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ASSUMPTIONS UNDERLYING THE USE OF ECONOMIC WEIGHTS – ARE THEY VALID IN BREEDING FOR EUCALYPT KRAFT PULP?

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ABSTRACT

An existing breeding objective cost function relating standing volume at harvest, basic density, pulp yield and stem form to the cost of producing unbleached eucalypt kraft pulp was used to examine assumptions underlying the use of economic weights in prediction of gain. The cost function showed a non-linear relationship between total pulp-cost and the levels of all traits in the breeding objective cost function, resulting in a decline in the true economic weight at higher trait values. The objective cost function also showed interdependence between traits: the economic weight for one trait was dependent upon the value of other traits. These effects resulted in predicted gains being overestimated, with errors being greater at high selection intensities: at a selection intensity of 1% expected gain was over-estimated by 25%. It is suggested that the use of economic weights for prediction of gain may be inappropriate where exploitable variation is great and selection pressure high. An alternative method of gain determination is proposed: predicted values of selection traits are used to generate values for objective traits which are substituted directly into the breeding objective cost function thus avoiding errors due to non-linearity and interdependence.

Keywords: breeding objective, density, pulp yield, growth, gain

INTRODUCTION

PONZONI (1986) divided the determination of a breeding objective into four stages: (1) the specification of the production system; (2) identification of sources of income and costs; (3) identification of the biological traits influencing income and costs; and (4) determination of the economic value or weight of each trait in the objective.

GREAVES *et al.* (1997) applied PONZONI's (1986) method to derive a breeding objective for minimising the total cost of producing unbleached eucalypt kraft pulp. The biological traits identified as having impact on the cost of producing kraft pulp were standing volume at harvest (incorporating growth and survival), basic density, pulp yield, and stem form. GREAVES *et al.* presented economic weights for these traits.

Whilst economic weights are commonly reported as absolute values (*e.g.* DEAN *et al.* 1990, GREAVES *et al.* 1997), they are an interpretation of an economic production function at nominal trait levels. Underlying the application of economic weights in the prediction of genetic gain are the assumptions of:

- *linearity*: that the slope of the production function is constant over the exploitable range of the trait; and
- *independence between traits*: that the economic weight for one trait is independent of the levels of other traits in the objective – i.e. that the product of the economic weights and the trait values are additive.

In breeding plantation eucalypts, populations are often large and selection intensities high: selection of the best 50 individuals from 5000 trees in a breeding population is a common scenario. The assumptions underlying the application of production functions via economic weights may well break-down at such extreme selection pressures.

This paper will examine the assumptions of linearity and independence using as the breeding objective the production function derived by GREAVES *et al.* (1997) for minimising the total cost of producing unbleached eucalypt kraft pulp. Assumed genetic parameters and selection intensities will be values applicable to selecting from early generation eucalypt populations. An alternative method of gain determination will be proposed which avoids errors due to nonlinearity and interdependence between traits in the production function.

METHODS

Biological traits in the objective

The biological traits used in the breeding objective cost function described by GREAVES *et al.* (1997) for the minimisation of the total cost of unbleached eucalypt kraft pulp are:

standing volume at harvest (*VOL*): the green volume of timber which can be harvested from a hectare of forest estate at rotation end – this trait incorporates both growth rate and survival and has the units of cubic metres per hectare (assumed population mean 250 m^3 ha^{-1})

basic density at harvest (*DENS*): the dry weight of wood per unit of green volume in oven-dry tonnes (ODt) per cubic metre (assumed population mean 0.5 ODt m^{-3});

pulp yield (*PY*): the oven-dry weight of kraft pulp produced as a fraction of the total dry weight of wood, in oven-dry tonnes of pulp per oven-dry tonnes of wood (assumed population mean 0.5 ODt ODt^{-1}, or 50%); and

stem form (*FORM*): the general form of trees at harvest (subjectively incorporating the straightness of stem and degree of branching) – this trait is defined here as a six point score where a score of six represents very good form and a score of one represents very poor form (assumed population mean score 3.5).

The breeding objective cost function

The total pulp-cost function where total pulp-cost (C_{total}), expressed in dollars per oven-dry tonne of unbleached eucalypt kraft pulp (\$ ODt^{-1}) discounted to the time of plantation establishment is (after GREAVES *et al.* 1997):

$$C_{total}=\frac{[C_{est}]}{(1-loss)}+\frac{[C_{main}+C_{land}]}{(1-loss)}\cdot\left[\frac{1-(1+d)^{-r}}{d}\right]+\frac{[C_{harv}+C_{trans}]}{(1-loss).(1+d)}$$

$$+\frac{[C_{chip}+C_{dig}+C_{chem}+C_{evap}+C_{rec}+C_{recaust}]}{(1-d)^{r}} \qquad [1]$$

where C_{est} is the cost of plantation establishment; C_{main} is the annual maintenance cost; C_{land} is the annual cost of land; C_{harv} is the cost of harvesting; C_{trans} is the cost of transport; *loss* is the fibre loss in the pulpmill expressed as a fraction of total delivered fibre (assumed to be 5%); *r* is the rotation length; *d* is the discount rate; C_{chip} is the cost of chipping; C_{dig} is the cost of digestion; C_{chem} is the cost of chemical other than effective alkali consumed during pulping; C_{evap} is the cost of black-liquor evaporation; C_{rec} is the recovery furnace cost; and $C_{recaust}$ is the cost of recausticizing. All costs are expressed in US dollars per oven-dry tonne of unbleached pulp produced (Table 1).

The cost of each stage should include a component of "normal" profit (BRASCAMP *et al.* 1985), and pulpmill capital costs (Table 1) are considered to be related to variable costs to the power of 0.6 (WILSON 1950). The annual discount rate and rotation length used are 5% and 15 years respectively.

Economic Weights

The economic weight of a biological trait can be defined as the change in the breeding objective (savings in total pulp cost) associated with a unit increase in that trait, calculated at the population mean. However, a unit increase in *PY* represents an increase from 0.5 ODt ODt^{-1} to a non-sensical 1.5 ODt ODt^{-1} (the mass of pulp per unit mass of wood cannot exceed 1 ODt ODt^{-1}). To overcome differences in the units and expected ranges of each trait savings in total pulp cost were calculated over an increase of 0.1 σ_a for each trait (Table 2), and economic weights (\$ per unit change) determined by dividing the observed savings by 0.1 σ_a.

Gain towards the breeding objective can be estimated for each tree by multiplying the respective economic weights by the observed estimates of genetic worth for each trait (given as deviations from the population mean), expressed in matrix notation as:

$$G = \mathbf{a}_0 \,.\, \mathbf{v} \qquad [2]$$

where *G* is the gain in savings in total pulp cost (\$ per ODt) for an individual tree; $\mathbf{a}_o$ is a vector of the estimated breeding values for the objective traits for the individual tree expressed as deviations from the respective population means; and **v** is a vector of the economic weights for the objective traits.

Data set

To compare gain predicted via (i) economic weights (Eqn. 2) and (ii) gain determination via direct substitution into the breeding objective cost function (Eqn. 1), fifty 5000 record data-sets of breeding values were simulated using the Monte-Carlo method. Breeding-values of the four traits in the breeding objective ($\mathbf{a}_o$ – Eqn. 2) were randomly generated assuming the genetic parameters presented in Table 2. The gain due to direct selection on breeding values was taken as the mean of the gains due to selection observed for each of the 50 data-sets individually

Table 1. The cost of each stage of production (in US dollars per oven dry tonne of unbleached eucalypt kraft pulp *i.e.*$ODt^{-1}) as a function of standing volume at harvest (VOL), stem form (FORM), pulp yield (PY) and density (DENS) after GREAVES *et.al.* (1997). Costs of pulping stages are split into total operating cost and capital cost (*operating / capital*), and numbers in parenthesis are negative.

Production stage	Cost function $COST \propto f(VOL, DENS, PY, FORM)$	Base cost $US per ODt	Timing of cost
Cost of land use	$C_{land} \propto \frac{1}{VOL.PY.DENS}$	1.6	Annual cost
Plantation establishment	$C_{est} \propto \frac{1}{VOL.PY.DENS}$	24	Rotation start
Plantation maintenance	$C_{main} \propto \frac{1}{VOL.PY.DENS}$	1.6	Annual cost
Harvesting	$C_{harv} = \frac{1}{VOL^{0.2}.FORM^{0.1}.PY.DENS}$	80	Rotation end
Transport	$C_{trans} \propto \frac{1}{PY.DENS}$	40	Rotation end
Chipping	$C_{chip} \propto \frac{1}{PY}$	20/15	Rotation end
Digester	$C_{dig} \propto \frac{1}{PY.DENS}$	30/50	Rotation end
Chemical (excluding EA)	$C_{chem} \propto \frac{1}{PY}$	5/10	Rotation end
Evaporation	$C_{evap} = \frac{\frac{1}{DENS} + 1.6(1-PY)-0.7}{PY}$	40/15	Rotation end
Recovery	$C_{rec} \propto \frac{(1-PY)}{PY}$	(50)/35	Rotation end
Recausticize	$C_{recaust} \propto \frac{(1-PY)}{PY}$	15/15	Rotation end

Table 2. Means, additive standard deviations (diagonal), and genetic correlations (upper diagonal) used in generation of the simulated data. Parameters were based upon DEAN *et al.* (1990), GREAVES *et al.* (1996), and Australian Paper Plantations Pty. Ltd. unpublished data and are typical of early generation *E. globulus* or *E. nitens* populations.

	Unit	Mean	VOL	DENS	PY	FORM
VOL	$m^3 \cdot ha^{-1}$	250	38	0.1	0.1	0.4
DENS	$t \cdot m^{-3}$	0.5		0.022	0.3	0
PY	$t \cdot t^{-1}$	0.5			0.0077	0
FORM	score 1....6	3.5				0.36

RESULTS AND DISCUSSION

Linearity

The linearity of cost function response to changes in the breeding objective traits was examined by determining the economic weight for each trait at the expected trait mean and at deviations from the mean equivalent to selecting either the highest or lowest 1% of the population to simulate the *extremes* of selection pressure which may be applied in a breeding program (*e.g.* selection of the best 50 trees from a population of 5000).

For each trait the economic weight declined with increase in the trait. The observed decline in the economic weights with increase in the value of each trait through the selectable range (from the mean of the lowest 1% to the mean of the highest 1%) represents a decline in the slope of the cost-response curve (depicted in Figure 1 for *VOL*). The observed responses are typical of a cost function where cost is proportional to the inverse of the value of a trait:

$$Cost \propto \frac{1}{[trait]} \qquad [3]$$

where *Cost* is the cost (per ODt of pulp produced) of a stage in production; and *trait* is the value of a given trait. Inverse relationships of this kind predominate in the assumed total-pulp cost function (Table 1).

VOL shows the greatest non-linearity over the range of exploitable genetic variation, and *PY* the least. Whilst these results somewhat reflect the effect of each trait upon the production function (Equation 1) they predominantly reflect the relative coefficients of genetic variation (the ratio of the additive variation to the mean): 15% for *VOL* and 1.5% for *PY*.

If gain (after Eqn. 2) is predicted using fixed economic weights calculated at the population mean, gain will be over-estimated for individuals with breeding values either above or below the population mean: for individuals with positive breeding values (breeding values above the mean) the *true* economic weights are lower than the economic weights calculated at the population mean and thus gain is over-estimated; and at negative breeding values (breeding values below the mean) the *true* economic weights are higher than the economic weights calculated at the population mean and thus individuals are not predicted to be as poor as they actually are.

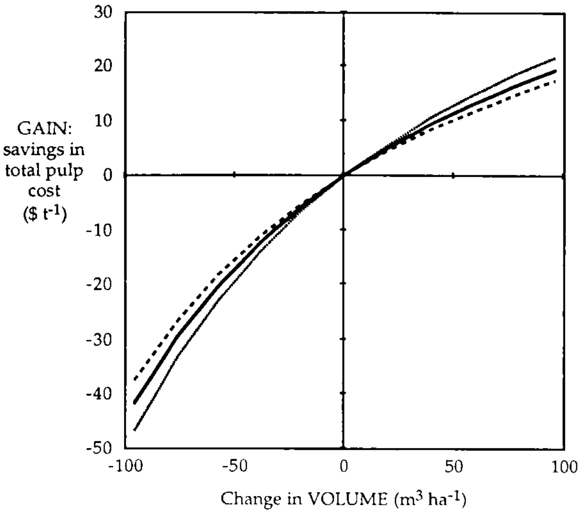

Figure 1. Response towards the breeding objective (Eqn. 1) due to changes in *VOL* (standing volume at harvest expressed as deviations from the mean of 250 m^3 ha^{-1}), for three levels of *DENS* (basic density at harvest), –0.055 ODt m^{-3}(·········), 0 (————), and +0.055 ODt m^{-3} (- - - -). The depicted range of change in *VOL* (±100 m^3 ha^{-1}) and *DENS* (±0.055 ODt m^{-3}) represent the extremes of gain which could be expected due to selection for either trait. The horizontal axis (Change in *VOL*) represents the breeding value of an individual expressed as a deviation from the population mean.

Independence between traits

If traits in the cost function are independent, the value of an increase in a trait (specified as the economic weight for that trait) will be independent of the values

Table 3 Economic weights for traits in the breeding objective calculated at the population mean (pop^n mean) and at the mean of the highest and lowest 1% of the population.

Trait	Unit	Economic weight		
		Lowest 1%	pop^n mean	highest 1%
VOL	$ $(m^3 \cdot ha^{-1})^{-1}$	0.730	0.269	0.142
DENS	$ $(t \cdot m^{-3})^{-1}$	432	349	289
PY	$ $(t \cdot t^{-1})^{-1}$	438	411	388
FORM	$ $(score\ 1....6)^{-1}$	1.59	1.15	0.90

Table 4 . Economic weight for *VOL* versus levels of *DENS* and *PY* (levels of *DENS* and *PY* represent the mean of the highest and lowest 1% for each trait in the population).

Eco. weight VOL (\$ (m^3.ha^{-1})$^{-1}$)	Unit	DENS (ODt·m^{-3})		
		Lowest 1%	pop^n mean	Highest 1%
PY (Odt·ODt $^{-1}$)	Lowest 1%	0.319	0.281	0.251
	pop^n mean	0.306	0.269	0.241
	Highest 1%	0.294	0.259	0.231

of other traits in the objective. The economic weights for *VOL* for different levels of *DENS* and *PY* are presented in Table 4. Economic weight for *VOL* declines with increase in either *DENS* or *PY*: an outstanding tree (say) with high breeding values for both *DENS* and *PY* (both traits at the extreme of their selectable ranges: 0.059 t m^{-3} and 0.021 t t^{-1} above their respective means) would not gain as much from a given increase in *VOL* (economic weight for *VOL* \$0.231 (m^3 ha^{-1})$^{-1}$ – Table 4) as a tree which has low *DENS* and *PY* (economic weight for *VOL* \$0.319 (m^3 ha^{-1})$^{-1}$).

The influence of *DENS* on the value of *VOL* is graphically depicted in Figure 1. At low levels of *DENS* (0.055 ODt m^{-3} below the population mean for *DENS*) the economic weight for *VOL* is higher than at high levels of *DENS* (+0.055 ODt m^{-3}).

The observed inderdependence between traits has the implication that an individual tree having high breeding values for more than one trait would not be as valuable as it appears if gain is calculated using a fixed set of economic weights (Eqn. 2).

Implications

The value (savings in total pulp cost) of an increase in a trait not only declines at high levels of that trait (*e.g.* trees of high *VOL* are not as valuable as they appear), but the value from a given level of *VOL* (for example) also declines if other traits in the objective are also high (Table 4).

To quantify the effect of the observed non-linearity and inter-dependence, a range of selection-pressures were applied to the simulated data-sets. Selection was made on the basis of a linear combination of economic weights and the simulated breeding values for all traits in the objective (after Eqn. 2):

$$G = 0.269.(VOL_a) + 349.(DENS_a) + 411.(PY_a) + 1.15.(FORM_a) \quad [4]$$

where *G* is the gain towards the objective (reduction in total pulp cost discounted to the time of plantation establishment) and *VOL$_a$*, *DENS$_a$*, *PY$_a$* and *FORM$_a$* are the breeding values of *VOL*, *DENS*, *PY* and *FORM* at harvest expressed as deviations from the respective population means ($\mathbf{a}_o$ – Eqn. 2). The "*true*" value of each tree in the simulated data-set was determined by directly substituting the simulated breeding values into the cost function (Eqn. 1). The gain overestimate due to prediction by economic weights, calculated as the difference between the economic weight gain and the *true* gain, divided by the *true* gain, is presented in Table 5 for selection of the best 1% of trees, and in Figure 2 against the proportion of the population selected.

Table 5. Expected gain due to selection of 1% of a population of 5000 trees on the basis of minimum total pulp cost. Pulp costs are expressed as expected savings at rotation end (bigger is better).

	Gain	Units
VOL	80.5	m^3·ha^{-1}
DENS	0.04	ODt·m^3
PY	0.88	% (ODt·ODt^{-1})
FORM	0.24	points
Pulp cost (using econ. weights Eqn. 6)	83	\$·ODt^{-1}
True pulp cost (Eqn. 3)	66	\$·ODt^{-1}
Difference	16	\$·ODt^{-1}
Difference	25	%

As predicted, the degree to which expected gain is over-estimated when economic weights are used in the prediction of gain increases as the proportion of the population selected decreases – and when 1% of the population is selected the gain is over-estimated by approximately 25% – or \$16 per ODt of pulp produced (Table 5).

There has been considerable debate, mainly amongst animal breeders, as to relevance and difficulties of non-linear production functions (HARRIS 1970, GODDARD 1983, BRASCAMP *et al.* 1985, SMITH *et al.* 1986, GROEN *et al.* 1995). However, the effect of non-linearity and interdependence between traits upon the estimated gain (or rather the over-estimation of gain) depends largely on the degree of exploitable variation and the intensity of selection pressure applied. *VOL* shows considerable exploitable genetic variation and a considerable change in economic weight over the exploitable range, whereas *PY* has a much lower relative variation and more consistent economic weight. The selection pressure applied to a population (the proportion of the population selected for further breeding or deployment) influences the error in predicting gain from using economic weights (Figure 2).

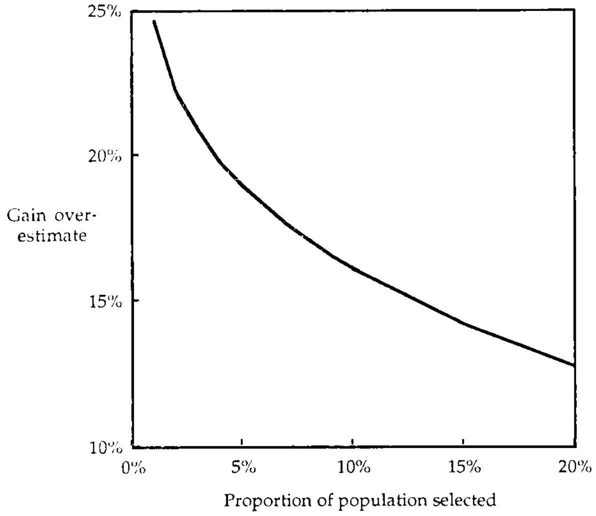

Figure 2. Over-estimate in gain towards the objective from use of economic weights (calculated as the difference between the economic weight gain and the *true* gain, divided by the *true* gain) versus the proportion of the population selected.

The gain overestimate depicted in Figure 2 is based upon genetic variations expected in early generation temperate eucalypt populations, and the range of selection intensities are representative of selection pressures which may be applied in early stages of breeding programs (selection of 50 individuals from 5000 is not uncommon). Moderate selection intensities applied to populations with reduced degrees of exploitable variation (as may be common in more advanced generation breeding) may not result in such appreciable gain over-estimation due to the use of fixed economic weights. A further consideration is that the use of economic weights only overestimates gain – it does not significantly alter the ranking of individuals in large populations. However, if breeders are using cost-benefit analysis in decision making, the potential overestimate in gain may warrant consideration.

Whilst all traits in the breeding objective show a decline in economic weight with increasing trait value (Table 3), there is no evidence to suggest that the cost function (Eqn. 1) will show a negative economic weight (an increase in total pulp cost with increase in a biological trait) at high levels of any trait in the objective. Cost functions which show change in sign of economic weight with increasing trait level have an optimum level above which further increase in a trait reduces profitability (*e.g.* AMER *et al.* 1994). The breeding objective under examination is the minimisation of the cost of producing unbleached kraft pulp. *DENS* and *PY* have been demonstrated to influence the properties of paper produced from pulp (HIGGINS 1984, IKEMORI *et al.* 1986, ARBUTHNOT 1991, DEAN 1995) and should the breeding objective be expanded to include conversion of pulp to paper, a decline in the value of paper with increasing *DENS* (say) may produce a negative influence on the economic worth of *DENS* at high levels. To date, however, little has been published which allows the construction of reliable relationships between traits used in the breeding objective and the costs of converting pulp to paper.

HARRIS (1970) pointed out that errors due to use of a non-linear objective function could be completely negated if breeding values of the objective traits could be directly substituted into the objective cost function. However, traits in the presented breeding objective (*VOL*, *DENS*, *PY*, and *FORM* at the time of harvest) are rarely directly assessed in tree breeding programs. Instead, these traits are indirectly assessed as (for example) tree diameter at 1.3 m, Pilodyn penetration at 1.3 m (GREAVES *et al.* 1996), and *PY* predicted using Near Infrared Reflectance Analysis (MICHELL & SCHIMLECK 1995), and usually these traits are assessed at an age earlier than expected harvest age. Selections are made by estimating breeding values for each selection trait and tree using BLP or BLUP techniques (WHITE & HODGE 1989). Economic weights for the selection traits (vector **b**) can be derived from economic weightings for traits in the breeding objective (vector **v**, Eqn. 2) after (SCHNEEBERGER *et al.* 1992):

$$\mathbf{a}_0 = \mathbf{G}_{11}^{-1} \cdot \mathbf{G}_{12} \cdot \mathbf{v} \qquad [5]$$

where $\mathbf{G}_{11}$ is the genetic variance-covariance matrix of the selection traits and $\mathbf{G}_{12}$ is the genetic covariance matrix between the selection traits and the traits in the objective - both assumed to be known without error. If the economic weights are assumed to be constant across the range of a trait the value of each tree, expressed in the units of the breeding objective (e.g. dollars per oven-dry tonne of unbleached eucalypt kraft pulp), is then determined after:

$$G = \mathbf{a}_s . \mathbf{b} \qquad [6]$$

where G is the gain in savings in total pulp cost ($ per ODt) for an individual tree; $\mathbf{a}_s$ is a vector of the estimated breeding values for the selection traits for the individual tree expressed as deviations from the respective population means; and **b** is a vector of the economic weights for the selection traits. Trees are then selected on the basis of maximum expected gain. This method does not, however, overcome the problems of gain over-estimation due to non-linearity of cost function.

Alternatively, the $\mathbf{G}_{11}$ and $\mathbf{G}_{12}$ parameters may be used to predict, by tree, breeding values for the breeding objective traits (vector $\mathbf{a}_o$) from the known selection trait breeding values (vector $\mathbf{a}_s$) after:

$$\mathbf{a}_0 = \mathbf{G}_{12} \,.\, \mathbf{G}_{11}^{-1} .\, \mathbf{a}_s \qquad [7]$$

The individual-tree values for each breeding objective trait can then be directly substituted into the breeding objective cost function (Eqn. 1) providing an estimate of gain which is free of the distortions of cost-function non-linearity and trait interdependence.

It must be noted that this method is computationally more difficult than prediction via economic weights as the set of selection trait estimates must be converted to objective trait estimates *for each tree individually* before being substituted into the relatively complex objective cost function. But even with large data sets the computing task is today relatively minor.

CONCLUSIONS

There is observable non-linearity between total pulp-cost and the levels of all traits in the breeding objective cost function examined, and the true economic weight for each trait declines at higher values of each trait. The breeding objective function examined also shows interdependence between traits in the objective – that is, the economic weight for one trait is dependent upon the actual value of other traits. These effects result in the expected gains (towards reducing the total cost of unbleached eucalypt kraft pulp) being overestimated. The error was greater at high selection intensities: when the best 1% of a population is selected, expected gain may be over-estimated by 25%.

It is suggested that the use of economic weights for prediction of gain may be inappropriate where exploitable variation is great and intensity of selection high. An alternative method of gain determination is proposed: predicted values of selection traits are used to generate values for breeding objective traits which are then substituted directly into the breeding objective cost function thus avoiding errors associated with non-linearity and interdependence.

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