OBJECTIVES AND SELECTION CRITERIA FOR PULP PRODUCTION OF *EUCALYPTUS UROPHYLLA* PLANTATIONS IN SOUTH EAST CHINA

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ABSTRACT

Breeding objectives for pulp, woodchip and standing wood volume production systems were developed in *Eucalyptus urophylla* under typical condition in South East China. The relative importance of the traits in breeding objective including volume, wood basic density and pulp yield were calculated. The selection indices for these objectives were also constructed based on selection criteria which included diameter at breast height, tree height, relative bark thickness and Pilodyn penetration. The results showed that volume is a dominant trait in determining the economic benefits in short-rotation species. The important of pulp yield in breeding objective cannot be materialised by selection index as the indirect traits are poor indicators of this trait.

Key words: pulp production, breeding objective, selection index, economic weight, *Eucalyptus urophylla*, tree improvement

INTRODUCTION

The breeding objective can be defined as the combination of characteristics or traits that the breeder wishes to improve, usually expressed as a linear combination, also denoted the aggregate genotype, of the traits of economical importance (HAZEL 1943). Defining the breeding objective is a fundamental step in breeding programs, required prior to the implementation of genetic evaluation (HARRIS 1970, BARWICK 1992, HARRIS & NEWMAN 1994, WOOLASTON & JARVIS 1995). Although gains in specific traits can be achieved even by simple selection techniques such as mass selection (*eg.* ADES & BURGESS 1982, CORNELIUS 1994), the economic benefits from those selections can be small or even negative if important economic traits have been ignored (*eg.* DEAN *et al.* 1983, ALLEN 1992, TALBERT 1995, WOOLASTON & JARVIS 1995).

It is therefore important to make a clear distinction between breeding objectives and the selection criteria (JAMES 1982b). Traits in the breeding objective are those with a direct impact on the profitability or cost, whereas the traits in the selection criteria are those that for practical reasons, the breeder uses to provide information about the traits in the breeding objectives; the distinction between the two has not always been well described in forestry. For example, standing volume production is often seen as the final objective, whereas key wood quality traits, known to be related to their end products, are ignored (*eg.* VOLKER *et al.* 1990, WHITEMAN *et al.* 1992, MAZANEC & MASON 1993). Even when key traits, such as wood density and pulp yield, are acknowledged as important, they may be too difficult to be measured (DE LITTLE *et al.* 1993, RAYMOND 1995). Moreover, in practice traits being measured are only an indication of breeding objective, and the quality of the information available for selection does not reflect the importance of the traits in the breeding objective.

Breeding objectives for pulp production systems have been recently developed for eucalypts (DEAN *et al.* 1990, BORRALHO *et al.* 1993, DA FONSECA *et al.* 1995, GREAVES *et al.* 1997b). These studies have concluded that the traits with greatest impact in increasing pulping mill capacity or reducing cost, are wood volume, basic density and pulp yield. These studies, however, assumed a vertically integrated enterprise, from growing the timber to processing the fibre.

In South East China, eucalypts are grown mostly for pulp production, but the sector is not well integrated. Currently, individual farmers or state forest farms, which constitute the large majority of the plantation estate in the region, trade based on standing volume or woodchip weight when exporting woodchips (*eg.*, MO *et al.* 1996), and very seldom, state forest farms are integrated with pulp mills. As a result, traits being improved can vary, depending on who is guiding the breeding programs. Although the end product is the same, the different intermediate economic objectives, namely improving standing volume or reducing the costs of producing dry weight woodchips, may dominate the selection criteria and therefore have an impact on the final economics of genetic improvement for pulp production.

Breeding objectives for eucalypt plantations in South East China are also expected to differ from those developed for more industrialised countries in temperate regions (BORRALHO *et al.* 1993, GREAVES *et al.* 1997b) in that, while labour costs are lower, land costs are higher, due to the competition with agricultural crops. Cost of fertiliser is higher due to the high nutrient requirement in the soils (ZENG *et al.* 1995). Another important difference is that eucalypt plantations in China have a much shorter rotation length compared with temperate eucalypts (CHEN 1995, GREAVES *et al.* 1997b).

The purpose of this study is therefore to derive appropriate breeding objectives, and investigate the impact of a range of selection criteria, for *Eucalyptus urophylla* grown in South East China.

METHODS AND MATERIAL

Development of breeding objectives

The breeding objective used in this study was based on the previous studies by BORRALHO *et al.* (1993) and GREAVES *et al.* (1997b), and followed the general approach developed in PONZONI and NEWMAN (1989): definition of production system, determination of cost structure in the system, determination of the biological traits affecting the system and finally derivation of economic value for each biological trait.

Production systems

Although pulp is the ultimate end use of most eucalypt plantations in South East China, the primary profit goal can differ between various growers. For simplicity only three possible production systems are considered: *pulp*, *woodchip* and *standing wood volume*. Currently, they would cover the majority of the eucalypt plantation growers, a situation which is likely to continue in the future (Zhongheng Wu, Zhanjiang Bureau of Forestry, Guangdong, China. personal comm.).

The pulp production system (*pulp*) includes the whole process from raising the seedlings to producing the pulp. Therefore, the aim is to reduce the cost per unit of pulp. This system is only relevant to a number of state forest farms, operating in joint ventures with proposed pulp mills in South East China (PAN 1997, ZHANG 1997).

The woodchip production system (*woodchip*) does not include the process of converting woodchip into pulp. Its objective is to reduce the production cost per unit of wood dry weight. This system is relevant to many state forest farms, which export woodchips directly to Japan and South Korea.

Finally, the standing wood volume production system (*standing wood volume*) aims at producing pulp wood only, and it is relevant to the individual farmers with no facilities to harvest, chip and process the wood. Because farmers sell their pulp wood in green weight to chip yards, the reduction in the cost of standing wood volume is their primary goal.

Cost structure

Table 1 lists the cost components for the three production systems mentioned above. Costs include growing the plantations, harvesting, transporting and pulping the wood.

Costs of establishing and growing the plantation (c_{est}) include the costs of land, site preparation, raising the seedlings in a nursery, fertilising at planting. Maintenance costs (c_{main}) include further fertilising, pest and disease control. For land controlled by the state forest farms and by individual farmers, land cost (c_{land}) should not be included. However, in South East China it is a common practice to rent land to grow trees or other crops, in which case, it is appropriate to include the rent of land as a direct component of the total growing cost. An average rate, typical from the Guangxi and Guangdong region, was used in this study.

Harvesting cost (c_{harv}) includes the cost of chopping down the trees, trimming the branches and debarking. Transporting cost (c_{tran_wood}) used here includes the cost of transporting the wood from land to chipping yard. Chipping cost (c_{chip}) includes the cost of the process of chopping wood into chips.

Transporting cost for the chips (c_{tran_chip}) covers the cost of transporting woodchips from chipping yard to the port. This does not apply to individual farmers which sell the wood as standing volume, but is often a substantial cost component for state forest farms. The cost figure for c_{tran_chip} used here is based on the average transport distances and other conditions in the Guangxi region.

Table 1. Cost structure ($US/ODt) in pulp, woodchip and wood standing volume production systems in South East China for *E. urophylla* (from Guangxi Forest Survey Institute 1993, CHEN 1995, ZHOU 1995, MO *et al.* 1996, Z. H. WU 1997 personal communication).

Cost Structure	Timing of cost	Base cost ($US/ ODt)	Cost function C_{total} µ $f(VOL, DEN, PY)$*		
			Pulp	Woodchip	Volume
Establishment (c_{est})	Rotation start	14	$\frac{1}{VOL.DEN.PY}$	$\frac{1}{VOL.DEN}$	$\frac{1}{VOL}$
Land (c_{land})	Annual cost	16.7	$\frac{1}{VOL.DEN.PY}$	$\frac{1}{VOL.DEN}$	$\frac{1}{VOL}$
Maintenance (c_{main})	Annual cost	4.9	$\frac{1}{VOL.DEN.PY}$	$\frac{1}{VOL.DEN}$	$\frac{1}{VOL}$
Harvest (c_{harv})	Rotation end	8.6	$\frac{1}{VOL.DEN.PY}$	$\frac{1}{VOL.DEN}$	$\frac{1}{VOL^{0.2}}$
Transport – green wood (c_{tran_wood})	Rotation end	32	$\frac{1}{DEN.PY}$	$\frac{1}{DEN}$	
Chipping (c_{chip})	Rotation end	12	$\frac{1}{PY}$		
Transport – woodchip (c_{tran_chip})	Rotation end	7	$\frac{1}{DEN.PY}$	$\frac{1}{DEN.PY}$	
Pulping (c_{mill})	Rotation end	188	$\frac{1}{DEN^{0.5}.PY^{0.7}}$		

* *VOL* = wood volume, *DEN* = wood basic density, *PY* = pulp yield

Pulping cost (c_{mill}) involves the cost of converting wood chip to pulp. This value was not available in China, and was taken from GREAVES and BORRALHO (1996) after excluding the cost of chipping.

The total cost were then calculated as the sum of the various cost components listed above as:

$$C_{total} = \frac{c_{est}}{(1-loss)} + \frac{c_{main}+c_{land}}{(1-loss)} \cdot \frac{1-(1+i)^{-r}}{i} + \frac{c_{harv}+c_{tran\ wood}+c_{tran\ chip}}{(1-loss).(1+i)^{r}} + \frac{c_{chip}+c_{mill}}{(1+i)^{r}} \quad [1]$$

where *loss* is the fibre loss in the pulp mill, assumed to 5% (GREAVES *et al.* 1997b); *r* is rotation age for *E. urophylla*, assumed to be 7 years (CHEN 1995) and *i* is the discount rate, assumed to be 5% (ZHOU 1995, MO *et al.* 1996). The same cost for each component, in dollars per unit of ovendry pulp, was used for each production system, hence making the three breeding objectives more comparable.

The costs of the components were assumed the same for the three production systems, however, this may not be always the case. For instance, currently the maintenance cost is higher for state forest farms than for individual farmers; whereas individual farmers have to pay higher tax than their farm counterpart. However, these differences are mainly the result of current national policies or managing structure, which are rapidly changing and are likely to become smaller with time.

Biological traits affecting breeding objective

The biological traits considered in this study are wood volume (*VOL*) in $m^3 \cdot ha^{-1}$, basic density (*DEN*), the ovendry weight per unit of green volume, in $tonne \cdot m^{-3}$ and pulping yield (*PY*), the ovendry weight of pulp per unit of ovendry weight of wood, in %. Their relationship with the cost components (cost function) in the different objectives are listed in Table 1. Their phenotypic and genetic parameters are listed in Table 2.

The relative economic weights for *VOL*, *DEN* and *PY* were calculated as the observed change in total pulp cost (equation 1) for a unit increase in σ_A for each trait

Table 2. Mean, additive genetic (σ_a) and phenotypic (σ_p) standard deviations, heritability, genetic (above diagonal) and phenotypic (below diagonal) correlations between *VOL*, *DEN* and *PY*[†]. Parameters for *PY* based on DEAN *et al.* (1990) and GREAVES *et al.* (1997b).

Traits	Unit	Mean	σ_a	σ_p	h^2	*VOL*	*DEN*	*PY*
VOL	$m^3 \cdot ha^{-1}$	100	30.2	69.3	0.26		−0.13	−0.13
DEN	$t \cdot m^{-3}$	0.5	0.033	0.039	0.53	−0.23		0.3
PY	OD UBEK*	0.5	0.0077	0.013	0.56	−0.1	0.31	

[*] ovendry unbleached eucalypt kraft
[†] *VOL* = wood volume, *DEN* = wood basic density, *PY* = pulp yield

(GREAVES *et al.* 1997b).

Selection criteria

Some of the traits in the breeding objectives are very difficult to measure directly, hence selection has to be based on indirect traits. Four traits commonly used in forestry have been used here as potential selection criteria: diameter over bark at breast height (*DBH*) in centimetres, tree height (*HT*) in meters, relative bark thickness (*BKR*) in % and Pilodyn penetration (*PP*) in millimetres. *BKR* is given as a percentage over *DBH*.

Construction of selection index

Let the breeding objective for the *i*th tree be defined as:

$$\mathbf{H}_i = \mathbf{v}'\mathbf{g}_i \qquad [2]$$

where v is a vector of economic weight for the traits in breeding objective (*VOL*, *DEN*, *PY*), and $\mathbf{g}_i$ is the vector of breeding values for the *i*th tree. The breeding values for the traits in the breeding objective are usually not estimated directly, but predicted from the traits in the selection criteria as SCHNEEBERGER *et al.* (1992):

$$\hat{\mathbf{g}}_i = \mathbf{G}_{os}\mathbf{G}_{ss}^{-1}\hat{\mathbf{u}}_i \qquad [3]$$

where $\mathbf{G}_{os}$ is the genetic (co)variance matrix between traits in the breeding objective and those in the selection criteria, and $\mathbf{G}_{ss}$ is the genetic (co)variance matrix between the traits in the selection criteria, $\hat{\mathbf{u}}_i$ is a vector of estimates of breeding values of the traits in the selection criteria (*DBH*, *HT*, *BKR* and *PP*) for the *i*th tree. Therefore, the same breeding objective for *i*th tree can now be defined by the selection index ($\mathbf{I}_i$) as:

$$\mathbf{I}_i = \mathbf{v}'\mathbf{G}_{os}\mathbf{G}_{ss}^{-1}\hat{\mathbf{u}}_i = \mathbf{b}'\hat{\mathbf{u}}_i \qquad [4]$$

with the economic weights for the selection traits being:

$$\mathbf{b} = \mathbf{G}_{ss}^{-1}\mathbf{G}_{so}\mathbf{v} \qquad [5]$$

For each breeding objective, five selection indices (equation 4) were constructed, by including a different set of selection criteria: including all available selection traits, *DBH*, *HT*, *BKR* and *PP* (I_{Full}); excluding *DBH* (I_{DBH}); excluding *HT* (I_{HT}); excluding *BKR* (I_{BKR}); and excluding *PP* (I_{PP}).

Phenotypic and genetic parameters for traits in the selection criteria are listed in Table 3. Genetic correlations between breeding objective traits and selection criteria are presented in Table 3. Except for the parameters related to *PY*, all were derived from progeny trials of *E. urophylla* at age 5 in China (WEI & BORRALHO 1997, 1998).

Correlation between breeding objectives or selection indices

The correlations amongst breeding objectives ($r_{H_i H_j}$) or selection indices ($r_{I_i I_j}$) were obtained according to JAMES (1982a) as:

$$r_{H_i H_j} = \frac{\mathbf{v}'_i\mathbf{G}_{oo}\mathbf{v}_j}{\sqrt{(\mathbf{v}'_i\mathbf{G}_{oo}\mathbf{v}_i)\,(\mathbf{v}'_j\mathbf{G}_{oo}\mathbf{v}_j)}} \qquad [6]$$

$$r_{I_i I_j} = \frac{\mathbf{b}'_i\mathbf{G}_{ss}\mathbf{b}_j}{\sqrt{(\mathbf{b}'_i\mathbf{G}_{ss}\mathbf{b}_i)\,(\mathbf{b}'_j\mathbf{G}_{ss}\mathbf{b}_j)}} \qquad [7]$$

where $\mathbf{v}_i$ and $\mathbf{b}_i$ are the vectors of economic weights for the traits in the *i*th breeding objective and selection index, respectively, and $\mathbf{G}_{oo}$ and $\mathbf{G}_{ss}$ is the genetic (co)variance matrix of traits in breeding objective and selection index, respectively.

Two types of correlations between selection indices were calculated: correlations among I_{Full} for the different objectives; and correlations among the different selection indices within each breeding objective. The first was aiming at measuring the similarity between

Table 3. Additive genetic and phenotypic variances (σ^2_a, σ^2_p), heritability, genetic (above diagonal) and phenotypic (below diagonal) correlations between *DBH, HT, BKR* and *PP in selection index for the breeding objectives (WEI & BORRALHO 1997 1998). Genetic correlations between selection criteria traits and breeding objective traits were also listed. Parameters for *PY* based on DEAN *et al.* (1990) & RAYMOND (1995).**

Trait	σ^2_a	σ^2_p	h^2	Correlations						
				DBH	*HT*	*BKR*	*PP*	*VOL*	*DEN*	*PY*
DBH	1.724	9.48	0.23 ± 0.03		0.83	–0.15	0.33	0.99	–0.36	–0.13
HT	2.098	14.542	0.24 ± 0.04	0.8		–0.36	0.15	0.88	0	–0.13
BKR	1.229	1.554	0.35 ± 0.08	0	–		–0.1	–0.21	0.24	0.05
PP	3.935	2.304	0.56 ± 0.11	0.21	0.07	–0.04		0.3	–1	–0.35

*) *DBH* = Diameter at breast height, *HT* = height, *BKR* = relative bark thickness, *PP* = Pilodyn penetration, *VOL* = wood volume, *DEN* = wood basic density, *PY* = pulp yield

breeding objectives when selection is based on a complete set of selection criteria, whereas the other one was to detect the efficiency of the different indices for each objective.

Relative importance of traits in breeding objectives and selection index

Two criteria were used to determine the relative importance of traits in the breeding objectives and the selection criteria. One, based on GREAVES *et al.* (1997b), estimates the importance of each trait for breeding purpose and is given as $\sigma_{a.t}\mathbf{v}/\sigma_{p.t}$, where $\sigma_{a.t}$ is a vector of additive genetic covariances between the trait being selected and other traits in the objective, $\sigma_{p.t}$ is the phenotypic standard deviation of the trait selected, and **v** is a vector of economic weights.

The second criterion partitions a one dollar increase in breeding objectives ($\Delta\mathbf{G}_b$) or selection indices ($\Delta\mathbf{G}_s$) into cents contributed by each trait (SCHNEEBERGER *et al.* 1992):

$$\Delta\mathbf{G}_b = \mathbf{n} \,\#\, \mathbf{v} \quad [8]$$

$$\Delta\mathbf{G}_s = \mathbf{d} \,\#\, \mathbf{b} \quad [9]$$

where # represents Hadamard or element-by-element product, and **v** and **b** are economic values for the traits in breeding objectives and selection criteria, respectively, **d** is a vector of the expected genetic gain for the traits in the selection index and **n** for the traits in the breeding objectives, estimated as:

$$\mathbf{d} = \frac{1}{s_I^2}\, var(\hat{\mathbf{u}})\mathbf{k}$$

$$\mathbf{n} = \frac{1}{s_I^2}\, \mathbf{G}_{os}\, \mathbf{G}_{ss}^{-1}\, var(\hat{\mathbf{u}})\mathbf{k}$$

where $\mathbf{k} = \mathbf{G}_{ss}^{-1}\mathbf{G}_{so}\mathbf{v}$, $s_I^2 = \mathbf{k}'var(\hat{\mathbf{u}})\mathbf{k}$, and $var(\hat{\mathbf{u}}) = \mathbf{B}'\mathbf{P}_{ss}\mathbf{B}$ while $\mathbf{B} = \mathbf{P}_{ss}'\mathbf{G}_{ss}$ and $\mathbf{P}_{ss}$ is the matrix of phenotypic (co)variance between the traits in selection index. The $var(\hat{\mathbf{u}})$ was estimated assuming the only information in the index was from the individual tree. The $\Delta\mathbf{G}_b$ gives a measure of the importance of the traits in the breeding objective (*VOL, DEN* and *PY*) when selection is based on indirect selection traits (*DBH, HT, BKR* and *PP*), whereas the $\Delta\mathbf{G}_s$ gives a measure of the importance of the traits in the selection criteria with direct selection is based on the traits of selection criteria.

RESULTS

Breeding objectives

The economic weights for *VOL, DEN* and *PY* in pulp, woodchip and volume breeding objective are listed in Table 4. Therefore the breeding objective for instance for pulp production can be expressed as:

$$H = 0.38\, EBV_{VOL} + 267.58\, EBV_{DEN} + 338.96\, EBV_{PY} \quad [10]$$

where EBV_{VOL}, EBV_{DEN} and EBV_{PY} are the estimated breeding values for *VOL, DEN* and *PY*, respectively. These coefficients can be seen as the reduction in costs of producing one tonne of pulp, when the trait is changed by one unit of genetic standard deviation. In the case of *VOL*, an improvement of 1 $m^3 \cdot ha^{-1}$ results in a reduction of \$0.38 $\cdot t^{-1}$ pulp. For *DEN*, an increase of 1 tonne$\cdot m^{-3}$ results in a reduction of \$267.58.

VOL was the most important trait across three objectives (Table 4), with gains in selecting *VOL* being consistently the largest and remaining relatively stable across the objectives. For instance, selection for *VOL* is twice as effective in reducing the costs as for *PY*, in the pulp production system. By contrast, the relevance to

Table 4. Economic weights for the traits in the three breeding objectives. Numbers in the parenthesis are the relative importance.

Trait	Breeding objectives		
	Pulp	Woodchip	Wood volume
*VOL**	0.38 (6.2)	0.38 (6.7)	0.38 (7.0)
DEN	267.58 (5.0)	144.55 (1.7)	0.0 (–1.3)
PY	338.96 (2.9)	0.0 (–0.4)	0.0 (–1.3)

* VOL = wood volume, DEN = wood basic density, PY = pulp yield

breeders of *DEN* and *PY* changed amongst production systems, decreasing markedly in importance from pulp to woodchip to volume production. *PY* had a negative impact in woodchip and volume production systems, and *DEN* in volume production.

Despite the substantial differences in cost structure, the relative importance of *VOL* reported here was about the same as reported in GREAVES *et al.* (1997b), and *DEN* and *PY* were only slightly less. These differences are due to the shorter rotation age and relatively higher volume production per hectare in *E. urophylla* plantations, compared with temperate eucalypts.

Despite the marked differences in economic weights across breeding objectives, correlations between them were always very high, ranging between 0.80 and 0.95 (Table 5). This suggests that selection for any breeding objective will result in substantial gains in any of the other objectives.

Table 5. Correlations between breeding objectives for *E. urophylla* in South East China

Breeding objective	Woodchip	Wood volume
Pulp	0.95	0.8
Woodchip		0.95

Selection index

Unfortunately, selection has often to rely on indirect traits, which are easy to measure, under genetic control, and hopefully strongly correlated with the traits in the breeding objective. In our study, we looked at the importance of *DBH*, *HT*, *BKR* and *PP*. The economic weights for these traits in the selection indices and for the different breeding objectives, are presented in Table 6. For example, when selection is based on the four selection criteria traits and for a pulp production scenario, the index became:

$$I_{Full} = 5.080\ EBV_{DBH} + 4.558\ EBV_{HT} + 3.192\ EBV_{BKR} - 7.625\ EBV_{PP} \quad [11]$$

where EBV_{DBH}, EBV_{HT}, EBV_{BKR} and EBV_{PP} are the expected breeding values for *DBH*, *HT*, *BKR* and *PP*, respectively. An improvement of 1 cm in diameter would be expected to result in a cost reduction of $5.1 per tonne of pulp. A reduction in 1 mm of Pilodyn, which means an increase of wood basic density, results in a reduction of $7.6.

Table 6. Economic weights for the traits in selection criteria for pulp, woodchip and standing wood volume production in E. urophylla grown in South East China. Selection indices are: I_{Full}, including all available selection traits, DBH, HT, BKR and PP; I_{DBH}, excluding DBH; I_{HT}, excluding HT; I_{BKR}, excluding BKR; and I_{PP}, excluding PP*.

Breeding objective	Selection index	Economic weight			
		DBH	*HT*	*BKR*	*PP*
Pulp	I_{Full}	5.08	4.558	3.192	–7.625
	I_{DBH}	–	7.789	4.384	–6.136
	I_{HT}	9.429	–	0.88	–8.47
	I_{BKR}	6.005	3.227	–	–7.952
	I_{PP}	1.733	5.968	4.139	–
Woodchip	I_{Full}	5.823	3.721	2.247	–3.695
	I_{DBH}	–	7.424	3.614	–1.988
	I_{HT}	9.746	–	3.078	–4.298
	I_{BKR}	6.473	2.784	–	–3.925
	I_{PP}	4.2	4.405	2.706	–
Volume	I_{Full}	7.058	2.352	0.995	–0.363
	I_{DBH}	–	6.841	2.652	1.706
	I_{HT}	9.302	–	–0.197	–0.799
	I_{BKR}	7.346	1.937	–	–0.465
	I_{PP}	6.898	2.419	1.04	–

* DBH = Diameter at breast height, HT = height, BKR = relative bark thickness, PP = Pilodyn penetration

Economic weights changed markedly when one trait was excluded from the selection index, which was most erratic in pulp production. For example when *PP* was excluded, weights for *DBH* reduced by about $\$3 \cdot cm^{-1}$ improvement but increased for *HT* by about $\$1 \cdot m^{-1}$ increment. Those weights remained almost unchanged in wood volume production.

The partition of a one-dollar increase in the selection index by these traits gave a similar result to that given by the relative importance of the traits in the

Table 7. The relative importance of DBH, HT, BKR and PP* in selection indices.

Assessing criteria	Traits	Pulp	Woodchip	Wood volume
Relative importance	*DBH*	4.93	5.74	5.74
	HT	5.47	5.75	4.91
	BKR	–0.23	–1.02	–1.91
	PP	–3.98	–0.03	1.2
Partition of a one-dollar increase in selection index	*DBH*	0.25	0.6	0.76
	HT	0.37	0.5	0.29
	BKR	–0.04	–0.07	–0.03
	PP	0.42	–0.03	–0.02

* *DBH* = Diameter at breast height, *HT* = height, *BKR* = relative bark thickness, *PP* = Pilodyn penetration

selection criteria (Table 7). Selection for *DBH* and *HT* always had the greatest impact on gains. This is a result of the strong correlation between *DBH* or *HT* and *VOL* and the overriding importance of *VOL* across the three objectives. Pilodyn penetration contributed with 42 cents in one dollar increase when selecting for pulp production, but had little or even negative contribution for woodchip and volume production, respectively (Table 7). Relative bark thickness contributed negatively to all the objectives, although values were negligible.

The importance of the traits in the breeding objectives, when selection was based on *DBH*, *HT*, *BKR* and *PP* (Table 8), was quite different from that obtained directly from the selection of the traits in breeding objective (Table 4). For instance, when selection was based on *VOL*, *DEN* and *PY*, *VOL* was two times more important than *PY*, and about one and half times more important than *DEN*. However, when selection was based on selection criteria such as *DBH*, *HT* and *PP*, *VOL* became 10 times more important than *PY* and 1.3 times more important than *DEN* in explaining changes in pulp cost.

Correlations among selection indices, for different objectives (Table 9), were almost identical to the correlations between the objectives themselves (Table 5). Within each breeding objective, the correlations between indices including all selection criteria traits and indices excluding one of the traits, were also high, being over 0.84 (Table 10). As expected, in the case of the volume production scenario, excluding *PP* from the index had no impact on the overall ranking, with $r_{I_i I_j}$ =1.0, since no wood quality traits were considered in the breeding objective. Also excluding *BKR* had little impact on the overall gain, with nearly perfect correlations with full index.

Table 8. Partition of a one dollar increase in breeding objectives into cents contributed by each trait: *VOL, DEN* and *PY* in breeding objectives when selection was based on *DBH, HT, BRK* and *PP*.

Trait	Pulp	Woodchip	Wood volume
VOL	0.54	0.98	1
DEN	0.41	0.02	0
PY	0.05	0	0

* *VOL* = wood volume, *DEN* = wood basic density, *PY* = pulp yield, *DBH* = Diameter at breast height, *HT* = height, *BKR* = relative bark thickness, *PP* = Pilodyn penetration

Table 9. Correlations between selection indices using all traits, for the three breeding objectives for *E. urophylla* in South East China.

Selection criteria	Woodchip	Wood volume
Pulp	0.94	0.79
Woodchip		0.94

Table 10. Correlations between selection indices including all selection traits (IFull) and excluding *DBH* (IDBH), *HT* (IHT), *BKR* (IBKR) or *PP* (IPP)* for pulp, woodchip and volume production system based on *E. urophylla* plantations in South East China.

Breeding objectives	IDBH	IHT	IBKR	IPP
Pulp	0.95	0.94	0.98	0.84
Woodchip	0.93	0.93	0.99	0.96
Volume	0.90	0.98	1.00	1.00

* *DBH* = Diameter at breast height, *HT* = height, *BKR* = relative bark thickness, *PP* = Pilodyn penetration

DISCUSSION

Despite some uncertainty on the genetic and phenotypic estimates and the cost components, the breeding objectives presented in this study, should be a reasonable first approximation for *E. urophylla* plantation in South East China. In previous studies, the relative importance of traits has been shown to be relatively insensitive to even large changes in costs, rotation length or discount rates (FOWLER *et al.* 1976, VANDEPITTE & HAZEL 1977, SMITH *et al.* 1986, BORRALHO *et al.* 1993, GREAVES *et al.* 1997b), providing all key traits are included. This was certainly the case here, as the economic values assigned to the three traits in the breeding objective differed only slightly to those listed in BORRALHO *et al.* (1993) and GREAVES *et al.* (1997b) for pulp production in *E. nitens* and *E. globulus* in Portugal and Australia, respectively. Wood volume had a larger weight (0.38 versus 0.27) and wood density a lower weight (269 versus 349 or 310), as a result of the lower growing cost and short rotation in China. Pulping costs were assumed the same. The higher weight for *VOL* was also due to the higher heritability and additive genetic variance for volume and shorter rotations in *E. urophylla*, compared with temperate eucalypts. Differences between the absolute weight reported here and those published elsewhere become more apparent for the wood volume production system (BORRALHO *et al.* 1993), although weights appear to be similar in relative terms.

More important when defining a breeding objective, is to ensure all the important traits are being formally included in the selection process (JAMES 1982B, BARWICK 1992, WELLER 1994, WOOLASTON & JARVIS 1995). This problem is particularly relevant in forestry, where the selection criteria are often based on a few indirect traits, which can be poorly related with some of the key variables in the breeding objective, or include traits with lower heritability. This situation obviously affect markedly the efficiency of the index (SMITH 1983).

Direct selection on *VOL*, *DEN* and *PY* results in *VOL* and *DEN* having similar importance, and both being 2 to 3 times more important than *PY* (BORRALHO *et al.* 1993, GREAVES *et al.* 1997b). However, in practice, the information available for selection is based on indirect traits such as *DBH*, *HT* or Pilodyn. This does not provide the same accuracy as a direct selection on the breeding objective traits. *DBH* and *HT* are reasonably good predictors of volume but Pilodyn is a more modest predictor of *DEN*, having generally high genetic correlations but often significantly lower heritability (Raymond & MacDonald 1998) and there is no good predictor for *PY*, as Pilodyn and other more direct measurements of *DEN* seem to be poorly related with *PY*. As a result, when selection is based on traits such as *DBH*, *HT*, *BKR* and *PP*, *VOL* increases its importance relative to *DEN*, and *PY* becomes much less important in accounting for changes in the breeding objective. This study found that when selection was based on DBH, *HT*, *BKR* and *PP*, the economic value of gain in *VOL* was 10 times the value of gain in *PY*. If selection could be based directly on *VOL*, *DEN* and *PY* (the same three traits in the aggregate breeding objective), the economic value of gain in *VOL* should have been only 2 time the value of gain in *PY*. This difference is a measure of the deficiencies in the selection criteria, and should be a stimulus for the development of easy methods to incorporate *PY* information in large-scale selection programs. The use of the near-infrared diffuse reflectance method (NIR) as indirect measure of *PY* (MICHELL & SCHIMLECK 1995, DOWNES *et al.* 1997) provides therefore an opportunity to increase gains from selection programs.

Another important factor is the relationship between economic weight and trait value which is generally assumed to be linear (WELLER 1994). GREAVES *et al.* (1997a) have proved that the linear relationship assumption and the use of mean economic values could overestimate genetic gain by up to 25%. GREAVES *et al.* (1997a, after HARRIS (1970)) proposed an alternative method to overcome this problem by incorporating the breeding values of traits in the selection index rather than those in the breeding objective. Selection on indices based on equation 9 could therefore diminish the error due to the non-linearity.

The selection indices assessed in this study use only the phenotypic information on the individual tree only. In practice, other indices could also be used, incorporating individual and family or progeny information. Owing to very high heritability in all selection criteria traits in this study, the result reported here may not differ markedly from other indices particularly if the same amount of information is available for all traits. However, a specific application using estimates from a multivariate BLUP analysis using all pedigree information will be reported by WEI and BORRALHO (in preparation).

The breeding objectives in this study were particularly relevant to the Guangxi Region, and to the Dongmen State Forest Farm in particular, a well documented eucalypt afforestation farm in South East China (MANNION & WEI 1989). Forest farms throughout South East China, using eucalypts as their main planting species, operate in very similar conditions, and should share similar production costs as used here. Difference in size between these forest farms and Dongmen State Forest Farm would have relatively small effect on the derivation of economic weights and in determining selection efficiencies from indices (SMITH *et al.* 1986, PONZONI 1988).

The results from this study have several implications on Chinese eucalypt breeding programs. First, volume plays a dominant role in determining the economic benefits in fast-growing short-rotation species such as *E. urophylla*. This could be achieved easily by selection for diameter at breast height and tree height. Secondly, wood quality traits which are strongly related to end-product are economically important in pulp production, but the benefits can only be materialised if tree breeders can find a reliable clue to control these traits. Thirdly, it is vital to include key traits in the selection index such as Pilodyn penetration, an indirect measure of wood density, for pulp production.

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