Methods of Assessing Crown Form of Pinus radiata

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Summary

Crown form is a visual characteristic having many component traits (branch thickness, branch angle, ramicorns, forks and uninodal/multinodal branch habit). Alternative methods of assessing each trait are evaluated in terms of their variance components and heritabilities in a progeny trial of *Pinus radiata*. A comparison is made between using one overall score for crown form and use of selection indices to combine traits. The efficiency of each alternative is compared in terms of the calculated selection response for each trait.

For assessing branch diameter and branch angle a six point score was preferred to the use of a three or nine point score. The six point score resulted in large additive genetic variance and a higher heritability, giving good discrimination of genotypes without being confusing to the assessors. For ramicorns and forks, counting the actual numbers present resulted in higher heritabilities than scoring for their incidence. Calculated responses from selecting one tree in 100 on either a single crown form score or multitrait indices indicated that response in each component of crown form is greater for the indices.

Key words: Pinus radiata, crown form, branch form, index selection.

Introduction

A major aim in breeding *Pinus radiata* D. Don in Australia, New Zealand, Chile and other parts of the world has been to improve what is generally described as crown form. Unimproved *P. radiata* tends to have rather heavy branching and breeders have exerted considerable selection pressure to reduce the branch diameter. Attention has also been given to branch angle with breeders preferring branches at a flat (90^0) angle to the stem. Thin flat branches leave much smaller knots in the timber compared with thick, acute angled branches. Selection pressure is exterted against malformations of the crown such as large ramicorn branches and forking of the main stem. There is some conflict regarding the desirability of uninodal versus multinodal branching habits. Most breeders select for a multinodal habit with short internodes and many whorls of thin flat branches as a large number of small knots is expected to cause less degrade in boards than a few large knots. However, one breeding program is underway in New Zealand to develop a uninodal type of *P. radiata* with long internodes Carson and Inglis (1986). The long internodes are intended to produce clear (knot-free) timber.

While there is broad agreement among breeders about what constitutes desirable crown form there seems little consensus on how crown form should be assessed. The problem is that crown form has many component parts (branch thickness, branch angle, ramicorns, forks, uninodal or multinodal branch habit). Methods of assessment range from separate visual scores or direct measurements of each trait to one overall score of crown form.

There is a need for comparison of the efficiency of selection under these various methods of assessing crown form. Previously, the efficiency of a subjective scoring system was determined by the ranking of the same families when assessed by a visual score and by more objective measurements. For example, Pawsey (1967) found that assessing the crown form of each tree as desirable or otherwise using a four point score resulted in almost the same ranking of families as a more detailed assessment of each trait. This author used 5 and 4 point scores to assess branch diameter and angle respectively, with each score defined by a particular measurement category (e.g. $>$ 38 mm, 38 mm to 32 mm, etc, for branch diameter; $<$ 45^0, 45^0 to 60^0, etc for branch angle). Use of the single score was much quicker in the field.

Visual scores have been used to assess crown form of *P. radiata* in Australia and New Zealand for over 20 years. Eldridge (1973) recommended using a 5 point score for branch diameter and angle with each score being defined relative to the average branch diameter and angle for the site. Six point scores have been used by most Australian radiata breeders in recent years. Cotterill (1981) suggested integrating branch diameter and angle into a single 6 point score defined relative to the particular site. Pawsey (1967), Eldridge (1973) and Cotterill (1981) all recommend different approaches for measuring other crown traits such as forks, ramicorns and number of branch whorls. In New Zealand it is common for all traits to be integrated into one 9 point score (Shelbourne and Low, 1980).

The manner in which a trait is evaluated can have a fundamental influence on estimates of genetic parameters (heritabilities and genetic correlations) and thus on responses to selection. The aim of this study was to evaluate the efficiencies of alternative methods of assessing crown form by comparing the genetic parameters and relative responses to selection estimated for each method. The use of a single overall score of crown form is compared with assessing the components separately and integrating the traits in selection indices. This study was conducted in an open-pollinated progeny test of *P. radiata* in South Australia. A parallel study was conducted on another site but nutrient deficiency caused abnormal tree form and poor heritabilities and the results are not reported here.

Materials and Methods

Progeny Test

An open pollinated progeny test (identified as 5031) planted in 1969 near Mount Gambier in south east South Australia and described in detail by Cotterill and Zed (1980) was used for the assessment of crown form. The progenies were grown from open pollinated seed collected in 1968 from 28 first generation selected clones growing in an unculled seed orchard established in 1957. The field design is based on 12 randomised complete blocks with 6 tree row plots.

Assessment of Crown Form

The progeny test was assessed by the same team of two assessors between February and April 1980 when the

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mean height of trees was about 18 m. The assessors arrived at a consensus about the subjective score for each tree. The assessment was done in five runs through the progeny test with the same traits assessed in different ways in different runs. A two week rest period occurred between runs to give the assessors time to forget the previous run. The following traits were assessed in each run :—

Run 1

(a) Branch diameter was assessed using a 6 point visual score with 6 = very thin branches for the site, 5 = thin branches, 4 = above average branching for the site, 3 = below average branching, 2 = thick branches, and 1 = very thick branches. These 6 point scores were assigned so that about 2/3 of the trees in the trial were classified in the just above or just below average categories of scores (4 and 3), about the best 2% of trees were scored 6, and the worst 2% were scored 1. This approach approximates a normal distribution with a mean score of around 3.5 points and standard deviation of 1 point (COTTERILL and DEAN, 1990). In order to achieve this normal distribution it was necessary for the assessors to walk around the site and get a feeling for the range in branch size before starting the assessment.

Branch diameter was evaluated independently of other characteristics of the crown. For instance, the assessors ignored ramicorn branches and forks in assigning the branch diameter score since these malformations are evaluated as separate traits. The branch diameter score was also assigned independently of tree size. A tree which had very heavy branching would have been scored 1 regardless of its stem diameter.

(b) Branch angle was assessed using the same type of 6 point score outlined above with 6 = branches at a flat (about 90^0) angle to the main stem, and 1 = steep branching.

(c) Ramicorn branches using a 3 point score with 3 = no ramicorns, 2 = less severe ramicorn branches, and 1 = presence of severe ramicorn branches which reduce the diameter of the main stem.

(d) Forking using a 3 point score with 3 = no forks, 2 = single fork in the main stem and 1 = multiple forks. It can be difficult for operators to distinguish between ramicorn branches and forks. In later discussion we suggest they should be regarded as the same trait.

(e) A count of the number of visible branch whorls between 1 and 6 metres, using height poles to determine the 1 and 6 m points on the stem. The 1 metre mark is used as a starting point for counting whorls because it is generally above the profusion of closely spaced branches which are produced as the tree establishes itself. The 6 metre mark is fairly arbitrary and has been chosen because it is sometimes difficult to see higher into the crown.

Run 2

(a) Branch diameter was assessed again but this time using a 3 point score with 3 = thin branching, 2 = average for the site and, 1 = thick branching.

(b) Branch angle using the same type of 3 point score with 3 = flat, 2 = average and 1 = steep angled branching.

Run 3

(a) Branch diameter was assessed using a 9 point score with 9 = thinnest and 1 = thickest branching.

(b) Branch angle using a 9 point score as for branch diameter.

Run 4

(a) Branch diameter and angle were integrated into a single 6 point score with 6 = fine flat branching for the site, 4 = just above average, 3 = just below average, and 1 = thick steep branching. The combined branch diameter and angle score is hereafter referred to as the "branch quality" score.

(b) Count the actual number of visible ramicorn branches and assign a score accordingly with 0 = no ramicorns, 1 = one ramicorn branch, 2 = two ramicorn branches and so on.

(c) Count the number of forks and assign a score 0 = no forks, 1 = one fork in the main stem, 2 = two forks and so on.

Run 5

(a) Branch diameter, branch angle, ramicorn branches, forks and uninodal/multinodal branch habit were integrated into one overall 9 point score of crown form. Trees with fine flat branches, no malformations and a multinodal habit scored 9, while trees with coarse branching, malformations and a uninodal habit scored 1. This overall score is hereafter referred to as "crown quality".

Analyses

The data were assessed by analyses of variance using a least-squares program (HARVEY, 1977) fitting a model including effects for family, replication, family × replicate interaction and within-plot error. Individual heritability (h^2) was estimated as the ratio of additive genetic variance (σ^2_A) over phenotypic variance (σ^2_P) — (1).

$$h^2 = \sigma^2_A/\sigma^2_P \qquad (1)$$

where σ^2_P is determined as the sum of the family (σ^2_f), family × replicate interaction and within-plot variances; and σ^2_A equals 4 σ^2_f assuming the progeny are half-sibs. Genetic and phenotypic correlations were estimated according to HARVEY (1977).

Selection indices were employed to combine components of crown form into single index values. The indices were constructed using the computer program RESI and equal emphasis weighting coefficients as described by COTTERILL and JACKSON (1985). The genetic gains expected in each component of form as a consequence of selecting on the indices were calculated according to COTTERILL and JACKSON (1985).

Results

Table 1 presents heritabilities and additive genetic and phenotypic variances for the 3 point, 6 point and 9 point scores used to assess branch diameter and branch angle. Both the 3 and 9 point scores have low individual heritabilities ($h^2 \leq 0.06$) while the 6 point scores produce high heritabilities of $h^2 = 0.30$ for branch diameter and $h^2 = 0.34$ for branch angle. In the case of the 3 point score, the small number of classifications available (either 1, 2 or 3) resulted in both relatively low phenotypic variances (σ^2_P = 0.52 and 0.61; *Table 1*) and low additive variances (σ^2_A = 0.02); giving low heritability values. In the case of the 9 point score, the large number of classifications available led to large phenotypic variances (σ^2_P = 4.06 and 5.07) but only moderate additive variances (σ^2_A = 0.23 and 0.29); again giving a low heritability. It seems that the 9 point score was too large, with the number of possible classes

Table 1. — **Heritabilites (h^2 ± standard error), additive genetic (σ^2_A) and phenotypic (σ^2_P) variances for 3 point, 6 point and 9 point scores for branch diameter and branch angle.**

Scale of score	Parameter	Branch diameter	Branch angle
1 to 3	h^2	0.04 ± 0.03	0.04 ± 0.03
	σ^2_A	0.02	0.02
	σ^2_P	0.52	0.61
1 to 6	h^2	0.30 ± 0.10	0.34 ± 0.11
	σ^2_A	0.43	0.60
	σ^2_P	1.45	1.77
1 to 9	h^2	0.06 ± 0.03	0.06 ± 0.03
	σ^2_A	0.23	0.29
	σ^2_P	4.06	5.07

Table 2. — **Heritabilities (h^2 ± standard error), additive genetic (σ^2_A) and phenotypic (σ^2_P) variances for forking and ramicorn branches.**

Method of assessment	Parameter	Forks	Ramicorn branches
1 to 3 score	h^2	0.04 ± 0.03	0.05 ± 0.03
	σ^2_A	0.007	0.042
	σ^2_P	0.168	0.836
Count	h^2	0.05 ± 0.03	0.13 ± 0.05
	σ^2_A	0.009	0.128
	σ^2_P	0.193	0.959

causing some confusion for the assessors. The 6 point score resulted in the highest heritabilities with moderate phenotypic variances and large additive variances indicating that this scale gave good discrimination among form types without being confusing to the assessors.

The heritabilities for the scores and counts of forks and ramicorn branches, together with the additive genetic and phenotypic variances, are given in *Table 2.* For forking, both the score and the count gave similar heritabilities with the low phenotypic variance reflecting the relatively low incidence of forking (around 16% of trees in the trial were forked). For ramicorn branches, the count gave a higher heritability due to a three fold increase in additive genetic variance, whilst the phenotypic variance was not greatly increased. The 3 point scoring system for ramicorn branches clearly had too limited a range to usefully detect the variation which exists among families in frequency of ramicorns.

Table 3 presents genetic (r_A) and phenotypic (r_P) correlations among the components of crown form and the overall crown quality score. Branch diameter and angle (6 point score) were strongly correlated genetically (r_A = 0.78 ± 0.09) and phenotypically (r_P = 0.66). These high correlations are reflected in the very strong associations between branch diameter, branch angle and the combined branch quality score (r_A = 0.94 and r_P = 0.84 to 0.85). Branch angle and, in particular, branch diameter were also positively correlated with the number of branch whorls. Multinodal trees tend to have finer flatter branching.

The number of ramicorn branches were negatively correlated genetically (r_A = −0.51 to −0.75) and phenotypically (r_P = −0.19 to −0.24) with branch diameter, angle and quality scores. Trees having finer flatter branching had fewer ramicorns. Number of ramicorn branches and whorls had a moderate genetic correlation (r_A = 0.21 ± 0.24) and near zero phenotypic correlation (r_P = −0.05). Correlations involving forking followed the same trends as those for ramicorns suggesting that the two traits are a continuation of the same trait.

The correlations involving overall crown quality reflected the criteria used in assigning the score. Crown quality was positively correlated with branch diameter and angle (r_P= 0.59; r_A = 0.99 to 0.91), and number of whorls (r_P = 0.36; r_A = 0.59). In contrast, the correlations between crown form and number of forks and ramicorns were negative.

Table 4 presents correlated genetic responses in component parts of crown as a consequence of selecting one tree in 100 on either crown quality score or multi-trait indices. The index 1 integrates branch diameter, branch angle, number of whorls, forks and ramicorns. It is ap-

Table 3. — Heritabilities (h^2 ± standard errors) and genetic (± standard errors) and phenotypic correlations among form traits.

Form trait	h^2±s.e.	Branch dia. (1-6)	Branch angle (1-6)	Branch quality (1-6)	Number whorls (count)	Forks (count)	Ramicorn branches (count)	Crown quality (1-9)
Branch dia.	.30±.10		.78±.09[A]	.94±.03	.70±.13	-.09±.31	-.51±.21	.99±.02
Branch angle	.34±.11	.66[B]		.94±.03	.27±.21	-.20±.31	-.75±.16	.91±.05
Branch quality	.33±.11	.85	.84		.49±.17	-.25±.31	-.70±.17	.99±.02
No. whorls	.32±.10	.32	.25	.33		.23±.31	.21±.24	.59±.16
Forks	.05±.03	-.12	-.13	-.17	-.10		.63±.29	-.34±.32
Ramicorns	.13±.05	-.19	-.22	-.24	-.05	-.02		-.65±.19
Crown quality	.25±.09	.59	.59	.66	.36	-.30	-.26	

A) Genetic correlations above the diagonal (r_A).
B) Phenotypic correlations below the diagonal (r_P).

parent that one generation of selection on this index can be expected to improve branch diameter and angle by 1.02 and 1.19 points; increase number of whorls between one and 6 metres by 0.94 whorls; and reduce malformations by 0.03 forks and 0.38 ramicorns per tree. The fundamental difference between the two indices is that index 2 integrates the branch quality score instead of the separate branch diameter and angle scores. Index 2 produced a greater relative gain in forking (compared with index 1) but the absolute magnitudes of the responses (0.04 and 0.03 forks per tree) are very poor due to the low heritability of forking. The indices 1 and 2 produced similar responses in branch diameter and angle indicating that the branch quality score is almost as efficient as separate scores for diameter and angle.

Selection on indices 1 and 2 is expected to produce a 16% to 17% greater response in branch diameter, 21% to 27% greater response in branch angle, and a 8% to 12% greater response in number of whorls compared with selection on the overall crown quality (9 point) score. The indices also produced far greater relative declines in incidence of ramicorn branches compared with selection on crown quality. However, like forking, the absolute re-

Table 4. — Correlated genetic responses expected in component parts of crown as a consequence of selecting either on the overall crown quality score or indices combining different components. The responses are in actual units of measurement and for selection of individual trees at an intensity of one tree in 100. Figures in brackets give the percent efficiency of the indices relative to selecting on the crown quality score. The overall mean values of traits for all trees in the progeny trial were 3.1 points for branch diameter and angle and counts of 8.26, 0.17 and 0.86 for whorls, forks and ramicorns respectively.

Selection based on	Branch dia. (1 - 6)	Branch angle (1 - 6)	Number whorls (count)	Forks (count)	Ramicorn branch (count)
Index 1[A]	1.02 (117)	1.19 (127)	0.94 (112)	-0.03 (75)	-0.38 (345)
Index 2[B]	1.01 (116)	1.14 (121)	0.91 (108)	-0.04 (100)	-0.38 (345)
Crown quality	0.87 (100)	0.94 (100)	0.84 (100)	-0.04 (100)	-0.11 (100)

A) Index 1 combines branch diameter, branch angle, number of whorls, forks and ramicorns.
B) Index 2 combines branch quality, number of whorls, forks and ramicorns.

sponses in ramicorn branching were fairly small due to the lower heritability of the trait.

Discussion

Crown form is a complex trait made up of many components and thus poses a problem when selecting to improve the overall trait. The aim in any assessment for crown form is to choose a scale which most accurately reflects the variability between genotypes. A major descision for the breeder is whether to treat the trait as a whole or to break it down to its component traits and assess each component separately.

The results of this study suggest that genetic gains may be enhanced by assessing the crown form of *P. radiata* as component parts rather than one overall score. Indices can be used to integrate the components in a objective way which takes account of the different economic importance, heritabilities and correlations among components. It seems hardly surprising that this index approach is more efficient than asking assessors to mentally integrate all the aspects of crown when assigning one overall crown quality score. Such mental integration allows for introduction of biases due to possible differences in interpretation and relative weighting of traits by different assessors (Busby, 1983). By assessing each component separately, as recommended here, the interpretation of each trait is clearer for the assessors and the weightings for traits may be set later during construction of the index.

It sems reasonable to integrate strongly inherited and favourably correlated traits, such as branch diameter and angle of *P. radiata,* into a single branch quality score. Assigning one score (branch quality) instead of two scores (diameter and angle) will save time during assessment. However, efficiency seems to be lost when the integration of components is taken one step further to include branch quality, multinodal/uninodal habit and malformations in one crown quality score. One important practical advantage of the component system is that traits such as number of whorls, forks and ramicorns can be measured objectively by counting (rather than using a subjective score).

The visual scores used here were specified to be site specific in that the extremes of the range were set by the best and worst trees at each site. Such a specification ensures that the entire range of available scores are used and a reasonably wide distribution of values result. A common failing with subjective scores is that assessors place all or the vast majority of trees into only two or three of the form categories available (see discussion in Dean *et al.* 1986; Cotterill *et al.* 1987). The distribution of the score is effectively truncated, leading to a restricted variance, as seen for the 3 point scores used here for branch diameter and angle.

The number of available categories in a visual score is also very important. If the number of categories is too small there will be a reduction in the variances and subsequently the heritability, as for the 3 point scale for branch diameter and angle and the scoring system used for forking and ramicorn branches. For these examples, the range was too limited to detect the existing variation. Alternatively, the number of available categories should not be so large as to confuse the assessor and lead to a large increase in the phenotypic variance with little increase in the genetic variance as observed for the 9 point scale for branch diameter and angle. The use of a 6 point scale for branch diameter and angle and an actual count of the number of forks and ramicorn branches were found to be the preferred options giving the best discrimination between genotypes without being confusing to the assessors. An even number scale (such as the 6 point scale) may have a practical advantage in requiring assessors to decide whether a tree has below or above average form. Odd numbered scales have a mid-point (such as the score 3 on a 5 point scale) which assessors sometimes use as a "dumping ground" for the majority of trees which seem average for the site.

Recommendations

We would recommend that *P. radiata* breeders assess crown form as component traits using a 6 point score for branch quality (including branch diameter and angle) and counting the whorls, forks and ramicorn branches. When using the 6 point score (or indeed any visual score) it is important to employ the full range of the available scale. This can be achieved by continuing the current practice of having assessors walk around the site to get a feeling for the variation in form before beginning the assessment. There may also be an advantage in using a team of two assessors working together to reach a consensus judgement on each tree.

Although this study has been conducted on only one site there is no reason to believe our recommendations should not apply more generally for *P. radiata* (or indeed other *Pinus* species) on other sites. We are not implying that breeders should follow exactly this recommended scoring system. Our intention is to present general guidelines for efficient crown evaluation.

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