Genetic parameters for early growth and biomass traits of *Pinus radiata* D. Don under different water regimes

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Abstract

In Chile, genetic improvement of Radiata pine has been directed towards characters such as volume, form and wood density. Estimation of genetic parameters for growth and biomass traits in young seedlings, as a tool for early indirect selection in the *P. radiata* breeding program, has not been explored yet. We aimed to estimate genetic parameters for growth and biomass traits. Five-month-old *P. radiata* seedlings grown under well-watered (WW) and water stress (WS) regimes were evaluated. Root collar diameter, height, shoot dry weight, root dry weight, total dry weight, height/diameter ratio and root/shoot ratio were analyzed in both treatments. Trait with the highest heritability was root/shoot ratio in WW and WS regime ($h^2 = 0.80$ and 0.63 respectively). The highest genetic correlation was between height and shoot dry weight ($r_g = 0.90$), under WW regime. In contrast, there were negative genetic correlations between root collar diameter and height/diameter ratio under WS regime. To breed for drought tolerance, traits such as height and root collar diameter would be effective targets for indirect selection since estimated heritabilities are high, there is sizable genetic variation, they are easily assessed, they can be measured non-destructively and they have a high genetic correlation with root/shoot ratio, a trait related to drought tolerance. The measurement of dry weights for early selection purposes is not recommended.

Key words: heritability, genetic and phenotypic correlation, Type B correlation, *Pinus radiata*, water stress, biomass.

Introduction

Radiata pine (*Pinus radiata* D. Don) is the most important exotic forest species in Chile where it has been planted on nearly 1.46 million ha. Rapid growth of *P. radiata* plantations in Chile (15 to $36 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$) has been a key factor for the plantation expansion of

this species. The climatic and soil conditions in the country, especially within Seventh and Ninth Regions, allow for faster tree growth compared to the growth in its native California (BURNS and HONKALA, 1990; MUÑOZ, 2008). Genetic improvement of radiata pine in Chile has started in the 70's and has been directed towards characters such as volume, form and wood density. In *P. radiata*, most of the studies on genetic parameter estimates have focused on young stands, older than four years, and not on seedlings (e.g. GAPARE et al., 2008; WU et al., 2008). There have been no estimates of heritability reported for morphological traits involved in drought tolerance in young *P. radiata* seedlings. Recent preliminary experiments in the greenhouse have shown that family by water availability interactions for morphological traits in five-month-old *P. radiata* seedlings are important and should not be ignored (ESPINOZA, 2012).

In young *Pinus pinaster* seedlings genetic parameters and genotypic stability for seedling morphology under different water and nutrient regimes were estimated (ZAS and FERNÁNDEZ-LÓPEZ, 2005). Also juvenile-mature correlations and selection efficiencies among one-year old *P. pinaster* seedlings and 8-yr field performance were analyzed in order to study the possibilities of early selection in the *P. pinaster* breeding program in Galicia (ZAS et al., 2004). In Chile, although greater drought events are expected in the future, resulting in a more Mediterranean climate (CONAMA, 2006; 2009) and affecting establishment and productivity of radiata pine, no breeding programmes have included drought tolerance as a breeding objective. Some reasons for this are probably that there is currently no requirement or market push for improving drought tolerance in the breeding programmes. Also, the direct measurement of some traits is costly and time-consuming. Because of the long rotation lengths typically used in forestry, early evaluation of genotypes is often an important component of tree improvement programmes. Nonetheless, the question of exactly what age to select has been debated for many years (LAMBETH and DILL, 2001). In retrospective studies, genetic correlation and selection efficiency are tested usually between three months to two years (LAMBETH, 1980). Thus, easier and inexpensive methods to evaluate trees with minimal damage are required (i.e. indirect selection; to select for one trait and to improve another trait). The objective of the present study was to investigate whether growth and biomass traits in five-month-old nursery seedlings of radiata pine shows exploitable genetic variation relevant to utilization in breeding programs. The specific objectives include: (1) to estimate heritability of growth and biomass traits in well-watered and water-stress five-month old seedlings,

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Table 1. – Origin of radiata pine investigated: geographical and climatic features of their zones of origin.

Plus-trees origin	Annual precipitation (mm)	Parent material	Location		Number of families
			Latitude S	Longitude W	
Sandy Soils Eight Region	1100-1208	Sandy	37° 31'	72° 04'	21
Seventh Region Coast	450-950	Granitic-metamorphic	35° 21'	72° 27'	18
Eight Region Coast	1300	Granitic-metamorphic	38° 14'	73° 17'	27
Foothills of the Andes Eight Region	1600	Volcanic ash	36° 39'	71° 40'	5
Central Valley Eight Region	1000-1300	Red clay	36° 56'	72° 22'	9

(2) to quantify the genotypic correlation between traits, as a tool for indirect selection, and (3) to estimate Type B correlations for the analyzed traits across different watering regimes.

Materials and Methods

Material

We used a subset of the first generation open-pollinated families of the radiata pine breeding programme in Chile. Seeds from these families were provided by Forestal Celco S.A. and Forestal Mininco S.A., and were randomly selected from seed orchards of these companies. Seed originated from 25 year old plus trees selected between 1976–1978 for traits such as superior growth, stem form and volume, at five different sites in Central Chile, ranging from Coastal Range, across Central Valley to Foothills of the Andes in the Seventh and Eight Regions (Table 1, Figure 1).

Nursery experiment

Seeds from 69 open-pollinated families were sown on 140 cm³ pots filled with a mixture of composted bark of radiata pine and perlite (8:2), combined with the slow-release fertilizer Basacote™ plus 6M. These pots are currently used by the main Chilean forestry companies to raise millions of seedlings because they allow for adequate water supply, good aeration and root growth. The material was raised in the nursery for twenty weeks under normal watering regimes (watering every day). Seven weeks after sowing, those 69 families were placed following a split-plot design, with watering regime as the whole plot and family nested within site as the sub-plots. Five sites of origin, 69 families and two watering treatments were used. The two watering treatments, well watered (WW) and water stress (WS), were applied to three replicates of 69 families, with 16 seedlings of each family included per sub plot (Figure 2). The watering treatments were not applied to individual families; instead they were applied to trays containing 6 families

each. Local micro-environmental conditions were strictly controlled (i.e. wind, position of the trays with respect to the solar angle, and drift of water mist), in order to allow all seedlings to receive the same growth conditions, except for the watering regime.

Twenty weeks after sowing, seedlings from the 69 families were subjected to two watering regimes based on predawn plant water potentials (ψ_{pd}): (1) well-watered treatment, in which seedlings were watered daily to container capacity to maintain a ψ_{pd} of -0.5 ± 0.1 MPa, as measured with a pressure chamber. (2) cyclic water stress treatment in which seedlings were subjected to cyclic water deficits by watering to contain-

Figure 1. – Location of the *Pinus radiata* plus-trees collected between 1976–1978 (* = Families from Sandy Soils Eight Region, ● = Families from Seventh Region Coast, ▲ = Families from Eight Region Coast, + = Families from Foothills of the Andes Eight Region, ◆ = Families from Central Valley Eight Region).

Figure 2. – Experimental layout for 69 successfully germinated families. Family plots were randomized within replications.

er capacity on three 12-days cycles when ψ_{pd} reached -1.5 ± 0.1 MPa on average. Water potential was measured in the three 12-days cycles by using a subsample of three seedlings per six families per watering regime. According to SQUIRE et al. (1988), with ten days of withholding of water, five-month old *P. radiata* seedlings reach a water potential of -1.9 MPa with seedlings been wilted. During this period, the water supply was withdrawn until the water content of each tray (with 88 containers and 6 families each) reached 40% of field capacity (determined by weight). Water availability was homogeneous among families, and this watering level was maintained approximately constant until the end of the stress period.

Assessments

Seedlings were harvested after the last 12-day cycle finished. Total height (H) from the edge of the plastic container to the top of the plant, root collar diameter (D), shoot dry weight (SDW) and root dry weight (RDW) were measured (80°C , 24 h). The total dry weight (TDW = SDW + RDW), the root/shoot ratio (RSR = RDW/SDW) and the height/diameter ratio (HDR = H/D) were also calculated. 15 seedlings per water regime treatment and per family were harvested. All weight and linear measurements are in grams (g) and millimetres (mm), respectively.

Statistical analysis

Genetic parameter estimates were based on residual maximum likelihood method. A mixed linear effects model was used to estimate the genetic variance components and narrow-sense heritability associated with each trait. A linear mixed effects model used was as follows:

$$Y_{ijkl} = \mu + W_i + O_j + F(O)_{kj} + W_i * F(O)_{kj} + e_{ijkl} \quad (1)$$

where Y_{ijkl} is the observed phenotypic measurement (all the morphological traits), μ is the overall mean, W_i is the fixed effect of i^{th} watering regime, O_j is the fixed effect of j^{th} plus-tree origin, $F(O)_{kj}$ is the random effect of the k^{th} family nested within the j^{th} plus-trees origin, $W_i * F(O)_{kj}$ is the interaction between the i^{th} watering regime and the k^{th} family nested within the j^{th} plus-trees origin, and e_{ijkl} is the experimental random error. ASReml program (GILMOUR et al., 2005) which was used for the data analyses was also used to check the normality of the distribution of the residuals.

Observed variance components were used to estimate the causal variance components and narrow-sense heritability for each trait under each of the watering regimes. Heritability was calculated as:

$$h^2 = \frac{4 * \sigma_f^2}{\sigma_f^2 + \sigma_e^2} \quad (2)$$

where σ_f^2 is the family genetic variance, and σ_e^2 is the error variance component. Additive genetic coefficient of variation (CV_A) was calculated as:

$$CV_A = \frac{\sigma_A}{\bar{x}} \times 100\% \quad (3)$$

where CV_A is the coefficient of additive genetic variation, σ_A is the square-root of the additive genetic variance for a trait, and $\bar{x}$ is the mean for the trait. The CV_A expresses the genetic standard deviation relative to the mean of the trait of interest and gives a standardized measure of the genetic variance relative to the mean of the trait. The higher the CV_A for a trait, the higher is its relative variation.

Phenotypic correlations between different traits were calculated using the coefficient r of Pearson. Genetic correlations between two traits within a watering regime were calculated from the variance/covariance estimates as:

$$r = \frac{\sigma_{Axy}^2}{\sqrt{(\sigma_{Ax}^2)(\sigma_{Ay}^2)}} \quad (4)$$

where σ_{Axy}^2 = additive genetic covariance component between traits x and y , σ_{Ax}^2 = additive genetic variance component for trait x , σ_{Ay}^2 = additive genetic variance component for trait y . Type B correlation between the same trait in different treatments (r_B) was estimated from the joint analysis of each pair of treatments (BURDON, 1977).

$$r_B = \frac{\sigma_f^2}{\sigma_f^2 + \sigma_{f*W}^2} \quad (5)$$

where σ_f^2 = is the family variance component and σ_{f*W}^2 = is the family by watering regime variance component.

Results

Seedling growth, biomass and heritability of the traits

Initial plant size did not influence any of the plant growth or biomass traits. Before starting the water stress treatment root collar diameter and height were homogeneous for all families under study ($P < 0.01$). At 20 weeks of growth, and before the commencing of watering treatments, an average of 10.4 ± 0.12 cm in height and 1.85 ± 0.02 mm in diameter was observed. This indicates that the observed response in all families

after water stress is more attributable to the effect of the withholding of water than the ontogenetic state of the seedlings. *Table 2* shows the overall watering regime means for total height (H), root collar diameter (D), height-diameter ratio (HDR), root/shoot ratio (RSR), shoot dry weight (SDW), root dry weight (RDW) and total dry weight (TDW). Under the well-watered regime, total seedling height was 13.7 ± 0.009 cm and root collar diameter averaged 2.6 ± 0.09 mm. As expected, trait values under the water stress regime were lower than those under the well-watered regime. For example, there was a reduction of 13% and 23% in total height and root collar diameter, respectively, under the water stress regime compared to well-watered regime. Total dry weight (TDW) was reduced significantly by water stress in all families (*Table 2*). At final harvest, reduction in TDW was 13% less for water stress compared to well-watered seedlings. In general, there were significant differences for individual traits between well-watered and water-stress regimes.

Table 3 shows heritability and additive genetic coefficient of variation estimates for measured traits. Heritability estimates for all traits under the well watered regime were medium to high, ranging from 0.31 ± 0.10 to 0.80 ± 0.16 . The highest heritability estimates were observed for H and RSR (0.63 ± 0.14 and 0.80 ± 0.16 , respectively). Heritability estimates under the water stress regime ranged from 0.29 ± 0.10 to 0.63 ± 0.14 , the highest being for RSR. Family by watering regime interactions were significant ($P < 0.01$). For both treatments, family variance had a contribution up to 14.6% of the total phenotypic variance, which suggests that traits are under moderate to high levels of genetic control, while residual variance ranged from 77 to 90%.

Table 2. – Averages for different morphological traits among 69 half-sibs families of radiata pine growing in different watering regimes (mean $\pm$ S.E. of the mean; $n=840$).

Trait	Watering regime	
	Well-watered	Water stress
H (mm)	$137.2 \pm 0.1a$	$119.28 \pm 0.1b$
D (mm)	$2.5 \pm 0.0a$	$1.98 \pm 0.01b$
HDR	$5.3 \pm 0.0a$	$6.1 \pm 0.0b$
RSR	$1.14 \pm 0.0a$	$1.11 \pm 0.0b$
SDW (mg)	$2.060,1 \pm 0.0a$	$1.768,4 \pm 0.0b$
RDW (mg)	$1.805,1 \pm 0.0a$	$1.600,4 \pm 0.0b$
TDW (mg)	$3.865,1 \pm 0.0a$	$3.368,8 \pm 0.0b$

H = total height, D = root collar diameter, HDR = height/diameter ratio, RSR = root/shoot ratio, SDW = shoot dry weight, RDW = roots dry weight, TDW = total dry weight. Different letters indicate statistical differences for watering regime at $P < 0.01$.

Table 3. – Heritability estimates and associated standard errors, and additive genetic coefficient of variation (%) (*in italics*) for morphological traits among 69 half-sibs families of radiata pine growing in different watering regimes.

Treatment	D	H	SDW	RDW	TDW	HDR	RSR
Well-watered	0.49±0.13	0.63±0.14	0.48±0.12	0.37±0.11	0.37±0.11	0.31±0.10	0.80±0.16
	<i>6.02</i>	<i>8.03</i>	<i>2.41</i>	<i>0.58</i>	<i>1.86</i>	<i>2.91</i>	<i>1.20</i>
Water-stress	0.53±0.13	0.34±0.10	0.29±0.10	0.54±0.13	0.36±0.11	0.56±0.13	0.63±0.14
	<i>8.33</i>	<i>6.54</i>	<i>1.59</i>	<i>0.65</i>	<i>1.53</i>	<i>5.61</i>	<i>0.78</i>
Joined analysis	0.32±0.14	0.36±0.13	0.28±0.13	0.26±0.12	0.22±0.11	0.20±0.12	0.52±0.15
	<i>4.87</i>	<i>6.11</i>	<i>4.02</i>	<i>3.89</i>	<i>3.31</i>	<i>4.93</i>	<i>4.65</i>

H = total height, D = root collar diameter, HDR = height/diameter ratio, RSR = root/shoot ratio, SDW = shoot dry weight, RDW = roots dry weight, TDW = total dry weight.

Table 4. – Genetic (below diagonal) ± S.E and phenotypic (above diagonal) ± S.E correlations for morphological traits among 69 half-sibs families of radiata pine growing in different watering regimes.

Traits	D	H	SDW	RDW	TDW	HDR	RSR
Well-watered							
D	-	0.57±0.02	0.69±0.01	0.54±0.02	0.67±0.02	-0.32±0.03	0.25±0.03
H	0.72±0.10	-	0.76±0.01	0.60±0.02	0.75±0.01	0.56±0.02	0.28±0.03
SDW	0.80±0.08	0.90±0.04	-	0.70±0.02	0.93±0.00	0.19±0.03	0.47±0.03
RDW	0.32±0.18	0.42±0.16	0.45±0.16	-	0.90±0.00	0.14±0.03	-0.28±0.03
TDW	0.70±0.11	0.81±0.07	0.89±0.04	0.80±0.07	-	0.18±0.03	0.13±0.03
HDR	-0.05±0.22	0.65±0.13	0.43±0.19	0.28±0.22	0.43±0.20	-	*0.08±0.03
RSR	0.54±0.14	0.59±0.13	0.65±0.11	-0.37±0.17	0.25±0.19	0.23±0.20	-
Water stress							
D	-	0.50±0.02	0.54±0.02	0.53±0.02	0.59±0.02	-0.38±0.03	0.01±0.04
H	0.34±0.19	-	0.74±0.01	0.58±0.02	0.73±0.01	0.57±0.02	0.17±0.03
SDW	0.30±0.20	0.82±0.08	-	0.67±0.02	0.91±0.00	0.25±0.03	0.41±0.03
RDW	0.38±0.16	0.38±0.18	0.48±0.16	-	0.90±0.00	0.10±0.03	-0.39±0.03
TDW	0.40±0.17	0.66±0.12	0.82±0.07	0.89±0.04	-	0.20±0.03	0.02±0.03
HDR	-0.61±0.13	0.52±0.15	0.38±0.19	-0.05±0.19	0.15±0.20	-	0.17±0.03
RSR	-0.12±0.19	0.28±0.19	0.27±0.20	-0.70±0.11	-0.32±0.19	0.35±0.17	-

All phenotypic correlations with $P < 0.01$, except for * = $P < 0.05$. H = total height, D = root collar diameter, HDR = height/diameter ratio, RSR = root/shoot ratio, SDW = shoot dry weight, RDW = roots dry weight, TDW = total dry weight.

Genetic and phenotypic correlations among different traits

Genetic correlations for all traits were slightly higher than phenotypic correlations (Table 4). For example, genetic correlation between H and SDW for the well-watered regime was 0.90 ± 0.04 . Similarly, genetic corre-

lation between D and SDW was 0.80 ± 0.08 for well-watered regime. As expected, D and H were strongly correlated with the three biomass traits (SDW, RDW, TDW). A high and positive genetic correlation between SDW, RDW and TDW ($R > 0.45$) was found in both watering regimes. A negative and low correlation

Table 5. – Type-B correlations $\pm$ S.E among the same trait in different treatments.

Traits	r_B
$D_{ww}-D_{ws}$	0.00 $\pm$ 0.00
$H_{ww}-H_{ws}$	0.44 $\pm$ 0.19
$SDW_{ww}-SDW_{ws}$	0.13 $\pm$ 0.25
$RDW_{ww}-RDW_{ws}$	0.19 $\pm$ 0.23
$TDW_{ww}-TDW_{ws}$	0.20 $\pm$ 0.26
$HDR_{ww}-HDR_{ws}$	0.62 $\pm$ 0.15
$RSR_{ww}-RSR_{ws}$	0.06 $\pm$ 0.20

ww = well-watered treatment, ws = water-stress treatment, H = total height, D = root collar diameter, HDR = height/diameter ratio, RSR = root/shoot ratio, SDW = shoot dry weight, RDW = roots dry weight, TDW = total dry weight.

between RDW and RSR was detected for both watering regimes. The correlations were similar in sign but the magnitude changed in some cases between the two watering regimes (Table 4).

Genetic correlations among different treatments

Relatively low correlations were observed between the two watering regimes. Type-B correlations among the different treatments were generally low for growth and biomass traits (Table 5). For D and RSR there were very low correlations, indicating a high evidence of the family by watering regime interaction. The type-B correlations for $H_{ww}-H_{ws}$ and $HDR_{ww}-HDR_{ws}$, were higher but still suggested the presence of a strong genotype by watering regime interactions ($r_B = 0.44 \pm 0.19$ and 0.62 ± 0.15 respectively).

Discussion

In the present study, open-pollinated seed from radiata pine plus trees collected between 1976–1978 were used to estimate genetic parameters. The dataset includes families belonging to different sites, covering most of the current geographical distribution of this species in Chile (Table 1, Figure 1). Because conclusions regarding genetic parameters may differ dramatically if ontogenetic changes in seedling development are taken in consideration (ZOBEL and TALBERT, 1992), care was taken to assess seedlings in the same ontogenic stage, i.e. before the formation of dwarf shoots. With a significance limit of $P < 0.01$, no differences in height and root collar diameter of seedlings occurred at the two experiments. As far as we know this is the first study in Chile to include heritability estimates of morphological traits for radiata pine seedlings under different watering regimes. CODESIDO et al. (2012) also estimated heritability for young radiata pine seedlings in Spain. They found a high value and h^2 for RSR in water stress-low nutrient. Relative to the early-age estimates observed in other species (LI et al., 1992; JANSSON et al., 1998; SONESSON et al., 2002), and relative to older tree growth traits in conventional genetic tests (ZAS et al., 2004), seedling D, H and RSR in this study exhibited higher heritabilities (Table 3). The homogeneity of the growth

conditions under the controlled environment for young seedlings may explain these differences with older tree growth traits. The high estimates of heritability can partly be attributed to the uniform growth conditions resulting in a low environmental variance. When both treatments were pooled together (Table 3), the heritabilities were lower for some of the traits analyzed, because of the impact of family by watering regime interactions. According to FALCONER (1990), when one trait is measured in two different environments it must not be considered as one trait, instead, it must be considered as two traits (i.e. RSR in WW treatment is different from RSR in WS treatment). Estimates of heritability for most of the traits were generally higher under the well-watered regime than those under water-stress regime, which is similar to that reported in CODESIDO et al. (2012) for young radiata pine seedlings. This may suggest that the genetic expression of these traits was affected by water restriction imposed.

Overall trait means under the well-watered regime were generally higher and significantly different to traits under the water-stress regime, and water stress regime had a negative effect on seedling growth (Table 2). Although the water stress treatment applied may be too short to obtain informative data on drought regulation mechanisms at organ and whole plant level, the drought period was long enough to affect morphological traits. The significant effect of watering regimes had an important effect not only on growth and dry biomass but also on biomass partitioning. The water stress treatment resulted in smaller seedlings but relatively more biomass allocated to roots, especially in families from the interior areas (e.g. Sandy Soils Eight Region) (data not shown). Water stress generally favors more biomass allocated to roots at the expense of shoots (JOLY et al., 1989; TAN et al., 1995; HARFOUCHE, 2003). ESPINOZA (2012) in *P. radiata* young seedlings found that families belonging to interior sites develop different strategies for biomass allocation under water stress than those belonging to coastal sites, investing more biomass to roots at the expense of shoots. Heritabilities for biomass production tend to vary considerably under different experimental conditions. For example, in Norway spruce, SONESSON et al. (2002) showed that heritabilities were higher at high temperature and high moisture than at low temperature and low moisture. In contrast, SONESSON and ERIKSSON (2003) found that for Norway spruce, heritabilities were higher in drought stressed trees than well-watered ones.

It has been suggested that high RSR is a desirable trait when selecting clones for drier environments (GROSSNICKLE, 2000). In this study RSR had the highest heritability and a moderate to high genetic correlation with H. High RSR is considered essential in drought tolerance, because it indicates a high moisture extraction capacity of the roots relative to the transpiring shoots. Therefore, selection and breeding for high RSR could improve drought tolerance. However, processing and oven drying of plant parts is tedious, especially for large trees. This could limit the sample size and reduce accuracy in the estimation of genetic parameters and subsequently, reduce genetic gains. The correlation between

seedling dry weights and seedling traits such as height or root collar diameter could be used to simplify collection of biomass data. Instead of harvesting and weighing all seedlings, a representative destructive sample could be used to develop partition-specific allometric equations and use them to estimate dry weights of the remaining seedlings with diameter or height as predictor variables (e.g. SHAIK et al., 2011; LEVIA, 2008; MUUKKONEN, 2007). Our results shows that genetic correlation among plant D and H with most of the traits analyzed were relatively high in both water regimes, and furthermore both traits had a medium to high heritability in both treatments and they were the easiest to measure. Negative genetic correlations were also observed for RSR and RDW in WW treatment and with D, RDW and TDW in WS treatment, which suggest that different sets of genes regulate these traits. Total dry weight (TDW) was significantly genetically correlated with height measurements regardless of the watering treatments, indicating close genetic association between the two traits. On the other hand, relatively low correlations (i.e. Type-B correlations) were observed between the two watering regimes (Table 4), indicating a high plasticity for all traits and a high evidence of the family by watering regime interaction. In this case, a high family by watering regime interaction can result from plasticity (FALCONER, 1990) and agrees with results obtained in other forest species (e.g. BARNES and SCHWEPPEHAUSER, 1978; FARFÁN et al., 2002; SANCHEZ et al., 2003).

Based on the results of this study it may be concluded that H and D can be recommended for incorporation into early testing in a *P. radiata* breeding programme. To breed for drought tolerance, traits such as height and root collar diameter would be useful traits to utilize in indirect selections for drought tolerance because estimated heritabilities are high, there is sizable genetic variation, they are easily assessed, they can be measured non-destructively and they have a high genetic correlation with root/shoot ratio, a trait related to drought tolerance. However, and as a future work of this research, the evaluation of juvenile-mature correlations (J-M) should be considered before discarding any early selection trait. Early tests are an important issue for selection, but using a few weeks old and 15 cm high seedlings is probably not providing any generalisable result for the Chilean radiata pine breeding programme. The analyses of the greenhouse-field correlations should be carried out before establishing any early selection strategy for drought. Early performance under controlled conditions may reflect later field performance, and if testing and selections can be made based on growth nursery/greenhouse trials the lag time between selections and realized gains could be significantly reduced.

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