

Stem breakage and forking in low and high elevation *Pinus tecunumanii*

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Summary

The incidences of stem breakage and forking at ages five and eight years in low and high elevation *Pinus tecunumanii* were assessed in multilocation provenance-progeny tests comprising 16 provenances of both low and high elevation *P. tecunumanii*. Stem breakage and forking were found to be more severe at the highest test site (1760m a.s.l.), and progressively declined with decreasing altitude. The mean stem breakage at individual sites for the two ages ranged from 0.7% to 19.5% in the low elevation *P. tecunumanii*, while that of the high elevation *P. tecunumanii* was between 0% and 12.9%. The mean percent of forked trees ranged between 3.9% and 46.8% in the low elevation *P. tecunumanii* and from 5.3% to 27.5% in the high elevation *P. tecunumanii*. The wide provenance variation in stem breakage and forking suggests that genetic factors related to seed source influence these traits. The low elevation *P. tecunumanii* had significantly higher incidences of stem breakage and forked trees compared to the high elevation *P. tecunumanii*. Overall, provenances with very low levels of stem breakage and forking included San Jerónimo, Montana Sumpul, Las Piedrecitas and Jocón. Although tested on a limited number of sites, the genotype*environment interaction at both provenance and family level appeared to be inconsequential. The mean percent of trees with stem breakage and forks increased between the two assessment ages, with changes ranging from small to more than double, implying that decision on selection against stem breakage and forking should be avoided at five years or earlier. The results of this study showed that the challenges of stem breakage and forking in plantations can be managed by one or a combination of site and seed source selection, while intensive breeding and selection could also be used as a long term strategy.

Key words: Stem breakage, forking, low and high elevation *Pinus tecunumanii*, genotype*environment interaction.

Introduction

The potential of *Pinus tecunumanii* (Schwerdtfeger) Eguiluz and J. P. Perry Jr. as a plantation species in Zimbabwe has already been demonstrated in provenance trials (CROCKFORD *et al.*, 1990; NYOKA and BARNES,

1995; NYOKA *et al.*, 2010). Elsewhere, the species has also demonstrated high growth rates that are comparable and sometimes superior to established species (BIRKS and BARNES, 1995; HODGE and DVORAK, 1999; MOURA and DVORAK, 1998; DVORAK *et al.*, 1989; DVORAK *et al.*, 2000a).

Despite its good growth potential, *P. tecunumanii* has shown some unacceptably high levels of stem defects such as stem breakage and forking that may prejudice it against the other established plantation species. Stem breakage occurs when the leader tip of the tree snaps off. This may occur even in moderate winds or as a result of gravity (DVORAK *et al.*, 1993). The primary region of stem breakage is the upper portion of the crown, usually at heavily branched whorls or on region of foxtails. Branching tends to be courser on fertile sites, and this characteristic has been blamed for a significant proportion of broken stems. Foxtails are characterised by uninterrupted apical elongation and formation of the needle fascicles without production of branches or branch primordia. The foxtail may be up to eight metres in length and often ends in formation of branches, which in some cases may be dense and heavy. Where these dense or heavy branches form, often becomes a weak point where breakage occurs.

Forks develop when one or more side branches compete with the leader shoot, often to the extent where the leader shoot loses its dominance or even dies resulting in two or more leader tips. Although there is evidence of genetic control of natural forks, the loss of the terminal shoot could also be caused by severe weather conditions, mechanical damage from bird perching, animal browsing, pest and disease attack. The probability of developing forks is greatest among trees with a prolonged growth period (EKLUNDH-EHRENBORG, 1963; STÅHL, 1990).

Provenance and family variation in stem breakage and forking in *P. tecunumanii* has been reported in Colombia, Brazil, South Africa and Venezuela where average site incidences varied from as low as 0% to over 60% (DVORAK *et al.*, 1993; PARFITT, 1996; MOURA and DVORAK, 1998; HODGE and DVORAK, 1999). PARFITT (1996) found a significant relationship between stem breakage and branch diameter as well as branch angle. The leader tip of trees with large branches tended to snap off compared to trees with many thin branches. An undesirable relationship was also reported in which the preferred flat or horizontal branch habit was often associated with stem breakage (PARFITT, 1996). Levels of forking were found to follow the same pattern as stem breakage (HODGE and DVORAK, 1999).

Provenance and family variation in the frequency of forking has also been reported in other pines, *P. chia-*

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pensis, (DVORAK *et al.* (1996); *P. oocarpa* (MOURA *et al.* 1998); *P. kesiya* (COSTA and LARS, 2008) and in *P. caribaea* (MOURA and DVORAK, 2001). In the provenance tests that were on many sites, the location effect was found to be highly significant (MOURA and DVORAK, 2001; COSTA and LARS, 2008).

This paper reports on the incidence of stem breakage and forking in both the high and low elevation *P. tecunumanii* at four contrasting sites in Zimbabwe.

Materials and Methods

Open pollinated seeds were collected from 160 mother trees, representing 16 provenances of *P. tecunumanii* in its natural range by the Oxford Forestry Institute, University of Oxford, UK. The mother trees were selected on the basis of phenotypic superiority in branch quality, stem form, tree size and taper. The selected mother trees in the wild were separated by a minimum distance of 100m to avoid possibility of excessive neighbourhood inbreeding. Eight provenances were from the high elevation *P. tecunumanii* (above 1500 m a.s.l.) and the other eight were from the low elevation *P. tecunumanii* (below 1500 m a.s.l.). Each of the 16 provenances was represented in the test with 10 mother trees. There were thus 80 families each for the low and high elevation *P. tecunumanii*. Table 1 summarises the geographic location and climatic data of the provenances.

The seed was sown at the John Meikle Forest Research Station, Penhalonga (altitude 1246 m a.s.l.;

rainfall 1778 mm; mean temperature 18°C). Sufficient seedlings were raised to establish balanced trials at four sites in the pine plantation growing areas of the eastern highlands of Zimbabwe (Table 2).

Although all the 16 provenances were originally believed to be of *P. tecunumanii* at seed collection and trial establishment, later evidence from molecular makers and morphological traits indicated that one of the provenances, Juquila may not be pure *P. tecunumanii* (DVORAK *et al.*, 2000b; DVORAK *et al.*, 2007). In this paper, Juquila is taken as a provenance of *P. tecunumanii*, to demonstrate its relevance.

Field design

The field design was a randomised complete block with five replications and a split plot arrangement of the provenances and families. Provenances were randomised in main plots and the 10 families of each provenance were in turn randomised in subplots. The family was represented by a five-tree line plot with a spacing of 3x3m. Each provenance plot was therefore a 10x5 tree rectangular block.

Data analysis

The tests were assessed at five and eight years for presence and absence of stem breakage or broken tops (brt5 and brt8) and forking (fork5 and fork8). The data of presence and absence of stem breakage and forks was converted to percentages of family subplots based on common denominators. According to STEEL *et al.* (1997)

Table 1. – Geographic details of the provenances of *P. tecunumanii* used in the study.

Provenance	Code	Elevation group	Country	Altitude range (m)	Latitude (°N)	Longitude (°W)	Rainfall (mm)	Temperature (°C)
Yucul	Yuc	LE	Nicaragua	850-1000	12°55'	85°48'	1394	22.4
Culmí	Cul	LE	Honduras	550-650	15°06'	85°21'	1325	24.3
Villa Santa	Vil	LE	Honduras	850-950	14°11'	86°20'	1348	22.4
Mt. Pine Ridge	Mpr	LE	Belize	700-720	17°00'	88°55'	1558	23.9
San Esteban	Est	LE	Honduras	700-800	15°22'	85°35'	1400	25.0
Jocón	Joc	LE	Honduras	850-1100	15°16'	86°55'	1400	21.7
San Francisco	Fra	LE	Honduras	870-1100	15°05'	86°20'	1600	20.0
Finca las Victorias	Vic	LE	Guatemala	1200-1300	15°12'	89°22'	1700	22.4
Cusuco	Cus	HE	Honduras	1500-1650	15°30'	88°10'	2500	17.0
La Paz	Paz	HE	Honduras	1750-2000	14°19'	87°45'	1619	20.0
Guajiquiro	Gua	HE	Honduras	1835-2250	14°11'	87°50'	2000	15.0
San Jerónimo	Jer	HE	Guatemala	1700-2000	15°03'	90°18'	1600	17.0
Montana Sumpul	Sum	HE	Honduras	1950-2050	14°24'	89°08'	2200	16.0
*Juquila	Juq	HE	Mexico	2000-2250	16°15'	97°17'	1400	14.0
La Soledad	Sol	HE	Guatemala	2000-2300	14°35'	90°25'	1543	15.0
Las Piedrecitas	Pie	HE	Mexico	2300-2600	16°46'	92°35'	1228	14.8

HE, LE - High Elevation and Low Elevation *P. tecunumanii* respectively; * now classified as *P. herrerae*.

Table 2. – Details of climatic and Geographic factors of the four sites.

	Sites			
	Stapleford	Gungunyana	Cashel	Maswera
Altitude (m a.s.l.)	1 760	1 050	1 450	780
Latitude (°S)	18°41'	20°24'	19°25'	18°41'
Longitude (°E)	32°51'	32°43'	32°45'	32°55'
Mean annual rainfall (mm)	2159	1097	891	1498
Mean annual temperature (°C)	15.1	18.1	19.5	20.7

such data can be transformed by square root transformation provided that the percentages range from 0 to 20% or 80 to 100% but not both. However, for a fixed effect model, a lack of normality is not critical provided the departure from normality is not of extreme (NETER *et al.*, 1985, page 624; STEEL *et al.*, 1997, page 174). The F-test for equality of treatment means is less affected by lack of normality, either in terms of the level of significance or power of the test (NETER *et al.*, 1985; STEEL *et al.*, 1997).

The analysis of variance was conducted on the data from all the 16 provenances to estimate the provenance least squares means for both forking and stem breakage, and also to test whether the differences in stem breakage and forking between the low and high elevation *P. tecunumanii* were statistically significant. The analysis of variance was performed using PROC GLM in the Statistical Analysis System (SAS, 1998). The appropriate statistical model used for analysis of variance of individual site data was a fixed effect model:

$$Y_{ijk} = \mu + B_i + P_j + BP_{ij} + F(P)_{jk} + \varepsilon_{ijk}$$

Where,

Y_{ijk} is the observation in the ijk^{th} family plot, μ is the site mean, B_i is the fixed effect of the i^{th} block, P_j is the fixed effect of the j^{th} provenance, BP_{ij} is the interaction effect between the i^{th} block and j^{th} provenance, $F(P)_{jk}$ is the fixed effect of the k^{th} family of the j^{th} provenance and ε_{ijk} the experimental error, $E[\varepsilon_{ijk}] = 0$, $\text{Var}[\varepsilon_{ijk}] = \sigma^2_{\varepsilon}$.

In order to compare the means of the high and low elevation *P. tecunumanii*, a single contrast was also done in the same model. The provenance least squares means of both the five- and eight year stem breakage and forking at individual sites were plotted as graphs.

A combined analysis of data from three sites that had significant levels of stem breakage and forking was done to test the presence of genotype*environment interaction (provenance*site and family*site interaction). The fixed effect model used for the data was:

$$Y_{ijkl} = \mu + S_i + B(S)_{ij} + P_k + SP_{ik} + BP(S)_{ijk} + F(P)_{kl} + SF(P)_{ikl} + \varepsilon_{ijkl}$$

Where:

Y_{ijkl} is the observation in the $ijkl^{\text{th}}$ plot, μ = the across site mean, S_i the fixed effect of the i^{th} site, $B(S)_{ij}$ the fixed effect of the j^{th} block in the i^{th} site, P_k the fixed effect of the k^{th} provenance, SP_{ik} the interaction effect between the i^{th} site and k^{th} provenance, $BP(S)_{ijk}$ the interaction between the j^{th} block of the i^{th} site and the k^{th} provenance, $F(P)_{kl}$ the effect of the l^{th} family of the k^{th} provenance, $SF(P)_{ikl}$ the interaction between i^{th} site and the l^{th} family and ε_{ijkl} the experimental error, $E[\varepsilon_{ijkl}] = 0$, $\text{var}[\varepsilon_{ijkl}] = \sigma^2_{\varepsilon}$.

Results

Stem Breakage

Provenance effects for both five- and eight-year mean percent stem breakage were significant at different

Table 3. – ANOVA F-ratios for five and eight-year stem breakage (brt5 and brt8) and forking (fork5 and fork8) at individual sites.

Source of Variation	DF	Trait			
		Br5	Br8	Fr5	Fr8
(Stapleford)					
Block	4				
Provenance	15	5.00***	2.56**	5.54***	10.21***
High vs Low <i>P. tecunumanii</i>	1	37.92***	30.48***	63.02***	131.9***
Block x Provenance	60				
Family(Provenance)	144	1.16 ^{ns}	1.24*	1.23*	1.32*
Error	649				
(Gungunya)					
Block	4				
Provenance	15	2.87***	4.63***	2.46**	2.01*
High vs Low <i>P. tecunumanii</i>	1	25.64***	36.48***	7.82***	0.69 ^{ns}
Block x Provenance	60				
Family(Provenance)	144	1.51***	1.26*	0.97 ^{ns}	1.43**
Error	640				
(Cashel)					
Block	4				
Provenance	15	1.77*	2.27**	2.27**	3.07***
High vs Low <i>P. tecunumanii</i>	1	11.49***	4.58*	4.58*	20.30***
Block x Provenance	60				
Family(Provenance)	144	1.30***	0.90 ^{ns}	0.90 ^{ns}	1.25*
Error	649				
(Maswera)					
Block	4				
Provenance	15	0.87 ^{ns}	1.80*	2.24**	2.07*
High vs Low <i>P. tecunumanii</i>	1	0.01 ^{ns}	2.11 ^{ns}	2.21 ^{ns}	0.39 ^{ns}
Block x Provenance	60				
Family(Provenance)	144	0.98 ^{ns}	0.81 ^{ns}	1.12 ^{ns}	1.08 ^{ns}
Error	618				

^{ns} for not significant at 5%; *, ** and *** for significant at 5%, 1% and 0.1% respectively.

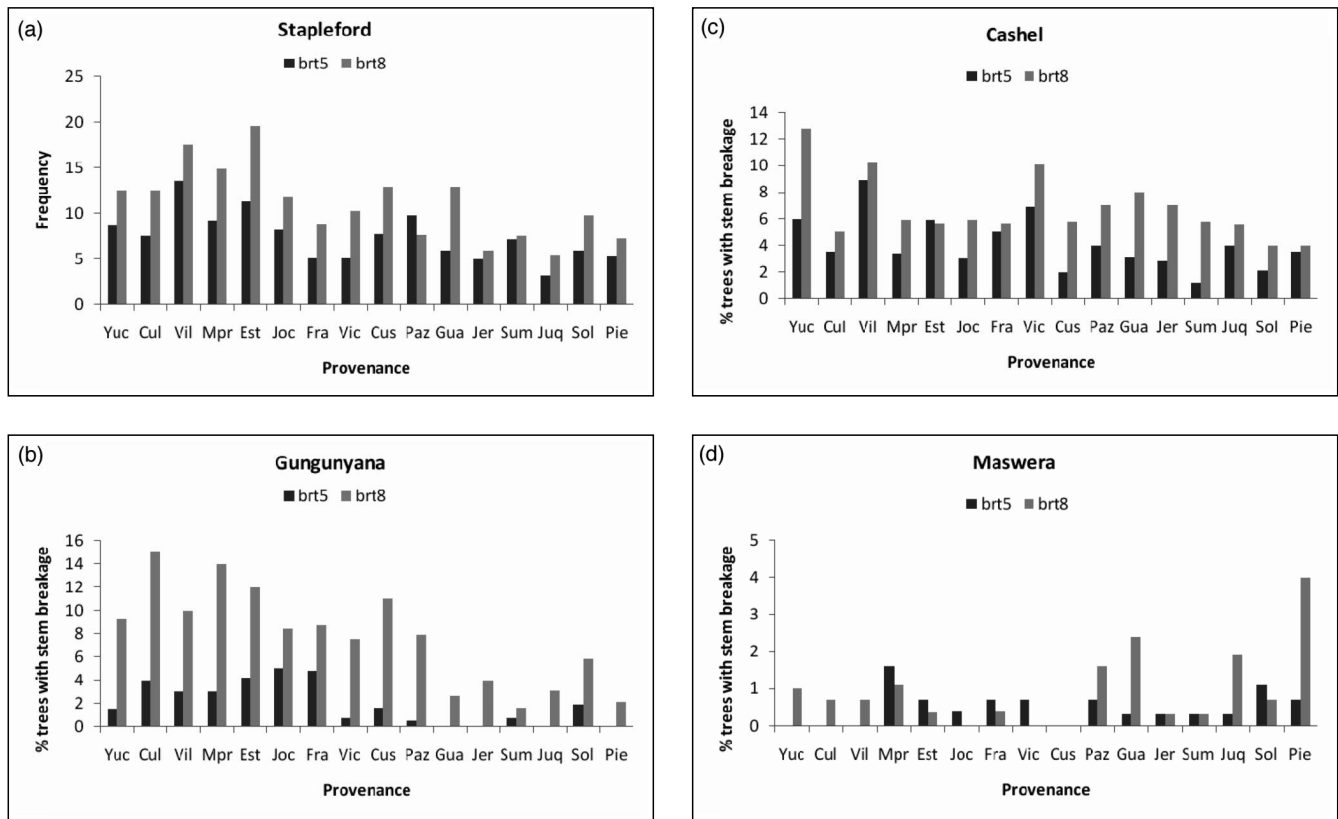


Figure 1. – Frequency of trees with stem breakage at (a) Stapleford, (b) Gungunyana, (c) Cashel and (d) Maswera at five and eight years. (Provenance codes are shown in Table 1).

probability levels at Stapleford, Gungunyana and Cashel but were only significant ($P < 0.05$) for eight-year stem breakage at Maswera, the 4th site (Table 3). The contrast between the high and low elevation *P. tecunumanii* was significant at varying probability levels for both five- and eight-year stem breakage at Stapleford, Gungunyana and Cashel but was non-significant for both ages at Maswera. The family within-provenance effect was significant at different probability levels at Gungunyana but was not significant at Maswera for both ages (Table 3). However, at Cashel and Stapleford, the family effect was only significant ($P < 0.05$) for five- and eight-year stem breakage respectively.

The mean percent stem breakage of the 16 provenances at individual sites is shown in Figures 1. The mean stem breakage ranged from 3.2% to 19.5% at Stapleford; 0% to 15.1% at Gungunyana; 1.2% to 12.8% at Cashel and from 0% to 2.4% at Maswera. The mean percentage of trees with stem breakage at five and eight years averaged 7.4 and 11.6% at Stapleford, 4.1 and 6.8% at Cashel, 1.9 and 7.7% at Gungunyana and 0.5 and 1.0% at Maswera respectively. Across the four sites, the incidence of stem breakage was highest at Stapleford, the highest altitude test site and declined with decreasing altitude of the test site.

Overall, the provenances with the lowest levels of stem breakage at all the four sites included San Jerónimo, Montana Sumpul and Las Piedrecitas, all high elevation *P. tecunumanii* sources; Jocón, a low elevation

P. tecunumanii source and Juquila non-*P. tecunumanii* seed source. The number of trees with broken tops increased between five and eight years. The change was small to more than double on some of the sites.

Forking

The provenance effect for five and eight-year forking was significant at different probability levels at all the four sites (Table 3). The contrast between the low and high elevation *P. tecunumanii* was also significant at varying probability levels at Stapleford and Cashel for both the five- and eight-year forking. However, the same contrast was non-significant for both five-year and eight-year forking at Maswera and for eight-year forking at Gungunyana. The family within-provenance effect for forking which was significant ($P < 0.05$) at Stapleford for non-significant at Maswera for both ages. At Gungunyana and Cashel, the same family within-provenance effect for forking was only significant at age eight years (Table 3).

Figure 2 shows the incidence of forking among the 16 provenances at the individual sites. The mean percent of forked trees ranged between 9.6% and 46.8% at Stapleford; 5.2% and 23.5% at Cashel; 1.8% and 23.5% at Gungunyana and 2.7% and 14.0% at Maswera. The percentage of forked trees at five and eight years averaged 18.1 and 31.2% at Stapleford, 9.7 and 15% at Cashel, 4.3 and 14.8% at Gungunyana and 5.4 and 8.0% at Maswera respectively. Overall, the incidence of forking was highest at Stapleford, the highest altitude test site

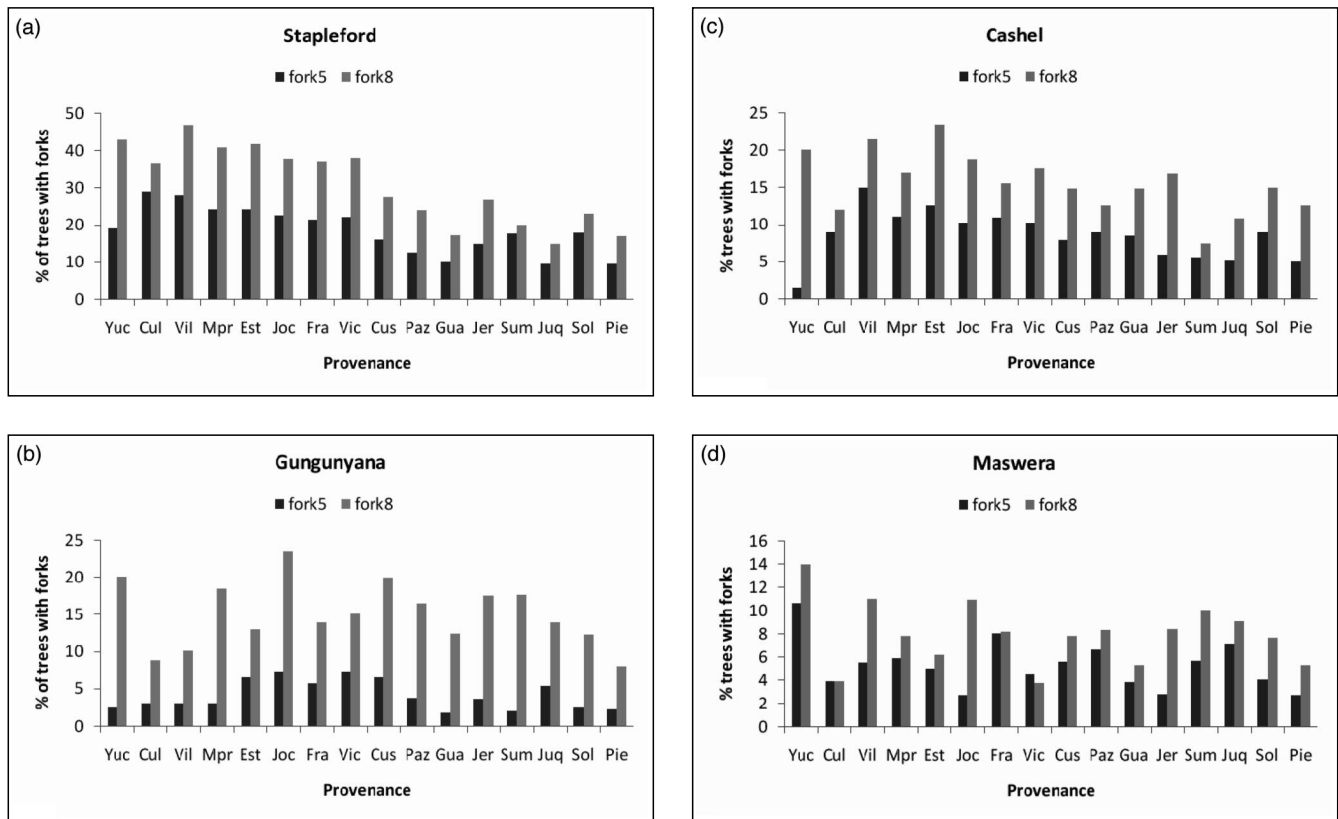


Figure 2. – Frequency of trees with forks at (a) Stapleford, (b) Gungunyana, (c) Cashel and (d) Maswera at five (fork5) and eight (fork8) years. (Provenance codes are shown Table 1).

and declined with decreasing altitude of the test site. The number of trees with forks increased between five and eight years. The change was small to more than double in some of provenances, depending on the site.

Low versus High *P. tecunumanii*

With the exception of Maswera site, where the differences were nonsignificant, the low elevation *P. tecunumanii* had significantly higher proportion of trees with stem breakage compared to the high elevation *P. tecunumanii* at the other three sites (Table 4). A similar pattern to that for stem breakage was also observed for forking in which, the low elevation *P. tecunumanii* had higher incidences of forked trees compared to the high elevation *P. tecunumanii* at again, three of four sites assessed (Table 4). The differences

between the two *P. tecunumanii* types were less evident at Maswera.

Genotype*Site Interaction

The frequency of forking and stem breakage were very low at Maswera and consequently, data from this site was excluded in the across site analysis. Only data from the other three sites (Stapleford, Cashel and Gungunyana) that had significant levels of stem breakage and forking was used. Across the three sites, the site effect was highly significant at varying probability levels for all the traits, with the exception of eight-year stem breakage in the low elevation *P. tecunumanii* (Table 5). The provenance effects for all the four traits were however non significant in both the low and high elevation *P. tecunumanii* (Table 5). The family within-provenance

Table 4. – Percent means for five- and eight-year stem breakage (brt5 & brt8) and forking (fork5 & fork8) of the Low and High elevation *P. tecunumanii* at individual sites.

Site	Type of <i>P. tecunumanii</i>	Trait mean (%)			
		Br5	Br8	Fork5	Fork8
Stapleford	Low Elevation	9.1	13.9	23.6	40.8
	High Elevation	6.1	8.8	12.6	21.7
Cashel	Low Elevation	5.4	7.7	12.4	18.7
	High Elevation	2.9	5.9	7.0	13.1
Gungunyana	Low Elevation	3.4	10.8	5.3	15.3a
	High Elevation	0.6	4.8	3.4	14.1a
Maswera	Low Elevation	0.6a	0.6a	5.8a	8.3a
	High Elevation	0.5a	1.0a	4.8a	7.7a

Means within a box followed by a common letter do not differ significantly at 5% based on the contrasts.

Table 5. – Analysis of Variance for five- and eight-year stem breakage (brt5 & brt8) and forking (fork5 & fork8) across three sites for both the Low and High elevation *P. tecunumanii*.

Source of variation	DF	low elevation <i>P. tecunumanii</i>				high elevation <i>P. tecunumanii</i>			
		Br5	Br8	Fork5	Fork8	Br5	Br8	Fork5	Fork8
Site	2	13.50***	1.98ns	52.08***	61.99***	22.67***	4.97*	24.30***	9.17**
Block (Site)	12								
Provenance	15	1.13ns	1.04ns	1.03ns	1.47ns	1.16ns	1.65ns	1.00ns	2.67ns
Site*Provenance	30	1.73ns	1.33ns	1.14ns	1.00ns	1.00ns	2.09*	1.45ns	1.25ns
Block(Site)*Provenance	180								
Family(Provenance)	144	1.32ns	1.16ns	1.47*	1.52*	1.13ns	1.43*	1.45**	1.29*
Site*Family(Provenance)	288	1.03ns	1.09ns	1.06ns	1.09	1.29*	1.00ns	1.00ns	1.17*
Error	1728								

ns for not significant at 5%; *, ** and *** for significant at 5%, 1% and 0.1% respectively

effect was only significant ($P < 0.05$) for five- and eight-year forking in both the low and high elevation *P. tecunumanii*, while that for stem breakage was only significant at age eight years in the high elevation *P. tecunumanii*.

The site*provenance interaction effect, which was only significant for eight-year stem breakage in the high elevation *P. tecunumanii*, was mostly non-significant. The second interaction, the family*site interaction effect was only significant ($P < 0.05$) for five-year stem breakage and eight-year forking in the high elevation *P. tecunumanii*. Overall, the two interactions were mostly non-significant and in few instances where they were significant, the level was always borderline and possibly of no consequence.

Discussion and Conclusions

The incidence of stem breakage and forking in both the low and high elevation *P. tecunumanii* was highest at the highest altitude test site (Stapleford) and declined with decreasing altitude. Stapleford is a relatively cool, wet and fertile site with a less pronounced dry season compared to Maswera, the lowest altitude test site, which although wetter, is relatively hotter, less fertile and has a very a long and pronounced dry season of up to 6 months. MOURA and DVORAK (1998) reported a similar pattern in Brazil in which stem breakage was practically absent in the “Cerrado” region of Brazil. The “cerrado” is characterized by good rainfall but infertile soils and a distinct dry season. HODGE and DVORAK (1999) also came to a similar conclusion based on an extensive study of international provenance trials in South Africa and a number of South American countries. In *P. kesiya*, COSTA and LARS (2008) found significant provenance differences for forking in only four out of the seven trials measured; again implying that provenance differences in stem breakage and forking can be masked on some sites.

The results of the present study indicate that site selection, could be effective in managing stem breakage and forking in *P. tecunumanii*. Because the incidence of trees with stem breakage was higher on fertile sites with less pronounced dry season compared to less fertile

sites that have distinct dry seasons, site selection could also be used as a tool to minimise the problem of forks and stem breakage. The ecological niche for *P. tecunumanii* in Zimbabwe as an exotic plantation species falls between areas that are currently being planted to sub-temperate species like *P. patula* and the subtropical species such as *P. taeda* and *P. oocarpa* (NYOKA *et al.*, 2010).

Provenances of the low elevation *P. tecunumanii* are more prone to stem breakage compared to the provenances from the high elevation *P. tecunumanii* on medium to high altitude sites. The differences are however less apparent at lower altitudes. This finding is however, not consistent with that of HODGE and DVORAK (1999), who reported greater incidences of stem breakage in high elevation *P. tecunumanii* compared to the low elevation *P. tecunumanii* in Colombia and South Africa. In their study, however, the two *P. tecunumanii* types were not evaluated in the same trials; therefore their comparison may probably have been less precise compared to the present one. Furthermore, only four high elevation *P. tecunumanii* provenances (Las Piedrecitas, San Jerónimo, La Soledad and Juquila) used in the present study, were also used in the study by HODGE and DVORAK (1999). Although Juquila provenance was not very conspicuous among the *P. tecunumanii* provenances, the level of stem breakage and forking was always among the lowest.

In the study by DVORAK *et al.* (1993), the incidence of stem breakage was up to 44% on some sites compared to less than 20% in the present study. It is also worth noting that although the correlation between stem breakage and growth traits was not investigated in the present study, such correlations have been reported to be non-significant in other studies (DVORAK *et al.*, 1993; PARFITT, 1996; MOURA and DVORAK, 1998; HODGE and DVORAK, 1999).

The fact that the two traits had a similar pattern among the provenances and sites gave further credence to the suggestion by HODGE and DVORAK, (1999) to treat the two traits as one because the two traits could be different aspects of the same trait. The incidence of stem breakage and forking if combined into one trait, aver-

aged over 25% at the worst affected site. This is a fairly high level that could deter planting of this species at some locations. In commercial forestry, trees with either broken tops or forked are usually targeted for silvicultural thinning in addition to other attributes such as trees with stunted growth, crooked stems and diseases. However a combination of site selection and seed source could be used as a management tool to minimise the impact of stem breakage and forking in *P. tecunumanii* plantations established from unimproved material. Based on stem breakage alone, as a selection criterion, provenances such as Montana Sumpul, Jocón, San Jerónimo and Las Piedrecitas for example, could be the right seed sources for planting at Stapleford where the incidence of stem breakage was less than six percent. In the study by HODGE and DVORAK (1999), the Jocón and Las Piedrecitas provenances were identified among the least susceptible to stem breakage, which is consistent with the present finding.

From this study, there is evidence that provenance and family variation in stem breakage and forking is present in both the low and high elevation *P. tecunumanii*. At individual sites, the variation appeared to be more pronounced at provenance level compared to family level. The genotype*environment interaction at provenance and family level for stem breakage and forking was less apparent in both types of *P. tecunumanii*. These results are in part consistent with other findings in the other species. In *P. chiapensis*, for example, DVORAK *et al.* (1996) reported significant provenance*site interactions for forking but the family*site interactions were non-significant. In a recent study of *P. kesiya* international provenance trials covering seven sites, COSTA and LARS (2008) also found the provenance*site interaction for forking to be less important.

Based on the results of this study, we concluded that the low elevation *P. tecunumanii* is more prone to stem breakage and forking compared to the high elevation *P. tecunumanii*. Stem breakage and forking appeared to be more pronounced on high altitude sites with prolonged growth period. On sites with a pronounced dry season, provenance and family differences are less apparent. Provenance and family variation in stem breakage and forking is present in both the low and high elevation *P. tecunumanii*. A combination of site and seed source selection could be used to minimise the negative impact of stem breakage and forking where unimproved material of *P. tecunumanii* is used in operational plantings.

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Heritabilities, Intertrait Genetic Correlations, G x E Interaction and Predicted Genetic Gains for Acoustic Velocity in Mid-rotation Coastal Douglas fir

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Abstract

Acoustic velocity (AV) data from 7,423 coastal Douglas-fir trees drawn from 347 wind-pollinated families on 14 sites, from four first-generation testing programs in the north Oregon Cascades, were analyzed. Families were measured on two or four sites at ages 23 to 41 years from seed using the Fakopp TreeSonic standing-tree tool. Height (HT) and DBH data collected at ages 15 and 16 from seed, from all trees in the four programs (95,795 trees, 955 families), were used to calculate volume index ($VOL = HT \cdot DBH^2$) and stem taper ($TAP = DBH/HT$). All traits were analyzed using multivariate mixed model analyses.

Across-site individual narrow-sense heritabilities for AV^2 ranged from 0.24 to 0.40 among first-generation programs, compared to 0.12 to 0.23 for HT, 0.10 to 0.16 for DBH, 0.11 to 0.20 for VOL and 0.14 to 0.17 for TAP.

Across-site type B correlations for AV^2 ranged from 0.85 to 0.95, compared to 0.62 to 0.83 for HT, 0.60 to 0.74 for DBH, 0.67 to 0.78 for VOL and 0.66 to 0.79 for TAP. AV^2 was negatively correlated with HT in three programs ($r_A = 0.17$ to -0.28), and negatively correlated with DBH (-0.12 to -0.46), VOL (-0.05 to -0.44) and TAP (-0.09 to -0.40) in all four programs.

Selecting the top 10% of the families sampled based on AV^2 gave predicted gains of 4.4% to 9.6% for AV^2 and

–9.3% to 10.6% for VOL. The adverse genetic correlations between AV^2 and growth, and the losses in gain in AV^2 from selection based on growth, may be overestimated by suppression of slower-growing families in these older tests.

Key words: acoustic velocity, dbh, Douglas-fir, genetic correlation, genetic gain, height, heritability, taper, volume index.

Introduction

Efficient selection and breeding of forest tree species to improve wood stiffness (modulus of elasticity, MOE) requires mass screening of progeny within large replicated field tests. Until recently (~2000), the main limitation was the cost of measuring MOE on a large scale. Therefore, wood density was often used as a surrogate trait to improve wood stiffness (dynamic MOE = density x acoustic velocity²). Within the last 10 years, however, it has become possible to measure and use acoustic velocity (AV) as a surrogate for MOE. This approach has been used in Douglas-fir and other conifers (JAYAWICKRAMA, 2001; KUMAR *et al.*, 2002; CHERRY *et al.*, 2008; MATHESON *et al.*, 2008; JAYAWICKRAMA *et al.*, 2009; WEILINGA *et al.*, 2009), and is gaining acceptance as an approach to improve wood stiffness in operational breeding programs (JAYAWICKRAMA *et al.*, 2009). In fact, compared to wood density, it may be preferable to measure and select solely on AV (e.g., LI *et al.*, 2007) because it seems to have a higher correlation with static and dynamic MOE (JOHNSON and GARTNER, 2006; CHERRY *et al.*, 2008).

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