Growth and dynamic modulus of elasticity of *Pinus patula* × *Pinus tecunumanii* hybrids in Mpumalanga, South Africa

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Field establishment of South Africa's most important commercial pine species, *Pinus patula*, is severely hampered by the pitch canker fungus, *Fusarium circinatum*. Importantly, hybrids between *P. patula* and other pine species tolerant to the pitch canker fungus, such as *P. tecunumanii* and *P. oocarpa*, have been identified as an alternative planting stock. In this study, variation in tree volume and dynamic modulus of elasticity (MOE_{dym}) of the *P. patula* × *P. tecunumanii* (low- and high-elevation [LE and HE] ecotypes) hybrid was compared with the *P. elliottii* × *P. caribaea* hybrid, and the pure species *P. tecunumanii* (LE) and *P. patula*. The MOE_{dym} was assessed using the Fakkop TreeSonic microsecond instrument across three sites. The results of the study showed that *P. patula* × *P. tecunumanii* LE performed significantly better than *P. patula* × *P. tecunumanii* HE for volume and MOE_{dym}, which in turn was significantly better than *P. patula*. The MOE_{dym} and tree growth decreased with an increase in elevation. There was significant taxon × site interaction for volume and MOE_{dym}. The results of these trials suggested that *P. patula* × *P. tecunumanii* LE is a suitable alternative to *P. patula* in the Sabie region of Mpumalanga in South Africa on frost-free sites, in terms of the traits that were assessed.

Keywords: modulus of elasticity, pine hybrids, productivity, site index

Introduction

Pinus patula extends from 24° to 17°30′ N latitude in Mexico between altitudes of 1 490 and 3 100 m (Dvorak et al. 2000c). This species occurs in temperate climates where annual precipitation ranges between 1 000 to 2 500 mm and experiences up to five dry months in some places. The average temperature in this region ranges from 10 to 18 °C. In South Africa, *P. patula* is the most important pine species used to establish plantations due to its superior growth and wood properties (Dvorak et al. 2000c). This species is insensitive to changes in climatic conditions with regard to growth (Leibing et al. 2013). *Pinus patula* has proved to be an ideal timber for the production of saw logs, veneer logs and pulpwood. All commercial plantations of this species are managed to yield one or more of these products at the end of a rotation. The genetic improvement of *P. patula* started more than three decades ago with the main focus on growth rate, adaptability and stem characteristics. *Pinus patula* does very well on colder sites and above 1 000 metres above sea level (masl) with an average annual rainfall of 800–900 mm. It performs poorly on tropical sites.

Pinus tecunumanii occurs in Mexico, Guatemala, Honduras and Nicaragua between 12°42′ N and 17°02′ N in an altitudinal range of 450–2 900 m. It is found in areas where the annual precipitation is 1 000–2 500 mm. The species is divided into two groups: low- and high-elevation populations (Dvorak et al. 2000b). On warmer sites it grows alongside other pine species, such as *P. oocarpa* and *P. maximinoi.*

In South Africa *P. tecunumanii* has shown outstanding growth, excellent wood properties and good tolerance to *Fusarium circinatum* (Dvorak et al. 2000b; Hodge and Dvorak 2000; Mitchell et al. 2012). Large variations between provenances and families of the high-elevation (HE) source of *P. tecunumanii* were reported (Hodge and Dvorak 2007; Mitchell et al. 2011). *Pinus tecunumanii* produces wood of similar or slightly higher density than *P. patula*, *P. taeda* and *P. elliottii.* In South Africa, Colombia and Brazil it was reported that *P. tecunumanii* was prone to stem breakage; however, this was noted to occur more frequently in the HE population (Hodge and Dvorak 1999; Leibing et al. 2013).

In the last few decades breeding to improve disease tolerance in pines has been a priority, particularly since the pitch canker fungus, *F. circinatum*, has become an established pathogen in South Africa (Viljoen et al. 1995). Post-planting survival of *P. patula* in South Africa has decreased as a result of this pathogen (Hodge and Dvorak 2007; Mitchell et al. 2012; Kanzler et al. 2014). The poor survival rates prompted the development of new hybrid combinations to overcome the mortality caused by

F. circinatum. Mitchell et al. (2012) argued that planting *P. elliottii* and *P. taeda* to replace *P. patula* was not a suitable solution because these two species did not perform any better than *P. patula* in terms of volume yield on certain sites.

Fusarium circinatum screening trials indicated that *P. elliottii* × *P. caribaea* and *P. patula* × *P. oocarpa* hybrids are more tolerant than the maternal parent to the pitch canker fungus (Hodge and Dvorak 2007; Roux et al. 2007). This suggests that there is potential to select for disease tolerance given the large pool of different species and wide range of provenance material available in South Africa. This puts the industry in a position to develop, test and cross and then select the best hybrid combinations. Research and development of the *P. patula* × *P. tecunumanii* hybrid has been ongoing for more than 20 years (Kanzler et al. 2014). Studies conducted in Swaziland and in the KwaZulu-Natal Midlands of South Africa demonstrated that *P. patula* × *P. tecunumanii* outperforms *P. patula* by an average of 23% in volume at the age of five years (Kanzler et al. 2012). The study also reported that 64% of the *P. patula* × *P. tecunumanii* families performed better than both *P. patula* and *P. tecunumanii* controls. Furthermore, the *P. patula* × *P. tecunumanii* hybrid was reported to be significantly more tolerant to *F. circinatum* than *P. patula* (Mitchell et al. 2012; Kanzler et al. 2014). Thus, due to these benefits, *P. patula* × *P. tecunumanii* is now widely planted as an alternative to *P. patula* in South Africa.

In addition to increasing growth and disease tolerance of commercially grown forest trees, there is a need to improve wood quality and this has become an important component in breeding programmes around the world (Apiolaza et al. 2008). There are both destructive and non-destructive methods used to measure wood quality. Acoustic technology is a non-destructive technology used to measure the time-of-flight of soundwaves through the wood of both standing trees and cut logs (Wielinga et al. 2009; Lowell et al. 2014). This technology has gained popularity as it is easy, quick and cheap to use, despite its limitations in that it measures the stiffness of the outer wood and is based on an assumption of constant wood density (Lowell et al. 2014). Strong correlations between modulus of elasticity (MOE), density and velocity have been reported (Johnson and Gartner 2006; Lindström et al. 2009). Johnson and Gartner (2006) reported a correlation of 0.91 for acoustic velocity and MOE of *Pseudotsuga menziesii*. Wang et al. (2007) reported a correlation of 0.89 for MOE and velocity, and 0.85 for MFA and velocity in *P. radiata*. The MOE is affected by wood density, microfibril angle (MFA) and moisture content (Johnson and Gartner 2006; Nilsson 2014).

The South African National Standard 1783 (SANS 1783-2 2012) makes provision for three structural grades for South African pine. Each grade has minimum requirements for MOE and density. Timber that is classified as S5 grade should have a minimum of 7.8 Gpa, S7 grade 9.6 Gpa and S10 grade 12 Gpa. In addition to MOE, each grade must have minimum densities of 360, 425 and 475 kg m³, respectively (SABS 0163-2 2001).

The objectives of this study were to measure and compare the growth, and also the dynamic modulus of elasticity (MOE_{dym}), of *P. patula* × *P. tecunumanii* and some other crosses and pure species across a range of sites for the purpose of evaluating any benefits that the hybrid pine might have over more traditional species choices.

Materials and methods

Study material
Camcore (International Tree Breeding and Conservation Program) is an organisation based at North Carolina State University, USA. Camcore has members in the Americas, Africa and Australia; members collaborate and share genetic material in the form of pollen, seeds and vegetative cuttings for research and breeding purposes. A number of Camcore *P. tecunumanii* provenance/family trials, testing unimproved material from Mexico and Central America, were planted in the early 1980s. Selections were made in these, some of which have been grafted into clone banks and seed orchards. Pollen harvested from these selections was used to produce the *P. patula* × *P. tecunumanii* hybrids in the current trials. The first- and second-generation *P. patula* selections used in the crossing program had been developed within the Komatiland Forests breeding program. The hybrid seeds were used to establish seedling hedges at the Tweefontein nursery near Sabie (Mpumalanga, South Africa). Hedges were kept in groups according to pedigree (family). Cuttings were harvested from the hedges and pedigree information was maintained during the rooting process and trial establishment.

Experimental design
Six sites were selected for the trial series (Table 1). Entries were arranged in six-tree row plots within a randomised complete block design, replicated six times except for the trial established at Bergvliet where entries were arranged as single-tree plots (replicated 30 times). The trees were planted at an espacement of 3 m × 3 m. *Pinus patula*, *P. taeda*, *P. elliottii*, *P. tecunumanii* (LE source) seedlings

Table 1: General trial details for the six trial sites. MAT = mean annual temperature, MAP = mean annual precipitation

Location	Planting date	Plot size (trees)	Number of replicates	Altitude (m)	MAT (°C)	MAP (mm)	Soil clay (%)
Spitskop1	10 December 2001	1 × 6	6	1 310	16–18	1 050–1 300	35
Bergvliet	11 December 2001	1 × 1	30	1 051	14–16	850–1 050	20
Jessievale	13 November 2007	1 × 6	6	1 723	14–16	850–1 050	15
Spitskop2	13 February 2008	1 × 6	6	1 460	16–18	>1 300	35
Witklip	10 March 2008	1 × 6	6	1 058	14–16	1 050–1 300	25
Tweefontein	13 March 2008	1 × 6	6	1 250	16–18	>1 300	40

and *P. elliotti* × *P. caribaea* var. *hondurensis* hybrid cuttings were included as controls in some of the trials (Table 2). *Pinus greggii* var. *greggii* (also known as the northern variety) was used in the *P. patula* × *P. greggii* cross. The actual species/hybrid, number of families and total trees used for the analysis (values in parenthesis), for each trial are shown in Table 2. The seedling control entries were represented as a seed orchard mix of families. The *P. patula* controls represented a mix of first-generation (F_1) and second-generation (F_2) families as two separate entries. In the case of the *P. patula* F_2 entry, a mix of the best 10 families was used and at Bergvliet, Spitskop2 and Jessievale an additional best families were added separately as controls.

Trial establishment

For each trial, the plants were planted into pits that had been prepared on the same day of planting. Plants did not receive water at planting as the soils at all sites were considered sufficiently moist from earlier rainfall events.

Data collection and analysis

Data collection

The first survival assessment was carried out one month after planting. The dead plants were blanked soon after the survival assessment between 30 and 40 d after planting. In cases where there were an insufficient number of plants to blank, *P. elliottii* or *P. taeda* were used as fillers and recorded as such; fillers were excluded from assessment during measurements. The first growth assessment was carried out at three years of age followed by a five-year assessment. During the five-year assessment, wood quality was assessed by measuring acoustic velocity using the Fakopp TreeSonic microsecond instrument (Malan 2010) at three sites: Tweefontein, Witklip and Spitskop2. All trees in the trials were assessed and recorded.

The diameter at breast height (DBH) and individual tree height (*H*) were assessed for all trees. Tree volume was estimated using the volume equation for juvenile trees (Ladrach and Mazuera 1978):

$$V = 0.00003 \times H \times DBH^2 \qquad (1)$$

where *V* is the stem volume (m³), DBH is the over bark diameter at breast height (cm) and *H* is the tree height (m).

Dynamic modulus of elasticity (MOE_{dym}) was estimated by using the average time it takes for the stress wave to travel through the wood over 1 m using the Fakkop TreeSonic microsecond instrument and the following equation (Wielinga et al. 2009):

$$MOE_{dym} = \rho V^2 \times 10^{-3} \qquad (2)$$

where MOE_{dym} is the modulus of elasticity (Gpa), *V* is the velocity of sound through the wood (km s⁻¹) and ρ is the wood density (kg m⁻³). The density is assumed to be constant at 1 000 kg m⁻³ (Wielinga et al. 2009; Malan 2010).

Data analysis

All analyses and results presented in this work were based on the five-year data. Data were analysed using SAS 9.3 (SAS Institute, Cary, NC, USA, 2010). PROC GLM and the Student Newman–Keuls (SNK) test were used to distinguish entry differences at the 5% significance level. Individual tree volume and MOE_{dym} were corrected by subtracting the difference between the repetition mean and the trial mean. Corrected volume and MOE_{dym} were used to calculate the least squares means for volume and MOE_{dym}. PROC GLM for individual sites was carried out to determine if there were significant differences between taxa (species/hybrid) for volume and MOE_{dym}. All ANOVA results presented are type III sums of squares.

The models used for the analysis were:

$$\bar{y}_{ij} = \mu + rep_i + taxa_j + \varepsilon_{ij} \qquad (3)$$

where $\bar{y}_{ij}$ is the *i*th observed mean growth response of the *j*th taxon, μ is the overall mean growth of taxa at possible environment, rep_i represents the effect of the *i*th rep, $taxa_j$ is the effect of the *j*th taxon, and ε_{ij} is the random error term.

$$\bar{y}_{jk} = \mu + site_i + rep_{ij} + taxa_k + taxa_k*site_j + \varepsilon_{ijk} \qquad (4)$$

where $\bar{y}_k$ is the *j*th observed growth response of the *k*th taxon, μ is the overall mean growth of taxa at possible environment, rep_{ij} represents the effect of the *i*th rep in the *j*th site, $site_j$ is the fixed effect of the *j*th site, $taxa_k$ is the effect of the *k*th taxon, $taxa_k*site_j$ is the interaction effect of the *k*th taxon in the *i*th site, and ε_{ijk} is the random error term.

Table 2: Outline of taxa used for each site showing the number of families and total number of trees (indicated in parentheses) used in the analyses. Mix = seedlot from two or more families from the same species

Taxon[1]	Spitskop1	Bergvliet	Jessievale	Spitskop2	Witklip	Tweefontein
P. elliottii			Mix (66)			
P. ell×car			Mix (49)	Mix (28)	Mix (34)	Mix (34)
P. patula (F_1)	Mix (11)	Mix (23)				
P. patula (F_2)	Mix (123)	Mix (121)	Mix (50)	Mix (27)	Mix (18)	Mix (7)
P. pat×greg	Mix (14)	Mix (20)				
P. pat×*tec*H		1 (19)	19 (503)	33 (1 108)	27 (840)	21 (716)
P. pat×*tec*L	26 (461)	22 (508)		87 (2 813)	76 (2 109)	78 (2 515)
P. taeda			Mix (69)			
P. *tec* LE				Mix (29)	Mix (31)	Mix (34)

[a] The taxon full names are: *P. ell×car* = *P. elliottii* × *P. caribaea* var. *hondurensis*; *P. pat×greg* = *P. patula* × *P. greggii*; *P. pat×tec*H = *P. patula* × *P. tecunumanii* High elevation (HE); *P. pat×tec*L = *P. patula* × *P. tecunumanii* Low elevation (LE); *P. tec*LE = *P. tecunumanii* Low elevation

Results

Survival

The five-year average survival for the six sites was more than 70% except for Spitskop1, which was 44%. The survival rates for the individual entries on this latter site were all below 60%, with F_1 *P. patula* being the worst (Figure 1). Both *P. patula* hybrids on this site had poorer survival than the other five sites. At Tweefontein, the survival for *P. patula* was 20%, which was worse than any of the other sites.

During the first year following trial establishment, dying *P. patula* plants from the Tweefontein site were sent to the Forestry and Agriculture Biotechnology Institute (FABI) at the University of Pretoria to be screened for the presence of *F. circinatum*. The fungus was found to be present on most samples, suggesting the poor survival of this entry was most likely due to infection by *F. circinatum*. The *P. patula* hybrids showed better survival than *P. patula* in the presence of *F. circinatum* in all cases for trials planted after 2007.

Growth

Site index is a tool used to measure a forest's potential productivity for a specific species at a defined base age (Kodani et al. 2010). Tree samples that have an undamaged stem, uniform annual height and dominant crown are used to determine the site index. Total tree height is measured and the growth rings are counted at 1.3 m to determine breast height age. The tree height and DBH is used to predict timber productivity, wood volume and growth rate on a specific site.

The estimated site indices for the trial sites range from 23 to 30 m at 20 years of age, calculated for either *P. patula* or *P. elliottii* as model species to calibrate each site. The estimated site indices were from the compartment registers developed by the Planning department at Komatiland Forests. Individual tree height, which was collected during assessment, was used to identify the tallest and shortest trees (data not presented). Actual measurements in trials had the tallest *P. patula* tree at 13.4 m with an average height of 7.8 m and the *P. patula* × *P. tecunumanii* LE tallest tree was 15.6 m with an average of 9.2 m. On average *P. patula* × *P. tecunumanii* LE was between 9.5% and 51% taller than the improved *P. patula* (F_2), and between 6% and 15% taller than *P. patula* × *P. tecunumanii* HE. Based on these assessments, the *P. patula* × *P. tecunumanii* LE hybrid, being faster growing than *P. patula*, *P. elliottii* and *P. taeda*, is predicted to be over 35 m at age 20 years. This assumption is based on the fact that at five years the hybrid is on average 30% taller than *P. patula*.
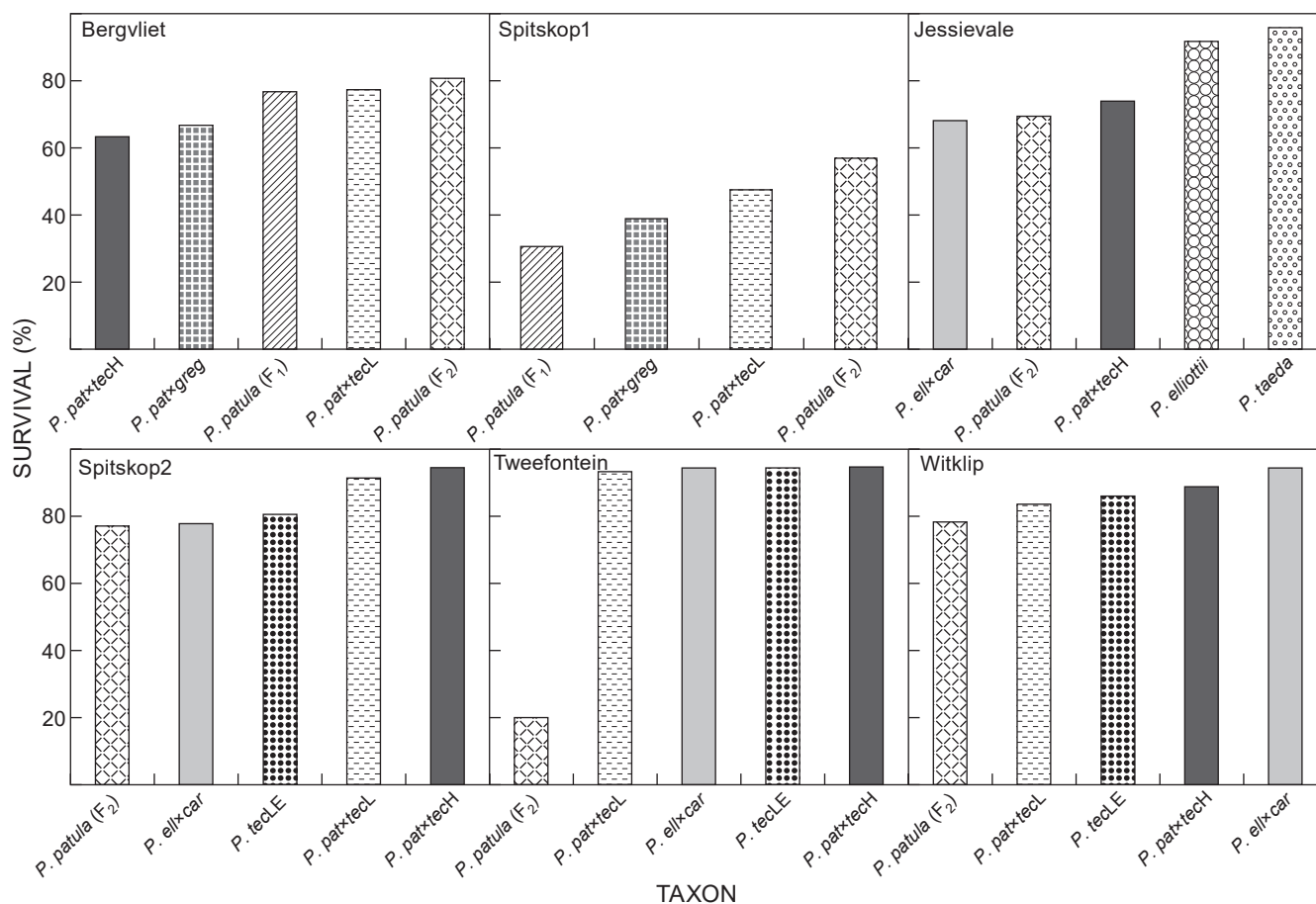
Figure 1: Five-year survival of the trials across six sites. *P. ell*×*car* = *P. elliottii* × *P. caribaea* var. *hondurensis*; *P. pat*×*greg* = *P. patula* × *P. greggii*; *P. pat*×*tec*H = *P. patula* × *P. tecunumanii* High elevation (HE); *P. pat*×*tec*L = *P. patula* × *P. tecunumanii* Low elevation (LE); *P. tec*LE = *P. tecunumanii* LE

Volume estimation

In forestry, productivity is measured by volume of wood produced. There were significant differences ($P < 0.0001$) between the species for volume at each site, when analysed individually (Table 3). The interaction between site and species was highly significant. Site and species effect was highly significant (Table 3). However, on Bergvliet volume of *P. patula* × *P. greggii* was greater than *P. patula* × *P. tecunumanii* LE. *Pinus patula* × *P. tecunumanii* LE was significantly larger than all other entries (Figure 2). Volumes of *P. elliottii* × *P. caribaea* and *P. patula* × *P. tecunumanii* HE at Tweefontein were not statistically different (Figure 2). At Tweefontein, Witklip and Berglviet, *P. patula* × *P. tecunumanii* LE was significantly different to *P. patula* (F_2). However, no difference was observed between the two entries at Spitskop1 and 2 (Figure 2). There were also no differences observed for *P. patula* (F_2) and *P. patula* × *P. tecunumanii* HE at Spitskop2 and Jessievale, but *P. patula* × *P. tecunumanii* HE was significantly different to *P. patula* at Tweefontein and Bergvliet.

The mean volumes at Jessievale and Spitskop1 were not significantly different (Table 4). The other four sites were significantly different from each other with Witklip having the highest volume (0.0774 m^3). The volume for *P. patula* at Witklip was 55% more than that at both Spitskop2 and Tweefontein. Volume of *P. patula* × *P. tecunumanii* LE was significantly higher than all other entries on all sites except for *P. elliotti* × *P. caribaea* at Spitskop2 with a 2% difference in volume, and at Tweefontein and Witklip the difference was 16% to 24% (Figure 2).

Table 3: Across site analysis of variance for volume at five years of age

Source	df	Sum of squares	Mean square	*F*-value	Pr > *F*
Replicate	29	0.1458	0.0050	6.82	<0.0001
Site	5	0.1537	0.0307	41.72	<0.0001
Taxon	9	0.1249	0.0139	18.84	<0.0001
Site*Taxon	14	0.0665	0.0048	6.44	<0.0001
Error	12 318	9.0811	0.0007		
Corrected total	12 375	13.2405			
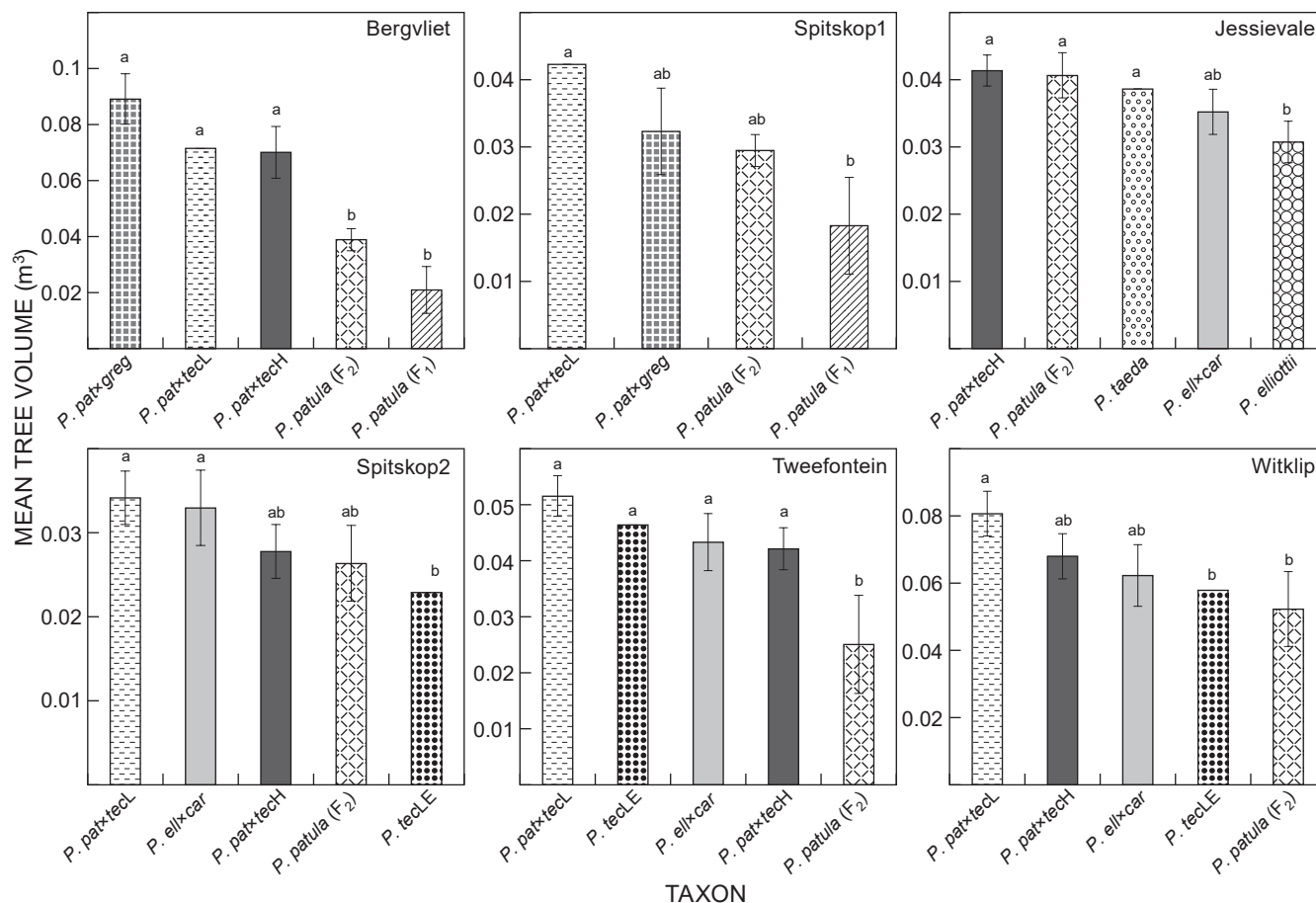
Figure 2: Mean tree volume for the various taxa at the six sites at five years of age. Error bars represent the SE. Different letters above bars indicate a significant difference at the 5% significance level

At Jessievale *P. patula* × *P. tecunumanii* HE was not significantly different from *P. patula* (Figure 2). At Tweefontein, *P. patula* × *P. tecunumanii* LE had 65.7% more volume than *P. patula* (F$_2$), and at Bergvliet it had 60% higher volume than *P. patula* (F$_2$) and 110% greater volume than *P. patula* (F$_1$). At Spitskop1 *P. patula* × *P. tecunumanii* LE had 38% more volume than *P. patula* and 39% gr*eater* volume than *P. patula* at Witklip. The volumes of *P. patula* (F$_2$) and *P. patula* × *P. tecunumanii* HE at Jessievale were not significantly different from each other (Figure 2).

Wood quality: modulus of elasticity

Data for MOE$_{dym}$ are presented for the three sites at

Table 4: Site means for volume at five years. Means followed by a different superscript letter differ at 5% significance level

Site	Mean volume (m³)
Witklip	0.0774[a]
Bergvliet	0.0648[b]
Tweefontein	0.0500[c]
Jessievale	0.0397[d]
Spitskop1	0.0390[d]
Spitskop2	0.0337[e]

Tweefontein, Witklip and Spitskop2. The other three sites were not measured for MOE$_{dym}$ during assessments. Significant differences ($p < 0.0001$) were observed between the taxa when analysed individually at each site (Figure 3). There were also significant site differences and a significant site × taxa interaction (Table 5). The mean MOE$_{dym}$ of *P. tecunumanii* LE was higher than that of *P. patula* at all three sites, and *P. patula* × *P. tecunumanii* LE produced larger MOE$_{dym}$ values than *P. patula* × *P. tecunumanii* HE.

At Spitskop2, MOE$_{dym}$ of *P. tecunumanii* LE was significantly different from all other entries. However, *P. patula* (F$_2$) and the *P. patula* × *P. tecunumanii* hybrids were not significantly different from each other. It was also observed at Tweefontein and Witklip that *P. patula* (F$_2$) and *P. patula* × *P. tecunumanii* were not significantly different from each other. On the latter sites, *P. patula* × *P. tecunumanii* had better wood properties than *P. patula* (F$_2$).

A site effect for MOE$_{dym}$ was observed (Figure 3). The Witklip site is at lower elevation (1 071 masl) than the other two sites. Furthermore, it is located close to the Witklip dam, which may have an impact on the microenvironmental conditions in the area. The differences in performance may be attributed to soil properties and elevation, as has been reported elsewhere (Dvorak et al. 2000a, 2000b).
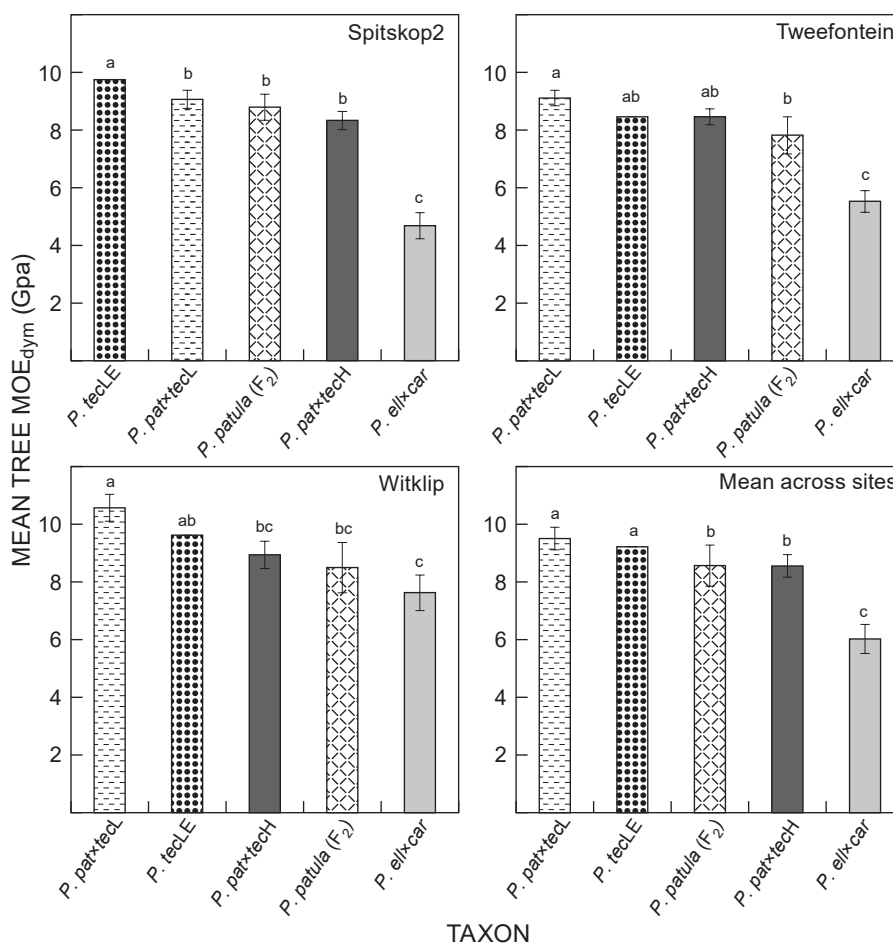
Figure 3: Mean dynamic modulus of elasticity (MOE$_{dym}$) at 5% significance level for the various taxa at the three sites, and interaction of the species across the three sites at five years. Error bars represent the SE. Different letters above bars indicate a significant difference at the 5% significance level

Discussion

Hybridisation provides new genetic combinations that potentially have better characteristics than the parent species (Garrett and Trew 1986; Dungey 2001). As a result of hybridisation, new genetic combinations may show improved growth, wood-quality traits and adaptability in different environmental conditions, which adds value to breeding programmes and subsequent commercial deployment. Results for *P. patula* × *P. tecunumanii* and *P. patula* × *P. oocarpa* hybrids demonstrates that hybridisation can result in improved tolerance to pathogens such as *F. circinatum* (Dvorak et al. 2000a; Kanzler et al. 2012), over that of *P. patula*. Dying *P. patula* seedlings were confirmed to be infected by *F. circinatum*, which also affected in-field survival. The results in this present study support earlier work reported by Kanzler et al. (2012) conducted in Swaziland (Usutu) and the KwaZulu-Natal Midlands.

Generally, *P. patula* × *P. tecunumanii* LE performed well for volume across all sites where it was tested. These studies have demonstrated that the *P. patula* × *P. tecunumanii* hybrid can produce greater volume than *P. patula* over a range of environmental conditions. Similar results were reported by Kanzler et al. (2012). The *P. patula* × *P. tecunumanii* LE hybrid had between 26%

and 66% more volume than on the Mpumalanga escarpment. There was no significant difference between *P. patula* and *P. patula* × *P. tecunumanii* HE at Jessievale. It was interesting to note that the *P. patula* × *P. greggii* hybrid, which was included on two lower-elevation sites, had 24% more volume than *P. patula* × *P. tecunumanii* at Bergvliet and 34% less volume at Spitskop1. This hybrid might do well on colder/harsher sites such as Jessievale.

The site at Bergvliet is approximately 300 m lower in altitude and is drier than Spitskop1 (Table 1). Spitskop2 is about 200 m higher than Tweefontein. The sites receive similar amounts of precipitation but *P. patula* at Tweefontein had 19% more volume than Spitskop2. The trend suggests that altitude has an impact on the volume and growth rate. The trials were planted 30 d apart and the survival was 50% better at Sptiskop2. Similar observations were made on *P. patula* × *P. tecunumanii* where, across an altitudinal range, volume decreased with increasing altitude (Figure 4). The gradient of the *P. patula* × *P. tecunumanii* LE is larger than that of *P. patula* and the volume of both species will be the same at a certain altitude; however, as altitude increases, *P. patula* × *P. tecunumanii* LE will be outperformed by *P. patula.* At 1 723 masl (Jessievale), the study found no difference between the volumes of *P. patula* and *P. patula* × *P. tecunumanii* HE. There was an inverse relationship between volume and altitude. This was also noted by Kanzler

Table 5: Dynamic modulus of elasticity analysis of variance for site and species across the three test sites at five years

Source	df	Sum of squares	Mean square	*F*-value	Pr > *F*
Site	2	150.3448	75.1724	22.14	<0.0001
Taxon	4	2 789.6659	697.4164	205.40	<0.0001
Site*Taxon	8	365.3565	45.6695	13.45	<0.0001
Error	9 900	33 613.7689	3.3953		
Corrected total	9 914	39 701.7523			
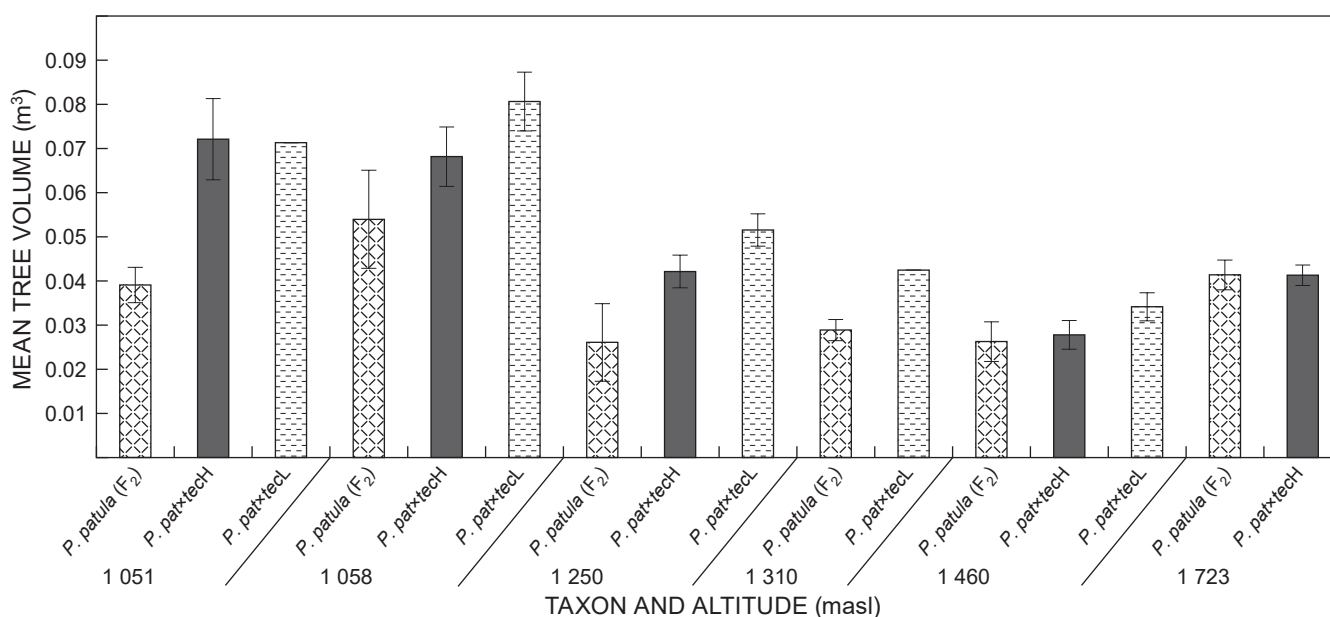
Figure 4: *Pinus patula* × *P. tecunumanii* and *P. patula* volume across an altitudinal range. The location of the altitudes are shown in Table 1. Error bars represent the SE

et al (2014) when comparing *P. patula* × *P. tecunumanii* LE and *P. patula* × *P. tecunumanii* HE across elevations.

The above discussion suggests that for maximum growth and production, there is a niche area in which the hybrid performs best. At this stage, it would appear to be temperature-driven, although an improved understanding of other environmental conditions, such as geology, climate, soil and water, will improve our understanding of these relationships. Plant growth is greatest on moist sites, whereas growth is reduced on colder and drier sites.

We might expect the taxa to perform best to worst from a warm to a cold environment, as the present study has demonstrated and as the trend shows in Figure 4. On the warmer sites *P. tecunumanii* LE and *P. patula* × *P. tecunumanii* LE might be expected to adapt very well. *Pinus tecunumanii* HE and *P. patula* × *P. tecunumanii* HE might be expected to adapt in the mid-range between warm and cold conditions, with *P. patula* adapting well on the colder sites.

The SABS 0163-2 (2001) has established a correlation between the MOE and minimum densities for each grading according to the SANS 10163-1 (2003) standard. The strength properties of *P. patula* × *P. tecunumanii* LE wood was comparable to or even better than that of *P. patula* and met the S5 requirements on two sites, namely Spitskop2 and Witklip. This trait is most likely to have been contributed by the *P. tecunumanii* LE parent (Figure 3), as supported in previous studies (Garrett and Trew 1986; Dvorak et al. 2000a, 2000b; Dungey 2001). If the *P. elliottii* × *P. caribaea* hybrid is removed from Figure 3, there would be no significant differences between the *P. patula* hybrids, *P. patula* and *P. tecunumanii*. *Pinus elliotti* × *P. caribaea* did not meet the S5 grade minimum specifications at this young age.

Conclusions

The *P. patula* × *P. tecunumanii* LE hybrids were found to have faster growth, better MOE$_{dym}$ and good survival across a range of sites in the Mpumalanga forestry region. This confirms the findings of Dvorak et al. (2000a) on the advantages of *P. tecunumanii* hybrids. The general MOE$_{dym}$ shows that sites at a lower elevation had higher MOE$_{dym}$ than those at higher altitude, which concurs with other reports that there is an inverse relationship between some wood-quality properties and elevation (Schutz et al. 1991; McCallum et al. 2007). *Pinus patula* × *P. tecunumanii* LE met the minimum requirement for MOE$_{dym}$ as specified by the SANS standard. The *P. patula* × *P. tecunumanii* hybrids were comparable to *P. patula*, and in the case of *P. patula* × *P. tecunumanii* LE, the evidence suggests that it is generally superior in volume and it is probably due to the contribution of *P. tecunumanii* LE as a parent.

This study has shown that the volume production for both species is comparable at five years of age, but the *P. patula* × *P. tecunumanii* LE hybrid can provide a more productive alternative to *P. patula* in the escarpment region of Mpumalanga. In the Highveld region, *P. patula* × *P. tecunumanii* HE and *P. patula* were not significantly different in volume. This could mean that *P. patula* is still the best option on very cold sites. This study has shown that the volume production for both species is comparable at five years of age. It is clear that the productivity of *P. patula* × *P. tecunumanii* LE decreases with increasing elevation and there is a cut-off altitude where it should be replaced by *P. patula* × *P. tecunumanii* HE hybrid. More studies are needed to determine the exact niche and altitude boundaries for each of the taxa.

More trials need to be established in the Highveld to find suitable alternative taxa. In-depth site and environmental studies need to be conducted where such hybrids are planted to understand their requirements and behaviour in those environments. With more studies conducted, environmental sensitivity of the pine hybrids may be understood, which in turn will help in successfully deploying them commercially.

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