Selection for solid wood properties in *Eucalyptus nitens*

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Date: June 2016

Publication No: SWP-T005

PUBLIC REPORT INFORMATION SHEET

Report Title	**Selection for solid wood properties in *Eucalyptus nitens***
Authors	**Mari Suontama, Toby Stovold, Russell McKinley, Mark Miller, Kane Fleet, Charlie Low, Heidi Dungey**
ISBN No	
Scion Publication No	
Sidney Output Number	
Signed off by	Heidi Dungey
Date	June 2016
Copyright	
Intellectual Property Category	Commercialisation

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EXECUTIVE SUMMARY

Eucalyptus nitens can be recognised as one of the tree species in New Zealand with an advanced breeding programme that is moving towards its fourth generation. *Eucalyptus nitens* is one of the most important commercially planted eucalypt species in the world, being the second most widely planted eucalypt in its native country Australia (Hamilton et al. 2008). In Australia, it is mainly grown for pulp wood but also for solid wood production (Hamilton et al. 2008). The majority of the production market for *E. nitens* is as pulp wood, hence breeding objectives and selection in this species is usually based on growth, wood density and form. In spite of the fact that environmental effects such as site characteristics and silvicultural regimes have influence on commercially important traits, we have a strong indication that these traits can be considerably improved by breeding.

New breeding objectives for solid wood production were proposed in the current breeding plan and regarded as an essential focus for selections in the next generation (Stovold et al. 2010). This initiated the current project with its objective to measure a progeny trial for wood properties at the estate of the New Zealand's largest *E. nitens* producer South Wood Export Ltd (SWEL). This project began as a part of the Diversified Species Programme in 2014-15, and was subsequently included in the Specialty Wood Products Research Programme Partnership in 2015-16.

The Keens Block progeny trial used for this wood quality study. The trial was assessed for growth, form, and wood density with a total number of 3600 trees at age six in 2013 (Baltunis et al. 2013). This third generation progeny trial comprising of 115 elite mother trees from the second generation. Phenotypic data for wood properties including wood density, growth strain, stiffness, shrinkage/collapse and internal checking was collected on 752 trees at age seven during 2014-2015. Quantitative genetic analysis was carried out to recommend an optimised seed-orchards establishment plan to SWEL.

All traits used in the selection for solid wood production showed moderate estimated heritabilities. This implies that breeding will result in improved tree material for sawn timber properties in this population. Genetic correlations between traits were mainly favourable but some of them only indicative and therefore inconclusive. Predicted genetic gains were considerable for the traits when selecting the top 5% of individuals in the population. The highest genetic gains were predicted for internal checking in sapwood and heartwood (30%, 51%). Air-dry and reconditioned shrinkage measurements on averaged 3-6m logs also showed good genetic gains (6 to 10%). Improvement in growth stress was estimated at 8% based on predicted gains. These estimated genetic gains did not take into account genetic correlations between the traits and therefore may differ when selecting simultaneously for all traits of interest. Indication of mainly favourable and not highly adverse genetic correlations is assuring in terms of the potential to achieve desired gains for the aggregate breeding objective. However, due to the indicative nature of genetic correlations, to maximise the progress for each production purpose, separate breeding objectives for solid wood and pulp wood production are recommended.

More information will be received through genomic prediction implemented into this population. Multiple trait analysis using genomic selection would further increase our knowledge of genetic correlations between traits and will finalise the decision of traits that should be included as selection criteria in future breeding plans for *E. nitens*.

INTRODUCTION

Eucalyptus nitens can be recognised as one of the tree species in New Zealand with an advanced breeding programme, moving towards its fourth generation. *Eucalyptus nitens* is one of the most important commercially planted eucalypt species in the world, being also the second most widely planted eucalypt in its native country Australia (Hamilton et al. 2008). In Australia, it is mainly grown for pulpwood but also for solid wood production (Hamilton et al. 2008). It is the most commonly planted eucalypt species in New Zealand, covering plantations of 12,000 ha. It has been predominantly grown for pulp wood production with a rotation age of 15 years, and is growing at above 20 m^3/ha/year mean annual increment (MAI) in Southland (Baltunis et al. 2013). Over the years, increasing interest for solid wood production has been reported in a number of wood property studies for this species (e.g. Raymond 2002, Kube 2005, Kube and Raymond 2005, Biechele et al. 2009, Hamilton et al. 2009). There has also been recent interest in New Zealand to use *E. nitens* for higher value solid wood products. This initiated the current project with its objective to measure a progeny trial for wood properties at the estate of the New Zealand's largest *E. nitens* producer, South Wood Exports Ltd (SWEL). This project began as a part of the Diversified Species Programme in 2014-15, and after that was included in the Specialty Wood Products Research Programme Partnership in 2015-16.

The New Zealand *E. nitens* breeding programme began in 1978 as an open-pollinated (OP) breeding population using forwards selection. Since the major production market is for pulp wood, breeding objectives were developed accordingly and selection is based on growth, wood density and form. In spite of the fact that environmental effects such as site characteristics and silvicultural regimes influence commercially important traits, we have a strong indication that these traits can be considerably improved through breeding. Genetic progress of growth and wood density is promising based on heritability estimates reported in a number of studies for *E. nitens.* Kube (2005) reported low to moderate (0.12 to 0.29) heritability estimates for diameter at age six across three sites in Australia but higher heritabilities at age twelve for the same trait (0.32 to 0.45). Another Australian study for this species observed that diameter at breast height (DBH) had variable heritabilities across two sites, being at the lower and higher end of moderate magnitude at age nine (0.19, 0.34; Hamilton et al. 2009). Across eight sites in South Africa, a wide range of heritabilities was reported for DBH at different ages, varying from 0.11 to 0.69 (Swain et al. 2014), but there was no trend in heritabilities with age. Baltunis et al. (2012, 2013) estimated low heritabilities (0.09, 0.10) for age six DBH at two sites in New Zealand. Wood density as one of the most heritable selection traits, has moderate to high heritabilities in *E. nitens*, of 0.50 to 0.96 (Kube 2005), 0.37, 0.42 (Hamilton et al. 2009) and 0.23, 0.48 (Baltunis et al. 2012, 2013).

New breeding objectives for solid wood production were proposed in the latest breeding plan and regarded as an essential part to focus on selections to be made for the next generation (Stovold et al. 2010). As stated by Raymond (2002), depending on the production system (pulp and paper, or sawn timber, veneers and reconstituted wood products), it is necessary to define breeding objectives accordingly and these should be based on the key economic parameters behind the production system. For solid timber markets, Raymond (2002) presented five economic drivers; recovery (green and dry), grade, drying cost, drying degrade and sawing productivity, affecting sawn timber products. Based on these economic factors: density, stiffness, shrinkage and collapse, tension wood and knot size were summarized as the wood property traits important to solid timber markets (Raymond 2002).

Figure 1. *Eucalyptus nitens* is the second most planted eucalypt species in its native Australia and the most important commercially planted *Eucalyptus* in New Zealand. Increasing interest growing this species for solid wood production is reported in many countries.

Eucalyptus species are known to suffer from growth stresses due to their fast growth. Traits important to sawn timber production are affected by the impacts of growth stress that are seen as the trees are felled (end-splitting) and in wood after it has been dried. The amount of growth stress in new wood tissue is believed to be determined by both genetic and environmental factors (Kubler 1987). Environmental factors such as silvicultural practises have an effect on the development of growth stress. These most likely happen in heavily thinned stands which can develop strong growth stresses in order to achieve improved orientation towards light. Trees that receive light from the same direction have no reason to reorient (Kubler 1987).These environmental stresses result in splitting, warping and dimensional instability when cutting, processing and drying the wood (Biechele 2008). During drying, wood also shrinks because of the different biological processes which causes flattening of cells, also known as collapse (Hamilton et al. 2009). ‘Normal’ shrinkage refers to reduction in the thickness of cell walls as bound water is removed (Hamilton et al. 2009), collapse being different from normal shrinkage as it occurs when moisture is removed from the cell lumens (Kube 2005). Checking can take place during drying and is expressed as cracks both internally (internal checking) or on the surface (Kube 2005). Both checking and collapse have been recognized as problems since the utilisation of eucalypts began (Kube 2005).

Overall, Kube (2005) considered that *E. nitens* has many of the qualities required for appearance products but based on sawing studies, collapse and checking were regarded as major problems for solid wood production. Lausberg et al. (1995) concluded that internal checking causes utilisation problems for solid wood production unless new drying methods are able to decrease the problem. A severe collapse in some samples of *E. nitens* was reduced by steam reconditioning and because of a large variation in wood properties, these traits could be improved by breeding (Lausberg et al. 1995).

For the definition of breeding objectives and breeding strategy including both solid wood timber and pulp wood products, it is necessary to investigate heritability of traits of interest and genetic correlations between them. Wood property traits are expensive to measure and a large amount of data is required for genetic evaluation. Therefore, favourable genetic correlations would be very helpful in selecting simultaneously for different breeding objectives and indirect selection could be utilised for the traits expensive to phenotype. Kube and Raymond (2005) stated that in addition to sawing techniques and reconditioning, breeding can be used to improve *E. nitens* in terms of collapse and internal checking. They found moderate to high genetic control for collapse which also had a high and favourable genetic correlation with basic density, but a high and adverse correlation with diameter. Based on this, it was concluded that collapse could be included in the breeding programme with very little additional cost and if selecting for diameter only, a large increase in checking would be expected (Kube and Raymond 2005). Hamilton et al. (2009) addressed the importance of considering multiple breeding objectives in the presence of markets for both pulp and solid wood. Gross shrinkage was found to be of moderate heritability across two sites, whilst net shrinkage had a low heritability and collapse of moderate heritability (Hamilton et al. 2009). Adverse genetic correlations between DBH and shrinkage traits, and among basic density, cellulose content and net shrinkage indicated difficulties utilising genetic material for two breeding objectives in one breeding population for *E. nitens* in Australia (Hamilton et al. 2009). On the other hand, selection for density would favourably affect also cellulose and collapse (Hamilton et al. 2009).

With the increased interest and great potential of *E. nitens* for solid wood markets and high value export products, this project was initiated to study the possibility of obtaining genetic improvement of wood quality within an advanced breeding programme. A third generation progeny trial at the SWEL's Keens Block in Southland was selected to phenotype for shrinkage, growth strain, wood stiffness and density. This trial has been assessed earlier for growth, form and density at age six progeny evaluation. This study had two objectives; 1) to make selections and establish new seed-orchards for both solid wood and pulp production, and 2) estimate heritability, and genetic correlations between the selection traits in order to design a breeding strategy for solid wood production. In addition to phenotyping, this research also included a collection of leaves for DNA extraction and genotyping that will form the basis of a genomic selection breeding strategy for the next round of selections.

Figure 2. *Eucalyptus nitens* is a fast growing species with a short rotation time of circa 15 to 18 years, offering a good option as a high-valued solid wood product for New Zealand and overseas markets.

MATERIALS AND METHODS

Progeny trial description

Keens Block progeny trial was used for this wood quality study was assessed for growth, form, and wood density with a total number of 3600 trees at age six in 2013 (Baltunis et al. 2013). This is a third generation progeny trial comprised of 115 elite mother trees from the second generation trials. Three different seed-sources were included in the trial design with genetic resources structures from: 25 parent trees from Tinkers and 90 parent trees from Waiouru seed-orchards as well as one control-seed lot from Australian Tree Seed Centre.

Wood property assessment

Phenotypic data was collected on 752 trees at age seven in 2014. However, in the final data, the number of observations for each trait group varied due to compromised labelling in a small number of samples. The following traits were considered to be important in describing solid wood properties and included in the data collection.

- Acoustic wave velocity (km/s) was used as a surrogate trait for wood stiffness. Measurements were taken at the time of data collection in October 2014 at two heights 3m and 6m log using HITMAN (HM200).
- Growth stress (e.g. growth strain) was assessed at the time of the data collection in October 2014. It was measured by ripping the 3m and 6m logs and measuring opening (mm) on logs as an indication of growth stress.
- Two discs for each log at 3m and 6m height were taken to measure shrinkage and collapse as per standard wood quality procedure (Treloar and Lausberg 1996). Shrinkage was assessment conducted during March-June 2015 and it included air-dried and steam reconditioned tangential, longitudinal and radial measurements. Wood density was measured on these blocks at both heights.
- Internal checking was measured on air-dried breast height discs. Phenotyping was initiated in October 2015 by cutting discs into two 25 mm slices. The trait was measured by counting the number of checks separately within a ring for sapwood, heartwood and finally, the total number of checks.

Phenotyping process for wood properties and preliminary results on heritabilities, selections and seed-orchard establishment have been described earlier in a number of interim reports (Low et al. 2015, Stovold and Suontama 2015, Suontama 2015a, Suontama 2015b, Suontama et al. 2016).

Genetic analyses

Variance components, heritability and genetic gains were estimated with spatial linear mixed tree models for progeny trial and wood quality traits using BLUP (Best Linear Unbiased Prediction). Genetic correlations between traits were estimated using a simple linear mixed model without fitting trial design effects. Fixed effects in the statistical model were the group of controls vs. trial trees and the seed-orchard, and the random effects included the additive genetic effect of an individual tree, and spatially independent and dependent residual variance components. Estimates of BLUP breeding values based on family predictions were used for ranking the best families and after that the best alive trees within a family were selected for the two seed-orchards that were first established during September 2015 and additional later selection were performed in November 2015 and included selections against internal checking.

Heritability was estimated as $\sigma^2_a / (\sigma^2_a + \sigma^2_\eta)$, where σ^2_a is the additive genetic variance and σ^2_η is the spatially independent residual variance.

Genetic correlation between the traits were estimated as $r_g = \sigma_{a1a2}/\sqrt{}\,(\sigma^2_{a1}\sigma^2_{a2})$, where σ_{a1a2} is the additive genetic covariance between traits 1 and 2 and σ^2_{a1} is the additive genetic variance for trait 1 and σ^2_{a2} is the additive genetic variance for trait 2.

Predicted genetic gains were estimated for radial and tangential log 3-6 m average air-dry and reconditioned shrinkage measurements, acoustic wave velocity at 3 m log, growth strain at 3 m log, sapwood internal checking, heartwood internal checking and density at 3 m log. Genetic gains were estimated as a percentage improvement over the population average following: average BLUP estimate of the top 5 % of individuals at Keens Block progeny trial/the predicted mean from the fixed effects solution, multiplied by 100.

RESULTS & DISCUSSION

Phenotypic variation

Progeny trial traits measured at age six are presented in Table 1 and are as discussed earlier by Baltunis et al. (2013).

Phenotypic measurements for wood properties are presented in Table 2. Phenotypic variation is describe as SD (standard deviation) that describes the total variation for each trait in this population. The average stiffness of *E. nitens* logs was comparable with results presented in the native country of this species (Farrell et al. 2008, Blackburn et al. 2010). Stiffness was greater in the 6 metre samples compared to the 3 metre logs. An Australian study reported that the average stiffness value for *E. nitens* was from 3.22 to 3.97 using Hitman at five sites located in Tasmania (Farrell et al. 2008). Blackburn et al. (2010) reported acoustic wave velocity of 3.18 to 3.36 for three different races in standing trees and in logs 3.51 to 3.61 of *E. nitens*.

Growth stress expressed as a measurement of split in sawn logs was larger in the upper part of the tree. It has been indicated in other studies that a large number of factors affect growth strain and they differ at different stages of the development (Biechele et al. 2009). A study for *E. nitens* in Chile, where growth strain was measured as a change in microns, indicated variability for the trait over time and at different stem heights, being moderate in the youngest trees (age 3) and increased with age to 10 years (Biechele et al. 2009). A New Zealand study on 63 *E. nitens* trees reported log bending on average of 19.05 mm, the trait being the function of longitudinal growth strain, log diameter and log length (Chauhan and Entwistle 2010).

The average 3-6 metre log tangential air-dry shrinkage was much larger than radial measurement but also a recovery after steam reconditioning was more substantial than for radial shrinkage in the present study. The large number of phenotyped individuals in our study probably contributes to differences in shrinkage measurements when comparing with other reports for the same species. Miller et al. (1992) reviewed tangential and radial shrinkage in *E. nitens* both in Australia and New Zealand, being lower than in our study, radial shrinkage from 2.7 to 3.0 and tangential from 5.5 to 5.7 per cent. Lausberg et al. (1995) reported higher values for air-dry (4.87) and lower for steam reconditioned radial shrinkage (2.26) but lower values for both tangential shrinkage measurements than in our study (5.15, 3.72).

Internal checking appeared to be much larger for sapwood than for heartwood and phenotypic variation for both traits was large. Similarly to this result, Lausberg et al. (1995) reported that the majority of checks occurred in sapwood in *E. nitens.* Shelbourne et al. (2002) reported a large phenotypic variation for the New Zealand *E. nitens* across many sites with an average within-site standard deviation of 28 checks per disc.

Wood density measured at the time of phenotyping for solid wood properties was lower than measured on the same material at the age 6 progeny trial assessment. This is due to the fact that the wood property sampling was done using only a part of the total tree material at Keens Block progeny trial. Wood density was smaller for lower than upper logs, but very comparable with other studies in *E. nitens* (Lausberg et al. 1995, Kube 2005, Hamilton et al. 2009).

Table 1. Statistical description of age six growth, form and density at the progeny trial assessment.

Trait	Mean	SD	Min	Max
Dbh6	165.54	28.46	39.0	274.0
Htm6	14.94	1.48	8.36	20.58
De6	486.03	31.15	375.0	600.0
Str6	7.11	1.36	1	9
Mal6	7.24	2.62	1	9
Acc6	0.67	0.52	0	2

Diameter at breast height **(Dbh6, mm)**, height **(Htm6, m)**, Density **(De6, kg m^3)**, Straightness **(Str6, score)**, Malformation **(Mal6, score)**, Acceptability **(Acc6, score)**

Table 2. Statistical description of age seven wood property traits in *E. nitens.*

Trait	Mean	SD	Min	Max
Ht1	3.33	0.19	2.43	4.52
Ht2	3.41	0.23	2	4.65
Sp1	27.75	5.51	12	57
Sp2	30.34	6.46	16	71
A15	3.20	0.72	1.3	7.0
A16	2.05	0.33	1.1	3.9
A17	7.98	1.45	5	13.7
A18	4.99	0.53	3.6	6.9
A33	2.85	0.58	1.4	5.9
A34	2.08	0.32	1.2	3.3
A35	6.79	1.04	4.2	11.8
A36	4.65	0.45	2.9	6.6
A39	3.09	0.61	1.4	6.1
A40	2.06	0.3	1.2	3.4
A41	7.44	1.19	5	12.3
A42	4.84	0.47	3.6	7.4
SIC	28.66	25.3	0	170
HIC	3.32	4.96	0	37
TIC	31.97	27.18	0	172
De3	441.13	25.65	371	541
De6	456.91	28.35	368	562
Dea6	486.03	31.15	375	600

Stiffness 1.4 – 3 m log **(Ht1, km per s)**, Stiffness 3 – 6 m log **(Ht2, km per s)**, Growth strain 1.4 – 3 m log **(Sp1, mm),** Growth strain 3 - 6 m log **(Sp2, mm),** Radial air-dry shrinkage 3 m log **(A15, %),** Radial reconditioned shrinkage 3 m log **(A16, %)**, Tangential air-dry shrinkage 3 m log **(A17, %)**, Tangential reconditioned shrinkage 3 m log **(A18, %)**, Radial air-dry shrinkage 6 m log **(A33, %)**, Radial reconditioned shrinkage 6 m log **(A34, %)**, Tangential air-dry shrinkage 6 m log **(A35, %)**, Tangential reconditioned shrinkage 6 m log **(A36, %)**, Radial air-dry shrinkage average 3-6 m log (**A39, %)**, Radial reconditioned shrinkage average 3-6m log **(A40, %)**, Tangential air-dry shrinkage average 3-6 m log (**A41, %)**, Tangential reconditioned shrinkage average 3-6 m log **(A42, %)**, Sapwood internal checking **(SIC, no.)**, Heartwood internal checking **(HIC, no.)**, Total internal checking **(TIC, no.)**, Density 3 m log **(De3, kg m^3)**, Density 6 m log **(De6, kg m^3)**, Density age 6 progeny trial **(Dea6, kg m^3)**

Figure 3. *Eucalyptus nitens* discs showed a great phenotypic variation for internal checking. A substantial part of this variation was due to genetics that ensures good possibilities to improve the tree material by breeding.

Genetic variation and estimates of heritability

Heritability estimates of progeny trial traits were higher than reported earlier by Baltunis et al. (2013) and can be explained by use of different models in the two analyses. Spatial within-site variation for rows and columns contributed substantially to phenotypic variation and taking this into account in the model improved heritabilities estimated here. This spatial variation was considerable for all progeny trial traits except for acceptability. Growth traits, density and stem straightness showed moderate heritabilities and therefore have good prospects for genetic improvement. Heritability estimates of growth in *E. nitens* appear to vary from low to moderate, DBH sometimes having an increasing trend in heritability with age (Kube 2005) or great variability according to site (Hamilton et al. 2009, Swain et al. 2014).

All traits used in selection for solid wood production showed moderate heritabilities. This implies that breeding will result in improved tree material for sawn timber properties in this population. Heritabilities for stiffness and growth strain indicated even greater selection possibilities for the lower part of logs compared to upper logs. This was evident in particular for stiffness. Similarly remarkable differences in heritabilities were not present between log heights in shrinkage measurements. Also no obvious differences or trends in estimated heritabilities emerged between radial and tangential shrinkage measurements or between air-dry and steam-reconditioned variables. Genetic variation between individual trees and heritability estimates for internal checking were larger for sapwood than for heartwood. Genotype by environment interaction (G x E) was not investigated in this study because the measurements were taken within one site only. It must be therefore pointed out that in the existence of G x E, selections made for Keens Block are applicable only to sites of comparable environmental attributes. Kube (2005) reported occasional presence of G x E for wood properties in *E. nitens*, although these interactions were always small.

Mostly moderate heritability estimates have been reported for wood density, shrinkage, collapse and internal checking in *E. nitens* (Kube and Raymond 2005, Hamilton et al. 2009, Blackburn et al. 2010). Kube and Raymond (2005) estimated moderate heritabilities for wood density that were rather similar across three sites, but heritabilities for collapse varied greatly according to site, being from 0.23 to 0.61. Hamilton et al. (2009) reported low heritabilities for net shrinkage for both sites and low to moderate for collapse that were different between the sites. Their study indicated no or non-significant G x E for basic density, gross shrinkage, net shrinkage and collapse as well as for DBH and cellulose content. Acoustic wave velocity for both standing trees and logs showed high heritabilities in *E. nitens* by Blackburn et al. (2010). In the same study, internal checking had a heritability estimate of 0.20 for wedge score and 0.52 for board wafer score (Blackburn et al. 2010).

Estimates of genetic correlations

Estimated genetic correlations between the traits of interest were mainly favourable regarding the breeding objective for solid wood production (Table 5). In some cases, standard errors were large due to a relatively small data size for estimation of genetic correlations. However, some of these correlations are definitely worthy of a closer examination. The highest estimated genetic correlations tended to be between the same solid wood properties for different log lengths implicating that the traits for 3 and 6 m logs are principally genetically the same traits. This was observed for both stiffness and density at different log lengths (Table 5). In addition, estimated genetic correlations for the same shrinkage measurements at different lengths were from 0.93 to 1.00 indicating that breeding against shrinkage could be done based on one log length. Another remarkably high and favourable estimate of genetic correlation was between density and stiffness. This was a consistent result for the two density measurements, one that was taken at the progeny trial assessment at age six and another measured on log length 3 m at the wood property study at age seven. Both these density measurements also had high (0.71) genetic correlation with acoustic wave velocity. Stiffness was also highly genetically associated with heartwood internal checking, the estimated correlation was beneficial for selecting simultaneously for both traits. Growth strain was highly and favourably genetically correlated with two shrinkage traits which were log average 3-6 m radial and tangential re-conditioned shrinkage measurements. Diameter at breast height, which selection has been strongly focused on, did not show remarkable or high genetic correlations with any of the wood property traits important for solid wood production. The highest genetic correlation for diameter at breast height was estimated with stiffness at 3 m log which was of moderate magnitude (0.34) and can be regarded only as indicative due to a large standard error.

Estimates of negative genetic correlations between diameter at breast height and density have been reported in other studies for *E. nitens*. Hamilton et al. (2009) estimated genetic correlation of -0.36 and Kube (2005) moderately negative but not significant genetic correlation between these traits in *E. nitens*. Similar to our report, Blackburn et al. (2012) estimated a moderately favourable genetic correlation between diameter at breast height and basic density, which however, was not significant. Highly positive genetic correlation between density and stiffness in *E. nitens* was also reported by Blackburn et al. (2012) which is in agreement with our results. Blackburn et al. (2012) considered that tree breeders could use acoustic wave velocity in the standing tree as a selection criterion for both pulpwood and peeled veneer products. Kube (2005) noted that selection for high stiffness can be made using indirect selection for density because of a favourable genetic association between the two traits and there would be only a small additional genetic gain when selecting directly for stiffness. We are not able to conclude any implications for selection based on non-significant genetic correlations between diameter and shrinkage. However, further information on this, is found in the literature, where Hamilton et al. (2012) showed an adverse estimate of genetic correlation between DBH and all shrinkage traits as well as among basic density, cellulose content and net shrinkage. This was interpreted to imply that it could be difficult to use only one population to breed for both pulpwood and solid-wood production. Kube (2005) concluded that collapse should be included in breeding programmes if the aim was to produce appearance grade products in *E. nitens*. This was based on moderate heritability, and a strong and favourable genetic correlation with basic density and on the other hand strong and adverse genetic correlations with diameter (Kube 2005).

Predicted genetic gains for wood properties

Predicted genetic gains based on estimated BLUP breeding values when selecting the top 5% of individuals at the third generation *E. nitens* progeny at Keens Block in Southland indicated the potential for good genetic improvement for all wood property traits (Table 6). The greatest genetic gains were predicted for sapwood and heartwood internal checking. Predicted genetic gains indicated that considerable genetic progress could be also expected for air-dry and re-conditioned shrinkage measurements and growth strain. Predicted genetic gains were estimated using univariate analysis so it must be pointed out that when selecting for target traits, genetic gains here may be somewhat different. However, due to mainly favourable estimated genetic correlations, it would be possible to optimise selection for all traits using a desired genetic gains approach (Li et al. 2016).

Table 3. Estimates of additive genetic variance (σ^2_a) and heritability (h^2) with standard errors (s.e) for age six growth, form and density measured at the progeny trial.

Trait	σ^2_a	$h^2 \pm$ ***s.e***
Dbh6	131.85	0.20±0.04
Htm6	0.36	0.20±0.04
De6	269.26	0.30±0.08
Str6	0.48	0.28±0.05
Mal6	0.75	0.11±0.03
Acc6	0.03	0.13±0.04

Diameter at breast height **(Dbh6, mm)**, height **(Htm6, m)**, Density **(De6, kg m^3)**, Straightness **(Str6, score)**, Malformation **(Mal6, score)**, Acceptability **(Acc6, score)**

Table 4. Estimates of additive genetic variance (σ^2_a) and heritability (h^2) with standard errors (s.e) for wood property traits in *E. nitens.*

Trait	σ^2_a	**h^2 ± s.e**
Ht1	0.01	0.40±0.13
Ht2	0.01	0.22±0.12
Sp1	8.57	0.34±0.17
Sp2	8.63	0.22±0.11
A15	0.16	0.35±0.12
A16	0.03	0.31±0.11
A17	0.79	0.41±0.12
A18	0.12	0.50±0.13
A33	0.1	0.33±0.12
A34	0.03	0.35±0.11
A35	*Not converged*	*Not converged*
A36	0.08	0.45±0.13
A39	0.14	0.43±0.13
A40	0.03	0.42±0.12
A41	0.6	0.45±0.13
A42	0.1	0.49±0.13
SIC	176.52	0.35±0.13
HIC	5.91	0.25±0.10
TIC	209.8	0.35±0.13
De3	259.71	0.51±0.14
De6	347.46	0.55±0.14

Stiffness 1.4 – 3 m log **(Ht1, km per s)**, Stiffness 3 – 6 m log **(Ht2, km per s)**, Growth strain 1.4 – 3 m log **(Sp1, mm),** Growth strain 3 - 6 m log **(Sp2, mm),** Radial air-dry shrinkage 3 m log **(A15, %),** Radial reconditioned shrinkage 3 m log **(A16, %)**, Tangential air-dry shrinkage 3 m log **(A17, %)**, Tangential reconditioned shrinkage 3 m log **(A18, %)**, Radial air-dry shrinkage 6 m log **(A33, %)**, Radial reconditioned shrinkage 6 m log **(A34, %)**, Tangential air-dry shrinkage 6 m log **(A35, %)**, Tangential reconditioned shrinkage 6 m log **(A36, %)**, Radial air-dry shrinkage average 3-6 m log (**A39, %)**, Radial reconditioned shrinkage average 3-6m log **(A40, %)**, Tangential air-dry shrinkage average 3-6 m log (**A41, %)**, Tangential reconditioned shrinkage average 3-6 m log **(A42, %)**, Sapwood internal checking **(SIC, no.)**, Heartwood internal checking **(HIC, no.)**, Total internal checking **(TIC, no.)**, Density 3 m log **(De3, kg m^3)**, Density 6 m log **(De6, kg m^3)**, Density age 6 progeny trial **(Dea6, kg m^3)**

Table 5. Estimates of genetic correlations with their standard errors as subscript for traits important in selection for solid wood properties in *E. nitens.*

	Ht1	***Ht2***	***Sp1***	***Sp2***	***A39***	***A40***	***A41***	***A42***	***SIC***	***HIC***	***De3***	***De6***
Dbh6	$0.34_{0.29}$	$-0.06_{0.39}$	$-0.26_{0.27}$	$-0.20_{0.32}$	$-0.11_{0.27}$	$-0.02_{0.28}$	$0.06_{0.27}$	$0.25_{0.25}$	$0.02_{0.30}$	$-0.17_{0.32}$	$0.24_{0.26}$	$0.17_{0.25}$
Dec-06	$0.71_{0.22}$	$0.57_{0.34}$	$0.16_{0.26}$	$0.32_{0.29}$	$-0.32_{0.24}$	$0.40_{0.24}$	$-0.16_{0.24}$	$0.46_{0.22}$	$-0.22_{0.27}$	$-0.46_{0.23}$	$1.00_{0.12}$	$1.00_{0.12}$
Ht1		$0.92_{0.20}$	$0.49_{0.24}$	$0.31_{0.29}$	$-0.40_{0.29}$	$0.04_{0.26}$	$-0.34_{0.23}$	$0.11_{0.24}$	-	$-0.83_{0.24}$	$0.71_{0.16}$	-
Ht2				$0.15_{0.41}$	$-0.41_{0.32}$	$0.03_{0.34}$	$-0.14_{0.33}$	$0.28_{0.31}$	$-0.55_{0.34}$	$-0.59_{0.39}$	-	-
Sp1					$0.50_{0.23}$	$0.76_{0.20}$	$0.46_{0.24}$	$0.70_{0.20}$	$0.31_{0.28}$	$-0.02_{0.30}$	$0.35_{0.22}$	$0.20_{0.23}$
Sp2					$0.34_{0.28}$	$0.59_{0.26}$	$0.46_{0.27}$	$0.70_{0.25}$	$0.09_{0.32}$	$0.36_{0.34}$	$0.14_{0.27}$	$0.05_{0.27}$
A39						$0.66_{0.14}$	$0.81_{0.11}$	$0.26_{0.22}$	$0.41_{0.24}$	$0.05_{0.28}$	-	-
A40							$0.53_{0.19}$	$0.76_{0.13}$	-	$-0.11_{0.28}$	-	-
A41								$0.55_{0.15}$	$0.59_{0.21}$	$-0.11_{0.27}$	$-0.36_{0.20}$	$-0.37_{0.19}$
A42									$0.24_{0.25}$	$-0.23_{0.27}$	-	-
SIC										$0.49_{0.25}$	$-0.22_{0.24}$	$-0.47_{0.21}$
HIC											$-0.54_{0.22}$	$-0.46_{0.23}$
De3												$0.91_{0.05}$

Stiffness 1.4 – 3 m log **(Ht1, km per s)**, Stiffness 3 – 6 m log **(Ht2, km per s)**, Growth strain 1.4 – 3 m log **(Sp1, mm),** Growth strain 3 - 6 m log **(Sp2, mm),** Radial air-dry shrinkage average 3-6 m log (**A39, %)**, Radial reconditioned shrinkage average 3-6m log **(A40, %)**, Tangential air-dry shrinkage average 3-6 m log (**A41, %)**, Tangential reconditioned shrinkage average 3-6 m log **(A42, %)**, Sapwood internal checking **(SIC, no.)**, Heartwood internal checking **(HIC, no.)**, Density 3 m log **(De3, kg m^3)**

Table 6. Predicted genetic gains by ignoring relatedness of selections for wood property traits when the top 5% of individuals are selected in the third generation.

Trait	***Genetic gain %***
A39	9.99
A40	7.50
A41	9.46
A42	6.30
Ht1	3.00
Sp1	8.20
SIC	39.00
HIC	51.58
De3	3.40

CONCLUSIONS

The estimated heritabilities indicate a good possibility for selection of solid wood production by breeding. Many favourable genetic correlations were found between traits important to breeding objectives. Genetic correlations between traits were mostly indicative due to large standard errors and therefore inconclusive. To maximise the genetic improvement for each production purpose, separate breeding objectives for solid wood and pulp wood production are recommended. Based on predicted genetic gains, great improvement in traits important for solid wood properties should be expected. Two seed-orchards, one for solid wood and another for pulpwood production were established based on estimated breeding values from this study. Genomic based breeding values will be implemented to this population and this may enlighten further genetics behind these traits and associations between the traits as well as expected genetic gains.

ACKNOWLEDGEMENTS

Diversified Species Programme, Scion Core Funding and Specialty Wood Products Research Partnership are acknowledged for funding this study.

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