature differences between blocks were less than 1 °C on average and differences between light intensity were more than 2000 lux (morning and late afternoon). Leaf, branch and root mass and tree height, generally also increased with water supply and N/K (Figure 6). The branch structure of trees was considerably different between species, where *P. ell* x *car* trees had the lowest branch mass values. Slenderness values were highest for *P. pat* x *tec*, although the patterns of SLA and tree slenderness were not as consistent. For all species, the average tree slenderness decreased by 29% between November 2017 and December 2018.

There was a good correlation between the tree diameter, for all species, and the dry mass of leaves (Table 3). Unsurprising, the leaves of trees in plots with both a higher N/K and water supply had greater mean N content (Figure 7). With

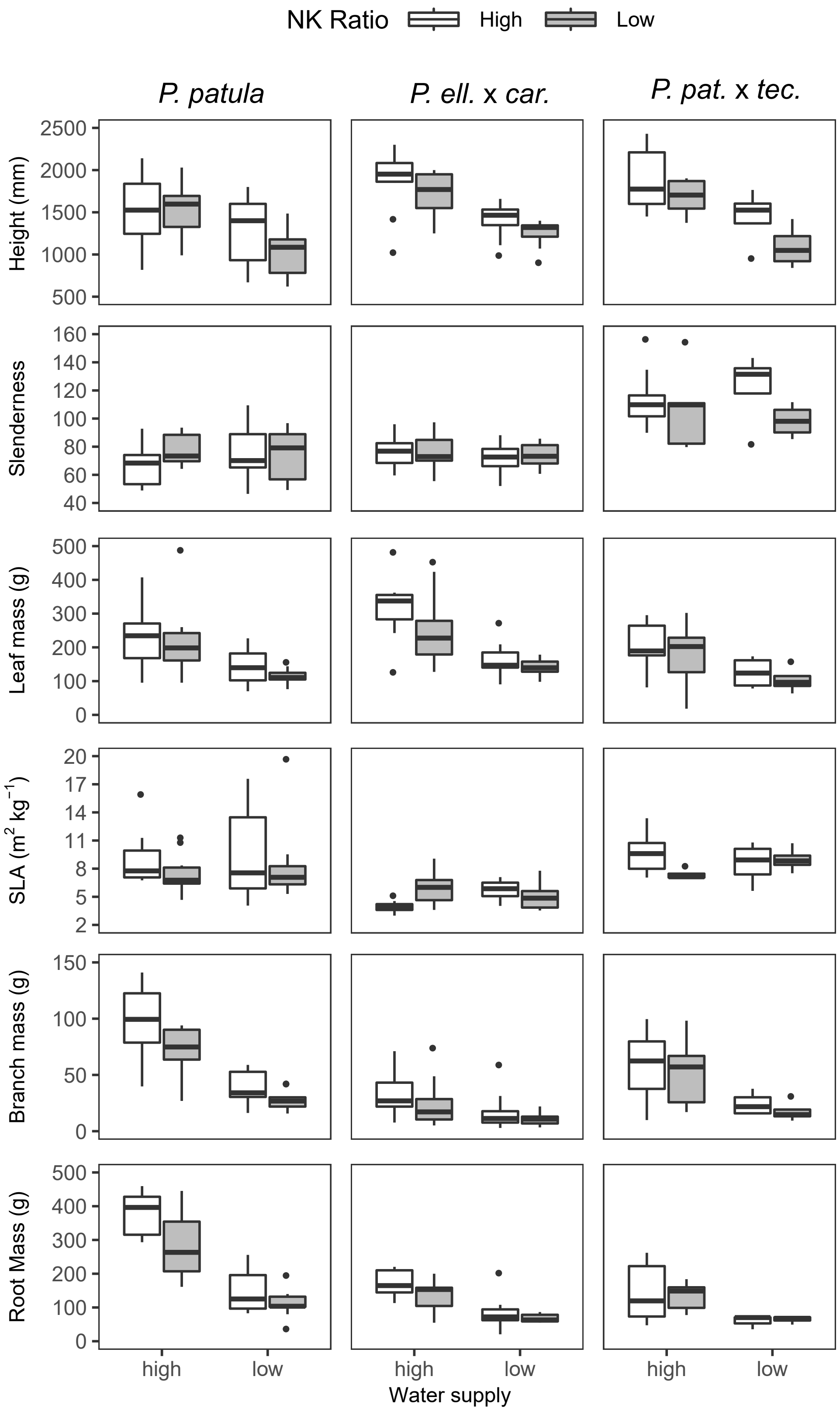

Figure 6: Boxplots of tree variables measured at the end of the experimental term.

the exception of *P. patula*, N content was also greater for the alternating water level treatment. The ratios of N and K content generally also followed the N/K concentration ratio patterns in Figure 8, while patterns of phosphorus (P) content across treatment levels were not that obvious. N content was strongly correlated with leaf mass, but the best predictor of leaf mass was manganese (Mn) (Table 4). Mn content also had a strong relationship with SLA (Table 4). N and K content in turn, could explain moderate proportions of diameter growth variation. Of all nutrient concentrations, the N (particularly for *P. ell* x car) and copper (Cu) concentration levels were critical with respect to adequate values (Figure 8). Values of P were also critical (below 0.1) for *P. ell x car*, but marginal/adequate for the other species.

Table 3: Spearman rank order correlations of tree-level variables. Bold and red correlations are significant at p < 0.05

Variable	Height	Leaf mass	SLA	Root mass	Diameter	MOE	Slenderness	Density	MFA
Height	1								
Leaf mass	**0.751**	1							
SLA	**-0.204**	**-0.331**	1						
Root mass	**0.324**	**0.469**	0.126	1					
Diameter	**0.613**	**0.770**	**-0.402**	**0.509**	1				
MOE	**-0.463**	**-0.646**	**0.572**	**-0.25**	**-0.838**	1			
Slenderness	**0.398**	0.004	**0.215**	**-0.222**	**-0.401**	**0.411**	1		
Density*	**-0.482**	**-0.563**	**0.292**	-0.144	**-0.591**	**0.647**	0.115	1	
MFA**	**-0.351**	**-0.192**	0.155	**0.315**	0.049	-0.03	**-0.475**	0.094	1

* Oven dry density values.

** Average MFA values per tree.

Table 4: Pearson correlation coefficients for subplot-level variables. Variables measured on single trees were averaged across sub-plots (N= 18 cases). Bold and red correlations are significant at p < 0.05

Variable	Leaves mass	Diameter	Root mass	SLA	MOE	N content	P content	K content	Cu content	Mn content
Leaf mass	1									
Diameter	**0.889**	1								
Root mass	0.365	**0.497**	1							
SLA	**-0.597**	**-0.581**	0.258	1						
MOE	**-0.697**	**-0.911**	-0.386	**0.57**	1					
N content	**0.73**	**0.755**	**0.744**	-0.06	**-0.578**	1				
P content	**0.576**	0.461	**0.685**	0.1	-0.191	**0.769**	1			
K content	**0.76**	**0.692**	0.338	**-0.48**	**-0.539**	**0.51**	**0.636**	1		
Cu content	**0.739**	**0.54**	0.259	-0.33	-0.318	**0.515**	**0.684**	**0.747**	1	
Mn content	**0.898**	**0.847**	0.176	**-0.81**	**-0.743**	**0.57**	0.338	**0.663**	**0.503**	1

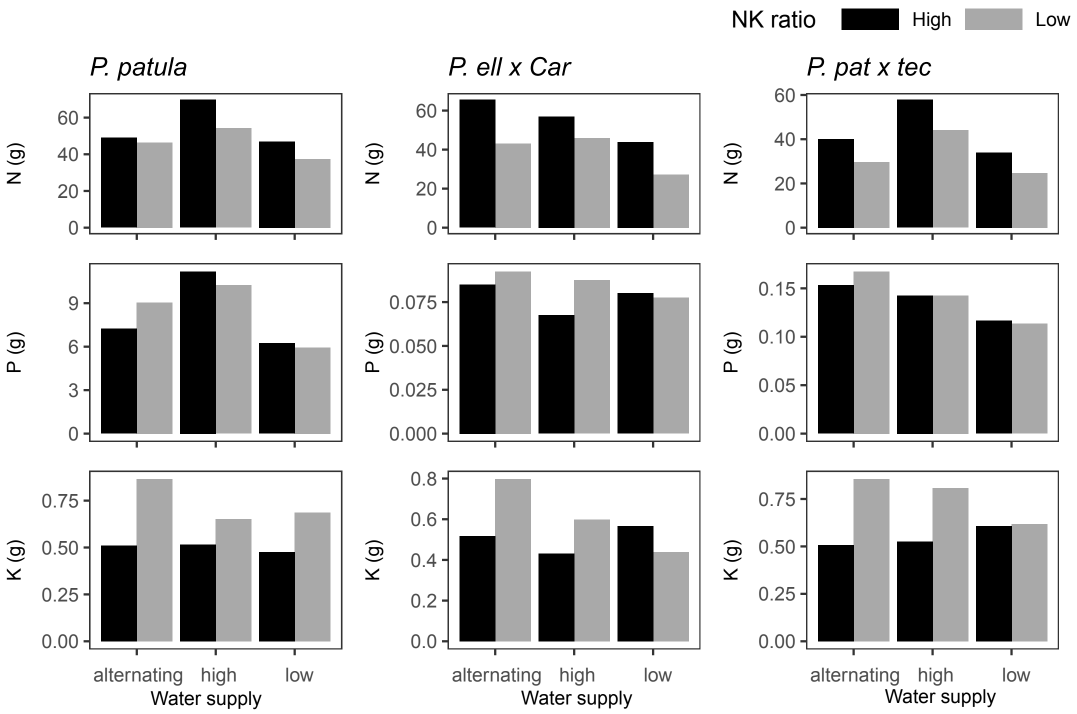

Figure 7: Bar chart of the average N, P and K contents, grouped per species and treatment combinations.

Tracheid production

Monthly tracheid production rates ranged from 0.2 to 1 tracheid day^{-1} across all water supply levels (data not shown). There was no difference in tracheid production rates, averaged across all trees and across all months, between high and low levels of water supply (both 0.5 tracheids day^{-1}). Rates in the alternating water level treatment decreased in periods of minimum water supply. For example, a decrease from 0.6 to 0.5 tracheids day^{-1} occurred from August to September 2017 (compare with Figure 5). Thereafter rates increased to between 0.6-1.0 tracheids day^{-1} up to December 2017. Similarly, the rate in February 2018 was 0.4 tracheids day^{-1} and then displayed a 100% increase in March 2018. The average radial diameter was also greater for trees in plots with higher water supply (27.9 μm) than a lower supply (24.9 μm).

Wood stiffness (MOE)

Values of stem MOE varied from roughly 0.1 to 5.8 GPa and, as indicated in Figure 9, were significantly greater for *P. patula* and *P. ell* x *car* in plots with lower N/K (Table 2). There was also a significant interaction between species and water supply (Figure 9). The increase in MOE from high to low levels of water

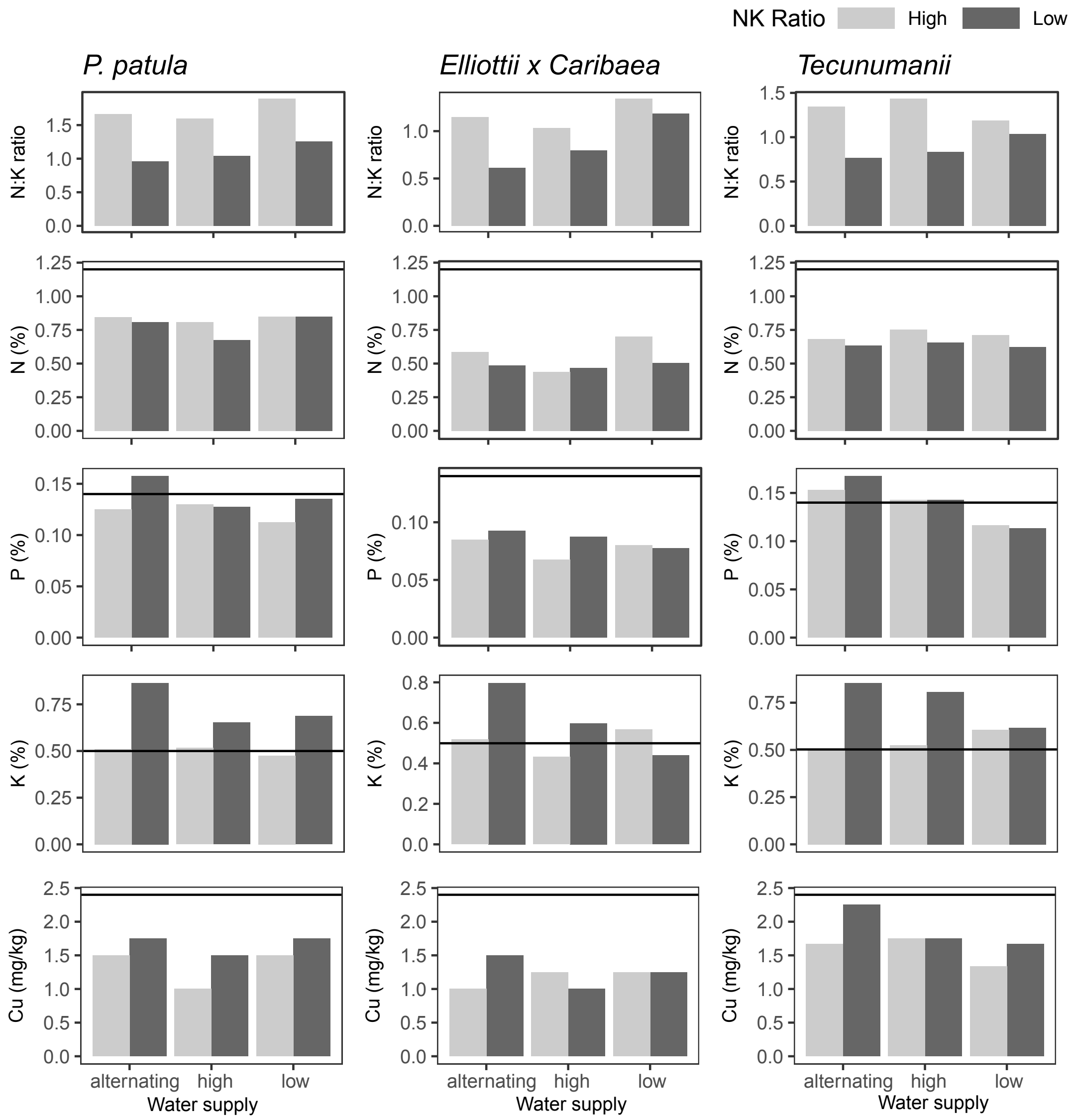

Figure 8: Bar charts of the average nutrient concentration levels with respect to reference values (horizontal lines) of adequate levels of nutrients given by Boardman et al. (1997).

supply was greater for *P. patula* than *P. ell* x *car*. MOE for *P. pat* x *tec* also followed the same trends: increasing with decreasing N/K and water availability. MOE for *P. patula* was higher than for *P. ell* x *car*, but the highest MOE values were found for *P. pat* x *tec* with an average MOE of 2588 MPa. This species also had slenderness values that were substantially greater than the other species (Figure 6). Slenderness had a significantly moderate association with MOE (Table 3). As with diameter, the MOE was closely, but negatively associated with leaf mass. Diameter in turn, was also closely related to MOE where the highest values were present in trees with the smallest diameters. Adding diameter to equation (2) accounted for the differences in MOE due to N/K ratio but not the interaction term (Table 2). The mean Silviscan MFA and oven dry WD, individually, explained MOE variation very poorly ($R^2 < 0.06$). When separating species, R^2 values for the relationship between MOE and oven dry WD became moderate, ranging from 0.44 to 0.59. Similarly, when excluding *P. ell* x *car*, MFA explained relatively much more MOE variation ($R^2 = 0.3$).

Wood density

The oven-dry WD of trees varied from around 380 to 600 kg m^{-3} and was not significantly influenced by N/K (Table 2). There was however a significant interaction between species and water supply on WD, where only *P. patula* differed significantly between water levels (Figure 9). *P. patula* and *P. pat* x *tec* had the highest average WD (497 and 500 kg m^{-3}, respectively). When adding diameter to the equation (2), the differences in growth rate accounted for differences in WD due to the interaction effect of species and water supply, which became non-significant (Table 2). There was some evidence that WD is inversely correlated with stem diameter ($R^2 = 0.3$).

There was high variation in WD at low temperatures, which decreased notably during the period of maximum daily temperatures around July 2018 (Figure 10). Temperature displayed a clear temporal pattern inverse to that of WD and had a moderate relationship with WD (r_s = -0.43, $p < 0.0001$). When averaging the variation of trees, the relationship increased considerably (r_s = -0.86, $p < 0.0001$) (not shown in Table 3 or 4). Up until September, the alternating level had the lowest growth rate and simultaneously had the highest WD during this time (Figure 10). Around September-November 2017, diameter increased notably beginning with the high water supply, then the alternating treatment and lastly the minimum supply of water (Figure 5). The same ordered pattern was observed in decreasing WD which accompanied the increases in growth around this time (arrows in Figure 10). The sparsity in data during July 2018 in Figure 10 was when the cambium remained inactive, which varied from tree to tree. Figure 11 indicates selected trees with reduced levels of noise which clearly highlights some decreases in WD in periods where the water supply was increased for each species.

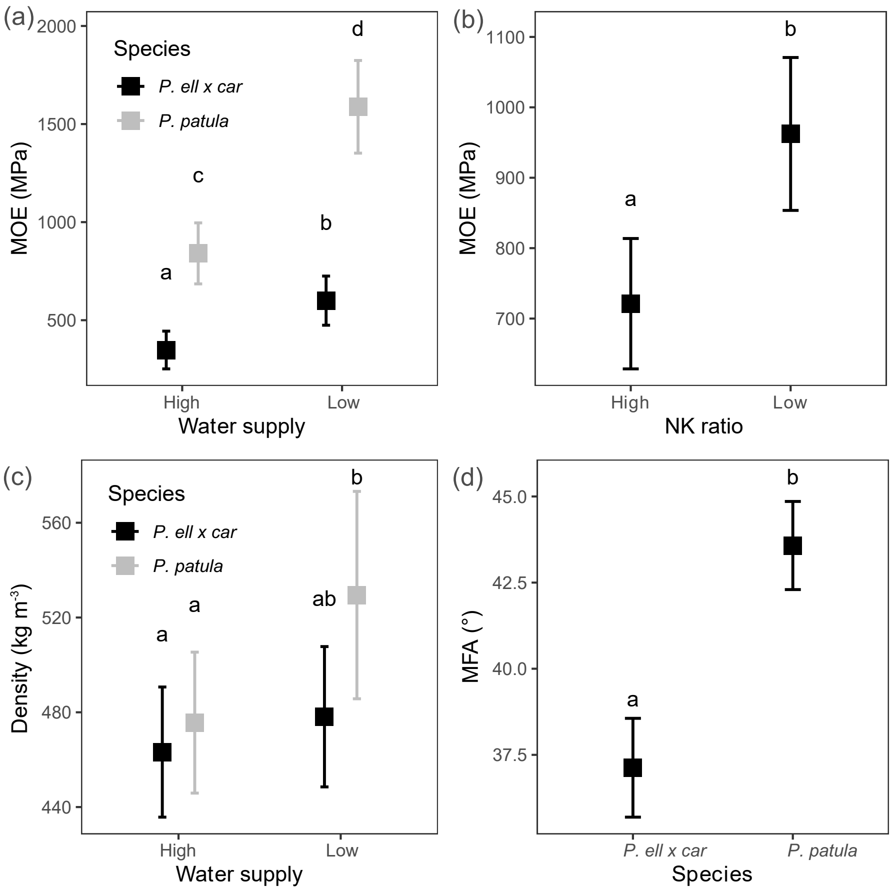

Figure 9: The means and confidence intervals from equation (2) for MOE grouped by the water supply and species interaction (a) and N/K (b), the oven dry WD grouped by the water supply and species interaction (c) and MFA grouped by species (d).

Microfibril angle

There was no significant effect of block, water supply or N/K on average MFA (Table 2). Species had a significant effect on MFA (Figure 9), where the average MFA decreased from *P. patula* (44°) to *P. ell* x *car* (37°) while *P. pat* x *tec* (33°) displayed the lowest MFA. Diameter had no significant effect on MFA (Table 2). MFA displayed the best relationship with stem slenderness across all species (Table 3), which increased considerably when *P. ell* x *car* was excluded ($r_s = 0.65$, $p < 0.0001$). The smoothing line in Figure 10 indicated that the trees receiving maximum water generally had slightly lower monthly MFA values. There were distinct changes in MFA gradient, where values began to decline, which coincided with periods of minimum water supply—notably in January 2018 (arrows in Figure 11).

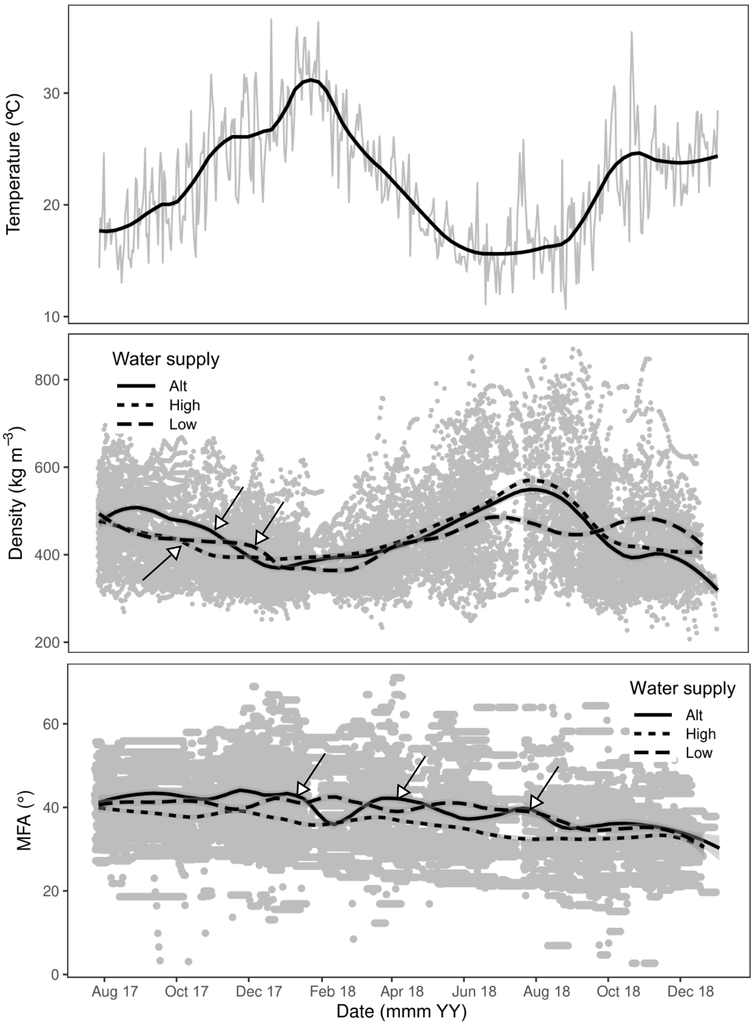

Figure 10: The variation of temperature (top), WD (middle) and MFA (bottom), fitted with a smoothing line for each treatment level of water supply. The arrows indicate periods when wood properties, for specific treatment levels, begin to decline.

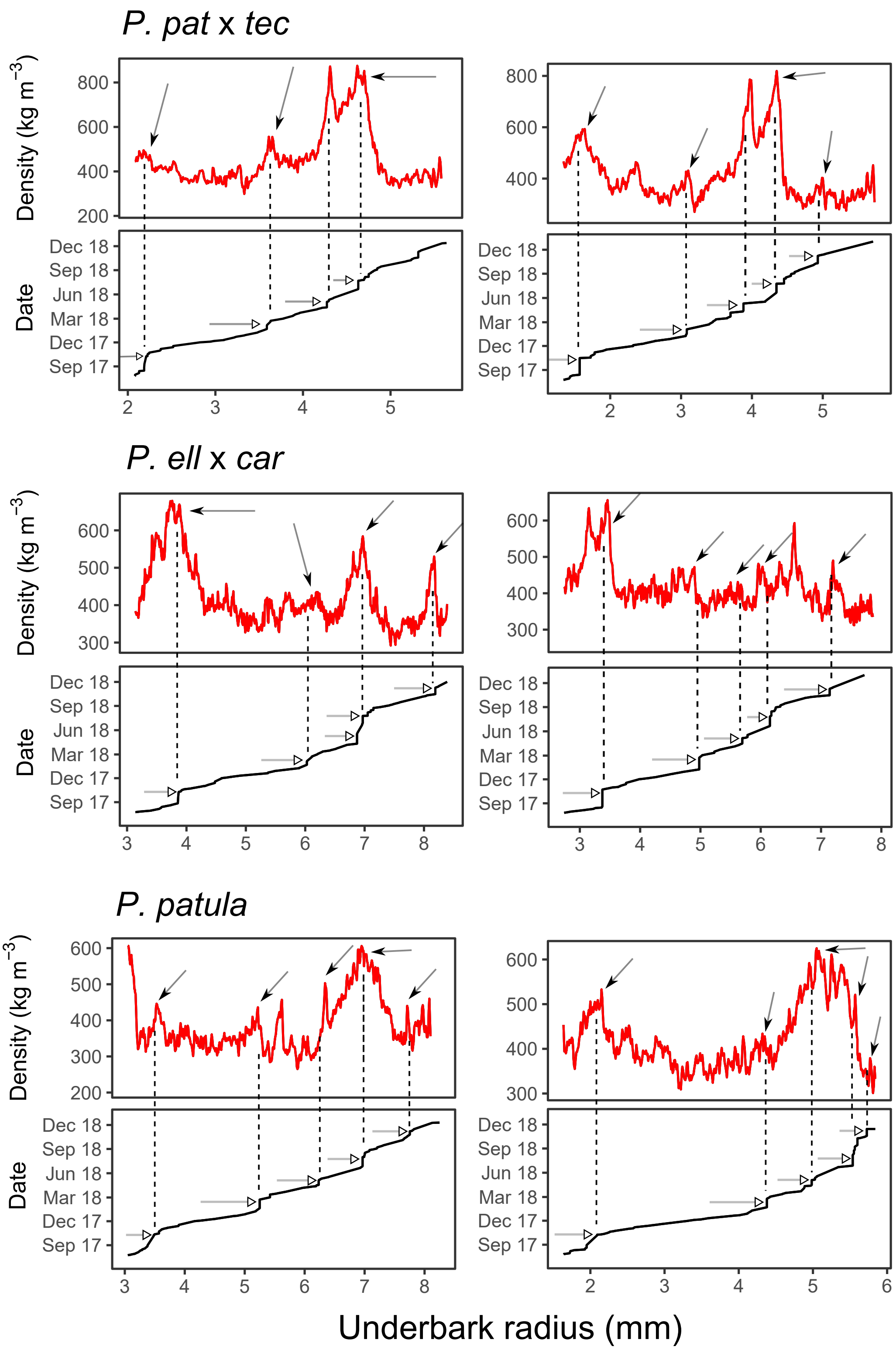

Figure 11: The temporal variation of WD for selected trees (two per species) with reduced noise within the data and growing in plots receiving alternating levels of water supply and grown in plots with a high N/K. Open arrow heads indicate the date at which water supply was switched to the maximum following a period of minimum water supply, while the closed arrows correspond to the start of the drop in density at the approximate date of wood formation.

Discussion

Stem growth and productivity

This study illustrated that the mass of leaves was the most influential growth factor for tree radial and longitudinal growth. The development of branches and foliage in trees are essential to the growth of a tree as it increases the area of the photosynthesizing surface of leaves and improves light interception (Bowyer et al., 2003). The mass of leaves was clearly limited by water supply and, to a lesser extent, the nutrient ratio of N to K concentration and content. Although water supply had a greater influence on growth of these trees, effects depend on the intensity of treatment levels. It was also clear that tree growth was responsive to fluctuations in soil water, which can impede the stomatal conductance and photosynthetic efficiency of trees (Sands and Mulligan, 1990). From Figure 5, the higher N/K ratio was also generally more effective in periods of higher water supply, particularly during the spring of 2018. *P. ell* x *car* was clearly more productive than *P. patula* over the duration of the experiment (Figure 2), while *P. pat* x *tec* generally performed poorly, even though the cuttings had generally thicker stems when planting into bags. The higher mortality rate and relatively poor productivity of the *P. pat* x *tec* is perhaps partly due to the environment in which it grew, which was more of a Mediterranean-type climate, favouring the *P. ell* x *car* hybrid (Hongwane et al., 2018). There was also a few cases of the *Fusarium circinatum* pathogen observed on some *P. patula* saplings which may have impeded growth.

Environmental effects on wood properties

The maximum variation of WD in this study was within trees. The variation of WD, per month, increased when temperatures were low, and in those cases were probably controlled more by factors other than temperature. From spring 2018, the WD of the droughted trees appeared to be less sensitive to the increasing temperatures, relative to the trees that received more water (Figure 10). In January 18, when watering was abruptly reduced (Figure 5) and temperature was high, WD rose notably. No wood was produced for a period. Then in Feb 18, watering was restored and the wood produced was immediately of a lower WD than the peak, but not as low as it had been earlier. Thus, the watering led to a growth response, and somewhat lower WD than the peak during the final stages of the mini-drought. But evidently the trees had shifted into a transition/latewood phase and density was increasing regardless. This may be a reason why there is little/no observable response in density to the drought in May 2018. Although Figure 11 showed that there were some distinct decreases in WD in individual trees, around this time, the average WD of trees was increasing where drought effects were perhaps obscured by the phenological effects of the "season end" (Begum et al., 2018). The fact that the watering was at "full speed" in the next spring meant that the decline in density with the spring flush is very marked.

Although there was no difference in tracheid production over the full period between maximum and minimum water supply, it was clear that the rate of cell production was hampered by the decreased water supply immediately after the treatment level had been switched. It can also be argued that the increase of radial diameter with water supply is mediated through stress related impairments to growth hormones from the crown (Larson, 1969). Since silvicultural interventions are designed to promote changes in growth rate, an important question is whether the treatments of silviculture influences wood properties independent of growth rates. This study showed that the variation of radial growth, expressed as diameter, when added to the models, could fully explain the significant differences in WD caused by the interaction of species and water supply. That is, the increase in average WD with water supply of *P. patula* (Figure 9) was accounted for by radial growth.

There have been many fertiliser trials established in South Africa using both pines and eucalypts, where the results generally indicate no significant effect of any practical value on the wood formed in pines due to changes in growth rate (Malan, 2012a) but an increase in WD in eucalypts (Du Toit et al., 2001). In fact, the results suggest that greater radial uniformity in WD is achieved through fertilization. Uniformity of practical importance could not be assessed in these young trees, but the results here indicate no significant effect of N/K on overall WD or MFA. The differences in N/K values between treatments were mainly driven by differences in K, which were all above the adequate level. But if we expect a minimum influence of K on yield above this level, then the differences in growth and wood properties, with respect to NK ratio, were likely due to difference in N, which were relatively small. This may explain the small effect of N/K on growth reported here. The effect on wood stiffness however was more pronounced (Figure 9). Previous research indicates that N accumulates during the active growing season (Louw and Scholes, 2003; Barrelet et al., 2006), whereas high concentrations of K are prevalent during the dormancy. This may have an effect on duration of latewood formation (Wessels et al., 2015b), which can improve the stiffness of wood (Watt et al., 2006a). It appears that concentrations of particularly N, P and Cu in needles may have dipped, especially towards the end of the pot experiment due to the dilution effect in the fast growing trees and due to the fact that most of these nutrients were not continuously topped up as the pot experiment progressed. The sub-optimal concentrations of particular nutrients, means that the effects of nutrition have to be interpreted with caution. There could have been a different and perhaps an improved growth response and wood development if the trees were treated to maintain nutrient profiles closer to optimum concentrations for the duration of the trial. Also note that an optimum K/N ratio of 0.35 had been proposed by (Linder, 1995) under controlled conditions (and if we invert that we obtain an N/K ratio of 2.8). However, this level is seldom realised in field. In practice, the N/K ratio commonly varies between 1.5 and 1.8 in south African pine stands, which is still somewhat higher than in our study.

Developement of wood stiffness

As expected, there were quite high MFA values in this study relative to typical mature wood values (Burdon et al., 2004), which are thought to be linked to greater flexibility of the small diameter stems when bending through large angles during early growth of the tree (Barnett and Bonham, 2004; Burgert, 2006). That is, instead of resisting external forces like wind loading, the tree at this developmental stage deploys a strategy designed to accommodate these dynamic forces. This has been well supported by numerous studies that show the strong dependence of wood stiffness on MFA and WD (Xu and Walker, 2004; Vikram et al., 2011; Wessels et al., 2015a; Auty et al., 2016). Additionally, this flexibility may also help position its leaders to capture light or respond to environmental factors. This strategy changes over time as the tree matures, where the cambium ages and the weight the tree now has to support, increases (Lachenbruch et al., 2011).

Tree slenderness displayed no obvious effect of water supply or N/K. While the trees in this study grew considerably in height over one year, the average slenderness was reduced, suggesting that they had primarily invested their resources in diameter growth and expanding its branches and foliage in order to capture light. A similar response was noted in *P. patula* mature trees (unpublished data); slenderness reduced at early cambial ages before it began to rapidly increase again up until harvesting. This would have added significant mass to the trees where a decrease in MFA would aid in increasing its stiffness to support this mass. As expected, MFA thus decreased over time and displayed a moderate relationship with tree slenderness. For a given tree weight and wood stiffness, a more slender stem has a greater risk of failing to support its own weight (Waghorn and Watt, 2013). In addition, less wind force is needed to offset the centre of gravity of the stem mass and induce a bending moment at the stem base (Lachenbruch et al., 2011), as the moment of inertia of the cross-sectional area is reduced. Tree slenderness in turn also had a modest relationship with wood stiffness. Similar or stronger relationships between the two have been documented for older trees in species like *P. radiata* (Waghorn et al., 2007) and *P. taeda* (Roth et al., 2007).

It was interesting that neither MFA, nor WD had as much explanatory power on stiffness as leaf mass (Table 3). One argument is that the presence of more crown producing auxins (which will result from higher leaf production) favour the production of wood with more juvenile characteristics (Larson, 1969), which has been supported on mature trees (Kuprevicius et al., 2013). There was no significant effect of N/K on either MFA or WD, but the stiffness of wood was affected. This effect was accounted for by diameter (Table 2), and had perhaps an indirect effect of crown development.

Diameter was strongly related to stiffness. On a tree-level, diameter had the highest Spearman rank order correlation with MOE (r = -0.838, Table 3) as well as on the sub-plot level (r = -0.911, Table 4). In contrast, on the tree-level MFA was not significantly correlated to MOE, whereas a moderate correlation of r = 0.647 existed with wood density (Table 3). The effect of diameter on MOE could partly be explained by the negative correlation of diameter and density. Also, in structural lumber grading the effect of size, also referred to as the size-effect, is a well researched concept, with larger pieces of lumber of the same grade being relatively weaker than smaller pieces (Madsen, 1992). This weakening effect is related to the larger chance of finding a debilitating defect in a larger volume of material than a smaller volume of material. It is not sure whether the strong effect of diameter on stiffness could maybe also be related to such a size-effect apart from the indirect effect of density.

Conclusion

This study showed that the young trees with increased water supply and an increased N/K experienced higher stem diameter growth. The stem diameters were also responsive to periodic changes in water supply. Wood stiffness was influenced by both water supply and N/K, which, in turn, effected neither average MFA nor WD. Wood stiffness was thus influenced by N/K independent of MFA or WD. There was some support for the argument that the amount of leaves produced by the trees was the underlying cause for stiffness variation (due to auxin production) combined with a size-effect similar to that experienced in lumber grading. Average MFA was not responsive to water supply, while only *P. patula* trees in plots with increased water supply had significantly lower wood density. This effect was dependent on radial growth as WD was not affected over and above the influence of diameter on WD. Part of the methods used in this study also revealed that temperature had a good correlation with monthly averages of WD and decreases in WD due to the release of drought stress, are limited as earlywood transitions into latewood at lower temperatures.

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Chapter 6

Summary of research results

The main results and conclusions drawn from the series of experiments as reported in chapters 2 to 4 are summarized as follows:

- The sawn lumber from the 16-20 year-old *Pinus patula* commercial compartments showed evidence of a significant increase in the mean MOE with an increase in stand density. Only lumber from the compartment with the highest stand density complied with the requirements for the lowest structural grade in South Africa.

- The 5th percentile bending strength improved with tree spacing (to a lesser extent than MOE) but was sufficient across the entire range of typical stand density regimes for *Pinus patula* in the region studied.

- The higher MOE of lumber from closely spaced trees was partly due to slower initial growth and subsequently an increase in the number of mature rings within lumber recovered closer to the pith. Additionally, there was an improvement of some wood properties independent from the effect of growth.

- The dynamic MOE, estimated on standing trees, improved significantly with an increase in planting density and displayed a significant relationship with microfibril angle.

- The volume per hectare yield increased with planting density and the lowest planting density had trees with the most deformed stems (expressed as deviations from perfect straightness).

- The variation of lumber MOE was best explained by a combination of microfibril angle, density and the number of knots, accounting for over 70% of its variation.

- Microfibril angle decreased non-linearly from 30° to 7° from pith to bark and was significantly influenced by tree spacing. Density and MFA in closely spaced trees had sharper wood property radial gradients and consequently a restricted juvenile wood proportion. This was due to a combination of both improvements in wood properties at equivalent cambial ages and a reduction in the growth rate.

- Tree spacing at establishment also influenced wood property gradient independent of growth rate, as expressed by the width of annual growth rings.
- Slenderness did not contribute significantly more to the models developed than ring width but the crown mass of trees across tree spacing induced considerably different loads on trees at the time of harvest and is an important consideration of the mechanics of trees. The leaf mass of the young saplings was also significantly influenced wood stiffness.
- Wood stiffness of the young saplings also decreased significantly with water supply and a higher N/K ratio. MFA was not significantly influenced by either water supply and N/K ratio. Density decreased significantly with water supply for *Pinus patula* and showed a clear sensitivity to temporal variations in water stress, which was limited by phenological effects in lower temperatures.

Outcomes of the study

This study successfully demonstrated the potential of stand density management as an intervention tool to mitigate the well established issue of increasing juvenile wood proportions. The results contribute significantly to the body of knowledge concerning our understanding of how wood quality can be improved and may be useful for growers and processors of *Pinus patula* intended for structural lumber. More work is required on *Pinus patula* to investigate comprehensive management regimes including fertilization and thinning and their effect on wood properties.

The study also showed that *Pinus patula* generally did not show a strong relationship between tree slenderness and wood stiffness, which is often the case with *Pinus radiata*. There is however differences in wind speed at the sites of previous studies using *Pinus radiata* and this study. Separating the effects of simultaneous changes in both resource availability and wind-induced swaying as a result of changes in stand density will be worth future investigations and will increase our understanding of the casual effects of stand density on wood properties.

Considering climate change and the ever-decreasing time between successive periods of drought, the negative effect of water supply on MOE and WD is an important consideration. Previous studies also typically focused on the effects of particularly nitrogen applications on wood properties. The examination of nutrient ratios in this study builds on previous work and suggests that the formulation of nutrient ratios should be an important consideration when manipulating tree growth through fertilizer applications. The results displayed an effect of N/K on wood stiffness independent of both wood density and MFA and was accounted for by growth rate, which displayed the strongest relationship with leaf mass. Further investigation into the relationship between foliar biomass (over time) and wood stiffness is therefore recommended as an area of future research that may be valuable.

Appendices

Appendix A

Declarations of candidate and co-authors

Deceleration by the candidate (Chapter 2):
With regard to chapter 2 "The effect of planting spacing on *Pinus patula* stem straightness, microfibril angle and wood density", the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution (%)
- Contributed to the concept - Sampling - Data analysis - Wrote the paper	85

The following co-authors have contributed to chapter 2 "The effect of planting spacing on *Pinus patula* stem straightness, microfibril angle and wood density":

Name	e-mail address	Nature of contribution	Extent of contribution (%)
A Kunneke	ak3@sun.ac.za	Collected Data Contributed to the writing	5
DM Drew	drew@sun.ac.za	Contributed to the writing	5
CB Wessels	cbw@sun.ac.za	Conceptualized Contributed to the writing	5

Signature of candidate: Declaration with signature in possession of candidate and supervisor
Date: 11 Dec 2019

Deceleration by co-authors (Chapter 2):
The undersigned hereby confirm that:

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to chapter 2 "The effect of planting spacing on *Pinus patula* stem straightness, microfibril angle and wood density",
2. no other authors contributed to chapter 2 "The effect of planting spacing on *Pinus patula* stem straightness, microfibril angle and wood density" besides those specified above, and
3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in chapter "The effect of planting spacing on *Pinus patula* stem straightness, microfibril angle and wood density" of this dissertation.

Signature	Institutional affiliation	Date
Declaration with signatures in possession of candidate and supervisor	Stellenbosch university	16 Dec 2019

Declaration by the candidate (Chapter 3):
With regard to chapter 3 "The effect of stand density management on *Pinus patula* lumber properties", the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution (%)
- Contributed to the concept - Sampling - Data analysis - Wrote the paper	85

The following co-authors have contributed to chapter 3 "The effect of stand density management on *Pinus patula* lumber properties":

Name	e-mail address	Nature of contribution	Extent of contribution (%)
CB Wessels	cbw@sun.ac.za	Conceptualized the study Contributed to the writing	15

Signature of candidate: Declaration with signature in possession of candidate and supervisor
Date: 11 Dec 2019

Declaration by co-authors (Chapter 3):
The undersigned hereby confirm that:

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to chapter 3 "The effect of stand density management on *Pinus patula* lumber properties",

2. no other authors contributed to chapter 3 "The effect of stand density management on *Pinus patula* lumber properties" besides those specified above, and

3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in chapter 3 "The effect of stand density management on *Pinus patula* lumber properties" of this dissertation.

Signature	Institutional affiliation	Date
Declaration with signatures in possession of candidate and supervisor	Stellenbosch university	16 Dec 2019

Declaration by the candidate (Chapter 4):
With regard to chapter 4 "The flexural lumber properties of *Pinus patula* Schiede ex Schltdl. & Cham. improves with decreasing initial tree spacing", the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution (%)
- Conceptualized the study - Sampling - Data analysis - Wrote the paper	85

The following co-authors have contributed to chapter 4 "The flexural lumber properties of *Pinus patula* Schiede ex Schltdl. & Cham. improves with decreasing initial tree spacing":

Name	e-mail address	Nature of contribution	Extent of contribution (%)
DM Drew	drew@sun.ac.za	Contributed to the writing	8
CB Wessels	cbw@sun.ac.za	Contributed to the writing	8

Signature of candidate: Declaration with signature in possession of candidate and supervisor
Date: 11 Dec 2019

Declaration by co-authors (Chapter 4):
The undersigned hereby confirm that:

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to chapter 4 "The flexural lumber properties of *Pinus patula* Schiede ex Schltdl. & Cham. improves with decreasing initial tree spacing",

2. no other authors contributed to chapter 4 "The flexural lumber properties of *Pinus patula* Schiede ex Schltdl. & Cham. improves with decreasing initial tree spacing" besides those specified above, and

3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in chapter 4 "The flexural lumber properties of *Pinus patula* Schiede ex Schltdl. & Cham. improves with decreasing initial tree spacing" of this dissertation.

Signature	Institutional affiliation	Date
Declaration with signatures in possession of candidate and supervisor	Stellenbosch university	16 Dec 2019

Declaration by the candidate (Chapter 5):
With regard to chapter 5 "The effect of water supply and Nitrogen/Potassium ratio on selected wood properties of *Pinus patula*, *Pinus elliottii* x *caribaea*, and *Pinus patula* x *tecunumanii* saplings", the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution (%)
- Contributed to the concept - Sampling - Data analysis - Wrote the paper	81

The following co-authors have contributed to chapter 5 "The effect of water supply and Nitrogen/Potassium ratio on selected wood properties of *Pinus patula*, *Pinus elliottii* x *caribaea*, and *Pinus patula* x *tecunumanii* saplings":

Name	e-mail address	Nature of contribution	Extent of contribution (%)
DM Drew	drew@sun.ac.za	Contributed to the concept Contributed to the writing	8
B du Toit	ben@sun.ac.za	Contributed to the writing	3
CB Wessels	cbw@sun.ac.za	Contributed to the concept Contributed to the writing	8

Signature of candidate: Declaration with signature in possession of candidate and supervisor
Date: 11 Dec 2019

Declaration by co-authors (Chapter 5):
The undersigned hereby confirm that:

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to chapter 5 "The effect of water supply and Nitrogen/Potassium ratio on selected wood properties of *Pinus patula*, *Pinus elliottii* x *caribaea*, and *Pinus patula* x *tecunumanii* saplings",

2. no other authors contributed to chapter 5 "The effect of water supply and Nitrogen/Potassium ratio on selected wood properties of *Pinus patula*, *Pinus*

elliottii x *caribaea*, and *Pinus patula* x *tecunumanii* saplings" besides those specified above, and

3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in chapter 5 "The effect of water supply and Nitrogen/Potassium ratio on selected wood properties of *Pinus patula*, *Pinus elliottii* x *caribaea*, and *Pinus patula* x *tecunumanii* saplings" of this dissertation.

Signature	Institutional affiliation	Date
Declaration with signatures in possession of candidate and supervisor	Stellenbosch university	16 Dec 2019