

Growing trees with the best genetics

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Abstract

Genetic improvement is fundamental to the financial success and international competitiveness of plantation forestry. It is important that private foresters get the best genetics to suit their production environments and can generate financial returns while addressing environmental needs. The Southern Tree Breeding Association (STBA) manages the national tree improvement programs for *Pinus radiata* and *Eucalyptus globulus* and provides genetic evaluation services in other species. Large volumes of data have been collected from hundreds of research experiments and genetic trials in both species. Until recently, breeders were unable to make full use of this resource in genetic evaluation and selection. Genetic evaluation has usually been done on subsets of data, ignoring much information, making it difficult to compare genotypes from different generations and programs. This has led to confusion in the marketplace as to the genetic quality of seed and plants available from different suppliers. The STBA, with assistance from the livestock industry, have developed genetic evaluation software that has the capability to process performance data on a national scale for a given species. This TREEPLAN® software allows us to benchmark and rank performance of genetic material on a single national basis for a full suite of commercially important traits. It is easy to incorporate data for new traits and allows us to target particular production environments and products. TREEPLAN® also facilitates the adoption of research outcomes into operational tree improvement. The paper discusses innovations like TREEPLAN® that have put Australian tree breeding at the leading edge internationally.

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Introduction

The performance of trees in plantations and farm forestry is determined by the genetics of the trees and the environmental conditions under which the trees are grown. Site selection and silvicultural regimes will significantly impact on the growing environment and influence productivity, quality and ultimately profit. Improved genetics can increase both profitability and quality, but without the need for expensive silvicultural inputs, further increasing profit. Productivity and profitability in plantations and from farm forestry will be maximised only by using the best genetics and silviculture in combination. Further, due to genotype by environment interaction (GxE), the best genotypes in one environment may not necessarily be the best in another production region. For example, genotypes best suited to high rainfall areas may perform poorly relative to other genotypes under drier and more marginal conditions.

The Southern Tree Breeding Association (STBA) was formed in 1983, and runs the national tree improvement programs for Radiata Pine (*Pinus radiata*) and Blue Gum (*Eucalyptus globulus*). These two species comprise about seventy percent of the national plantation estate, and are used for solid wood products and pulp and paper production.

Tree improvement programs fundamentally consist of:

- (i) Defining a breeding objective,
- (ii) Mating among selected parents (or getting seed from the wild),
- (iii) Measuring the performance of offspring in field trials,
- (iv) Analysing the data to calculate genetic values, and
- (v) Selecting trees for deployment and further breeding.

The amount of progress made in a breeding program depends on: (a) clearly defining a profit objective, (b) having traits under genetic control that influence profit, (c) efficient selection through measuring the appropriate traits and using all data optimally, (d) using high selection intensity and large populations and, (e) efficient deployment systems.

Historically, breeding programs have focussed too much on research, rather than delivering on commercial and environmental outcomes. Breeders have often failed to define the breeding objective in economic terms or customer needs. They tended to breed and select trees on characters that could be easily measured. Resources were wasted on less important traits, while those directly influencing profit were ignored. It is only recently that wood quality traits have been elevated in importance. Breeders have also failed to make optimal use of their data. Optimal evaluation requires consideration of all data and full pedigree linkages simultaneously. Most tree improvement programs also have numerous tree records (data) from research and breeding trials that have not been processed or used in genetic evaluation.

More focus on customer needs is required, particularly for plantations that are growing exotics or species outside its usual range. The customer wants genotypes adapted to their specific environments: 'fit for purpose'. They also want access to objective performance data on genotypes to support recommendations. Access to elite genetic material (seed and clonal propagules) at commercially competitive prices is fundamental. Performance of trees in plantations or farm forestry will be sub-optimal if the best genetics cannot be accessed.

The Southern Tree Breeding Association

The current membership of the STBA comprises most of the major plantation growers in Australia (Table 1). The STBA has 15 grower members, with ten participating in the Radiata Pine program and nine in the Eucalypt program. The technical excellence of the national tree improvement programs run by STBA is underpinned by the scientific

input from its five research members. These organisations are internationally recognised as the leading forestry and genetics research agencies in Australia and New Zealand. The Association carries out breeding on behalf of its members to produce the best quality genetics and to ensure future genetic gain is optimised. Cooperative breeding is more cost effective for individual members and, because of larger population sizes and increased selection intensity greater gains can be achieved for individual growers and companies. The cooperative approach has also allowed the development of sophisticated tools to support the breeding programs.

Table 1 - Membership of the STBA includes most major plantation owners.

Members	Research Members
AKD Softwoods	CSIRO Forestry and Forest Products
Auspine Ltd	CRC Sustainable Production Forestry
Forest Enterprises Australia Ltd	Forest Research NZ
ForestrySA	Forest Science Centre
Forestry Tasmania	University of New England – (AGBU)
Great Southern Plantations Ltd	
Green Triangle Forest Products Ltd	
Gunns Ltd	
Hancock Victorian Plantations Pty Ltd	
Midway Plantations Pty Ltd	
Norske Skog Paper Mills (Australia) Ltd	
Saxton Seed Pty Ltd	
Treecorp Pty Ltd	
Trees & Technology Ltd (NZ)	
WA Plantations Resources Pty Ltd	

Access to STBA Genetic Material

Member companies of the STBA access the best genetic material for deployment purposes cost effectively and free of royalties. Members can also influence the direction of breeding by ensuring the breeding objectives and programs are aligned with their needs as a customer. Non-members can also access STBA genetics, but only subject to its availability and the payment of royalties. Some members of the STBA supply seed and/or cuttings to non-members. *SeedEnergy* Pty Ltd is also licensed to supply STBA genetic material to both members and non-members of the Association, subject to the payment of royalties. Royalties are set on an annual basis, and in principle are designed to ensure it is significantly cheaper for companies to be members, sharing the cost of breeding up front. Due to lead times, contractual arrangements are the only effective way of ensuring supply of quality seed at reasonable prices.

Developing Genetic Material for Different Production Environments

Breeding and genetic improvement are based on well-established scientific principles of quantitative genetics and, more recently, the promises of molecular genetics and bioinformatics. Breeders and foresters who claim breeding is an art form, may occasionally be lucky, but the evidence from trees, other crops and livestock improvement, demonstrates that genetic gain is only achieved through

scientific rigour. Decisions on what to plant today should be based on objective performance data. If this data is not available, then it should be collected from trials. Planting large areas of land with untested genetic material can be a costly mistake.

Performance Testing of Genetic Material

The STBA tests genetic material of *P. radiata* and *E. globulus* on a range of sites spread across the plantation estate in southern Australia. The Association has access to hundreds of genetics trials that have been planted over the past 60 yrs for *P. radiata*, and the last 20 yrs for *E. globulus*. Data has been collected for each species on hundreds of thousand trees and for a range of traits.

Estimation of Breeding and Genetic Values for Deployment

Tree breeders and researchers have historically been busy planting trees and generating large volumes of data from research experiments and genetics trials. However, they have been far less effective at using the performance data collected on trees for genetic evaluation or improving the genetic worth of plantations. This situation is not unique to the STBA, but is still a problem internationally with tree and plant improvement programs.

Historically, tree breeding has emphasised experimental design features (replicates, plots and incomplete blocks in increasingly complex designs) in trials to account for local environmental effects, compared to more complete modelling of the genetic components. There has been too much emphasis on detailed planning and research, and not enough on the fundamentals of genetics and operational tree improvement, including industry wide genetic evaluation. Single-generation, single-site and single-trait analysis has been the norm in tree breeding. Breeders were limited by software and computing power, which could only handle small and highly structured data sets. Genetic evaluation was done inefficiently and breeding values were often biased, leading to an over or underestimate of the genetic worth of individual genotypes.

The optimal and preferred statistical method for breeding value prediction is best linear unbiased prediction (BLUP). It is not new technology, but its industry wide application by STBA is new and innovative.

Modern tree improvement programs demand a greater use of BLUP for several reasons. Breeding programs are progressing and now span several generations. Individual programs with different samples of the same base population (native provenances) are being consolidated into larger cooperatives. It is important to account for the effects of selection over time. Many programs are now making the transition to overlapping generations, where a proportion of all breeding activities is performed each year, and all families are not tested at all test sites at the same time. Finally, there is a need for integrating all data between trees and between traits, making it easier for selection and to monitor the genetic progress of breeding programs.

The STBA adopted the individual tree additive genetic model BLUP in its tree improvement programs during the 1990s (Jarvis et al. 1995). However, its application was limited to relatively small and uncomplicated data sets until the development of the TREEPLAN® system (Kerr et al. 2001, 2002; McRae et al. 2003). BLUP software that was previously available for tree improvement was designed mainly for research purposes, and lacked the industrial strength required for large-scale genetic evaluation.

The STBA, with assistance from the livestock industry and input by the CRC-SPF, have developed leading edge genetic evaluation software (TREEPLAN®) that has the capability to process performance data on a national scale. TREEPLAN® is based on BREEDPLAN software, which is used extensively in livestock improvement, and is the international benchmark for genetic evaluation in animals. The TREEPLAN® software allows STBA to rank performance of genetic material on a single national basis. It is easy to incorporate data for new traits and target particular production environments and products. Prediction of breeding values is a dynamic process, such that TREEPLAN® breeding values are updated regularly as traits are measured, data compiled and validated.

The TREEPLAN® software is being enhanced by AGBU in a new project funded by STBA and the Forest and Wood Products Research and Development Corporation (FWPRDC). The enhancements will include the capability to incorporate DNA information (markers and candidate genes). Currently, there is no efficient method for using results from genomic studies with breeding values for other performance traits, such as growth, form and wood quality. TREEPLAN® will be enhanced to fit complex spatial models of environmental heterogeneity within trials and simultaneously predict breeding and clonal genetic values. Studies on GxE will be done and this will allow STBA to target genotypes more strategically to different production environments. TREEPLAN® is designed to apply best practise genetic technologies to commercial tree improvement programs.

TREEPLAN® is being used routinely to predict genetic (breeding and deployment) values for Radiata Pine and Blue Gum. As new trials and traits are assessed, the data is entered into a database, analyses are done on a single site basis to allow for differences in productivity and heritability between sites, TREEPLAN® is run, and breeding values for all trees in the specified population are updated. The analysis of complex data sets with more than ten traits on over 100,000 trees is straightforward.

There has been major innovation in the management of information and data with the development of a modern web based data management system (STBA-DMS). The STBA-DMS acts as a dynamic repository for breeding information and has the capability to handle multiple species. The STBA-DMS facilitates efficient storage and retrieval of data for genetic evaluation, but also the delivery of genetic values and other information to STBA Members and clients through the Internet.

Table 2 - TREEPLAN® can handle data for many trials and traits with complex pedigree structures in a single analysis.

	Species	
	<i>Pinus radiata</i>	<i>Eucalyptus globulus</i>
Generations (Breeding Cycles)	3	2
Trials (sites) included in Analysis	68	87
Number of Selection Traits Analysed	19	10
Genetic (founder) Groups fitted	12	25
Families	3033	1550
Genotypes included in Analysis	117,778	149,475

Pinus radiata

The application of TREEPLAN® in *P. radiata* is used as an example of how we approach genetic evaluation on a national basis. The STBA is currently collecting performance data on trees in third-generation progeny trials for *P. radiata* that were planted in 1996/97. In the past,

breeding values for *P. radiata* were estimated using other methods (White *et al.* 1992 ab). Due to a lack of suitable BLUP software, multiple and independent lists of breeding values made it difficult to compare trees for genetic merit across a population. TREEPLAN® genetic evaluation has overcome this limitation.

Breeding values for 117,778 genotypes (different trees) in the national database for *P. radiata* were updated using TREEPLAN® in 2003 (Powell *et al.* 2003). Summary results are presented in Table 3. The analysis included 68 trials spread across the Radiata Pine estate in southern Australia. Breeding values are predicted for selection traits targeting the different production regions defined in the National Plantation Inventory for Australia (Wood *et al.* 2001). Selection traits for growth include: six production regions by four age classes (0-5 yrs, 6-12 yrs, 13-24 yrs and >24 years). Branch angle, branch quality, branch size, and stem straightness comprise the form traits. Basic density (0-12 yrs and >13 years) and Spiral Grain (0-6 yrs and ≥6 years) constitute wood quality traits. Data for disease and pest resistance/tolerance traits (for example, Dothistroma, Phytophthora, Pitch Canker, Cyclaneusma spring needle cast and Essigella pine aphid) are being incorporated. The inclusion of many (hundreds) of historical first- and second-generation trials will be done over time.

For selection and deployment purposes, the selection trait breeding values are expressed as Breeding Objective traits, for example, volume growth (VOLUME), whole tree density (DENSITY), branching (BRANCH) and stem straightness (STEMST). Breeding objective traits are those of commercial importance that directly influence the profit margins at harvest age. That is, selection traits measured at an early age or when using an indirect method of assessment (for example, tree diameter for growth) must be adjusted (discounted) to ensure breeding values are not over estimated for rotation age traits. Breeding objective traits for each genotype (tree) are then combined into a single index with different economic weights applied to each trait, reflecting its commercial importance.

Table 3 - Three generations of breeding has resulted in significant improvement for volume, branch characteristics and stem straightness. Average TREEPLAN® breeding values for VOLUME, DENSITY, BRANCH and STEM for *P. radiata* – August 2003. Trees were ranked on INDEX and gains as a percentage of base productivity are given in brackets (%).

	VOLUME	DENSITY	BRANCH Scale 1-6	STEM Scale 1-6	INDEX
Base Productivity*	500 m ³ /ha	400 kg/m ³	3.50	3.50	
Average of 117,778	5.23 (1%)	-2.48 (-1%)	0.07 (2%)	0.03 (1%)	15.1
Top 20 (3-Gen)	115.90 (23%)	-19.10 (-5%)	0.61 (17%)	0.12 (3%)	190.6
Top 100	109.40 (22%)	-17.60 (-4%)	0.51 (15%)	0.15 (4%)	176.5
Top 1,000	81.40 (16%)	-13.20 (-3%)	0.45 (13%)	0.25 (7%)	149.9
1-Gen Selections	-1.65 (0%)	-3.66 (-1%)	0.04 (1%)	0.03 (1%)	3.43
2-Gen Selections	11.00 (2%)	-3.66 (-1%)	0.08 (2%)	0.09 (3%)	26.12

*Base productivity is an average commercial performance indicator used for comparative purposes. Although, performance will vary across sites and years, breeding values provide a reliable prediction of relative genetic merit. Branch and stem traits are ranked on a scale of poor (1) to good (6).

Based on the Index, three generations of breeding have led to significant increases in volume, branch characteristics and stem straightness for *Pinus radiata*. Predicted gains for the best trees for each breeding objective trait considered independently will be even higher. For example, the top 20 genotypes for growth will have a mean predicted VOLUME gain of 128.70 m³/ha at rotation age (26%) above base productivity. Similarly, the top 20 genotypes will have higher DENSITY of 40.40 kg/m³ (10%), superior BRANCH characteristics of

1.09 (31%), or straighter STEM score of 0.90 (26%). It is important to note that predicted gain for density is expected to significantly increase in the next few years with large amounts of density measurement being done.

The current breeding objective function and coefficients in the INDEX have not been derived using economic data. In general, breeders have subjectively picked tree traits, which they have considered biologically and economically important, that could be manipulated through breeding and selection. The STBA, FWPRDC and CSIRO-FFP are currently undertaking a major research project to define the selection index in economic terms. The traits included in the index and respective economic weights will be defined in terms of their impact on profit margins for STBA member companies. Costs, revenue streams, production and business models will vary among companies, and breeding objective traits and economic weights will be customised for each member. It is likely that wood quality traits will increase in importance, particularly for vertically integrated enterprises.

Juvenile wood in *P. radiata* has undesirable characteristics that affect the quality of timber, including grade recovery, strength, distortion and surface checks, and finishing properties for structural timber. By using a genetic approach, we can alter the properties of juvenile wood itself, as well as reducing its proportion. The typical rotation age for Radiata Pine in Australia has been reduced from about 40-45 yrs to about 30, and as low as 27 yrs in the Green Triangle region. As a consequence the proportion of juvenile wood (first 10 growth rings) is increasing as a proportion of the harvested product. Australian pine does not suffer from the same problems facing the New Zealand industry with juvenile wood, due to different genetics, growing conditions and silvicultural practices. Regardless, there is an opportunity to reduce the amount and improve the quality of juvenile wood produced, thus retaining competitive advantage in the marketplace. The Juvenile Wood Initiative, a major research project among STBA, FWPRDC, CSIRO-FFP, QDPI Forestry and ArborGen, aims to improve juvenile wood characteristics of trees in the STBA breeding and deployment population for *P. radiata*. It is anticipated TREEPLAN® breeding values for juvenile wood traits will be available in 2004.

Eucalyptus globulus

Breeding values for 149,475 genotypes in the national *E. globulus* database were updated using TREEPLAN® in 2003. A summary of results is presented in Table 4. This included genetic values for native provenances (sub-races), native stand (founder) trees, first-generation and second-generation progeny. Data was included from 88 trials, including 14 second-generation progeny trials, spread across Tasmania, Victoria, South Australia and Western Australia (Pilbeam *et al.* 2003).

Breeding values for growth are predicted in four production regions by three age classes (0-4 yrs, 5-8 yrs and 9-12 years). Basic density, by two age classes, and pilodyn penetration comprise wood quality traits. Data for pest and disease resistances (defoliation), kraft pulp yield, NIRA pulp and cellulose content, collapse, shrinkage and tree form traits will be incorporated with time. Trees in the CSIRO collections (Gardner and Crawford 1987, 1988) are used to establish a baseline for monitoring genetic improvement over time.

Table 4 - One generation of breeding has boosted growth and density. Average TREEPLAN® breeding values for volume (VOL), wood density (DEN) and pulp yield (KPY) for *E. globulus* – August 2003. Trees were ranked on \$INDEX and gains as a percentage of base productivity are given in brackets (%).

	VOL	DEN	KPY	\$Index
Base Productivity*	313 m ³ /ha	542 kg/m ³	55.7 %	
CSIRO collection (616 trees)	0	0	0	0
Base Generation (all native stand founder trees)	0.14 (0%)	0.80 (0%)	0.01 (0%)	\$22.38
First Generation	2.98 (1%)	0.39 (0%)	-0.02 (0%)	\$40.67
Second Generation	46.52 (15%)	6.24 (1%)	-0.87 (-2%)	\$489.68
Top 20 genotypes	45.97 (15%)	63.68 (12%)	-0.74 (-1%)	\$1,885.52
Top 100 genotypes	45.27 (15%)	60.47 (11%)	-0.97 (-2%)	\$1,736.47
Best native Provenance	1.24 (0%)	21.52 (4%)	-0.03 (0%)	\$519.83
Worst native Provenance	-133.31 (-43%)	24.78 (5%)	1.27 (2%)	-\$731.73

*Base Productivity is a performance indicator used in the *Eucalypt Strategy* (Dutkowski *et al.* 2000). Although, performance will vary across sites and years, breeding values provide a reliable prediction of the comparable performance of genetic material.

The primary breeding objective for the national *E. globulus* tree improvement program is to maximise the net present value per hectare (\$NPV) from forests grown for kraft pulp production. The breeding objective traits are harvest volume (VOL), wood basic density (DEN) and kraft pulp yield (KPY). The profit index represents the additional profit that can be expected above unimproved material (CSIRO collection) by deploying the improved genotypes. That is, the top 20 genotypes selected on \$Index are expected to deliver an extra \$1,885/ha NPV due to superior growth rates and higher basic density. STBA members and seedEnergy Pty Ltd use individual TREEPLAN® genetic values to establish and cull orchards, and to select seedlots for deployment.

Based on the \$Index, breeding has led to significant increases in volume and density for *E. globulus*. Predicted gains for the best trees for each breeding objective trait considered independently will be even higher. For example, the top 20 genotypes for volume will have a mean breeding value of 129.7 m³/ha at rotation age (41%) above base productivity. Similarly, the top 20 genotypes for density will be 95.6 kg/m³ (18%) more dense than unimproved material. Predicted gains for elite genotypes are expected to significantly increase in the next few years as new genotypes and large quantities of data from second-generation progeny trials accumulate. In comparison, seed from the best provenance for volume will have genetic potential of only an extra 16 m³/ha (5%) above the base of unimproved material. The best provenance for density, will be 25.9 kg/m³ (5%) more dense on average. Clearly, companies continuing to use just native seed from the best provenances will be losing significant potential productivity.

Although the primary objective of most STBA Members is to produce wood chips for pulp markets, there is an increasing interest in sawlog regimes and other alternative products. The STBA, University of Tasmania and CRC-SPF are currently researching alternative breeding objective functions for other products and markets. It is likely that different traits and economic weights will be used in customised breeding objectives functions for the different markets.

Conclusions

Productivity and profitability in plantations and farm forestry will be maximised only by using the best genetics and silviculture in combination. Decisions on genetic quality for a particular species should be based on objective performance data made available in tree improvement programs. The TREEPLAN® genetic evaluation system, which uses best practise technologies, allows us to rank genetic material on a national basis for a given species. TREEPLAN® makes it easy to target particular production environments and end products, and incorporate data for new traits. The rate of genetic improvement for the major plantation species of *P. radiata* and *E. globulus* should increase rapidly as a result of this innovation.

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