An economic evaluation of alternative genetic improvement strategies for farm woodland trees

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Summary

A cost–benefit analysis (CBA), focusing on the Net Present Value (NPV) of a current genetic improvement programme for broadleaved trees was performed using Monte Carlo simulation, with an add-on software package ('@RISK') specifically designed to take account of the uncertainty associated with long-term projects. The CBA was undertaken by evaluating the total cost of achieving a given estimated genetic gain via each of the breeding strategies considered. The estimated values of genetic gain were then expressed in terms of the increased value of timber output. Cash flows were based on current estimated tree establishment costs and anticipated productivity of the four tree species included in the programme (ash, *Fraxinus excelsior*; sycamore, *Acer pseudoplatanus*; wild cherry, *Prunus avium*; and sweet chestnut, *Castanea sativa*), when grown primarily for a timber crop. The results of the NPV analysis indicated that tree improvement could be cost-effective for small genetic gains, but that current breeding strategies differed markedly in their cost-effectiveness. Improvement scenarios based on conventional selection and testing techniques, such as simple mass selection and recurrent selection (seed orchards), were found to be the most cost-effective at a discount rate of 6 per cent. In contrast, tree improvement scenarios based on clonal techniques consistently ranked lowest, despite the much higher genetic gains achieved. The use of clonal techniques was found to be particularly hard to justify with broadleaved tree species of relatively low timber value. Overall, with the current state of broadleaved timber markets in the UK, and the current areas being planted, investment in basic genetic improvement of high-value timber species appears financially worth while. The estimated direct additional financial benefit to growers, if new planting is undertaken with improved stock as opposed to unimproved stock, is estimated to range from £38 ha^{-1} with Simple Mass Selection to £100 ha^{-1} with Simple Recurrent Selection.

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Introduction

As forest trees are generally characterized by a high degree of intraspecific genetic variation and many commercially important traits are under at least moderate genetic control (Cornelius, 1994a), the gains to be made by genetic improvement are potentially high. However, tree improvement programmes tend to be both capital intensive and long term, primarily because of the high cost of establishing and maintaining the field trials necessary for genetic testing. For these reasons, cost–benefit analysis (CBA) is an important tool for assessing the overall cost-effectiveness of tree improvement programmes, and for evaluating the relative efficiency of different breeding strategies.

Previous CBAs have indicated that tree improvement is generally profitable, but that different breeding strategies differ substantially in their cost-effectiveness (see Thompson *et al.*, 1989). For example, Porterfield *et al.* (1975) estimated internal rates of return of between 10 and 14 per cent for tree improvement programmes undertaken by industrial and state forest organizations for loblolly pine in the USA. Progeny testing and subsequent roguing of the seed orchards established was estimated to increase profitability substantially, leading to a 10–20 per cent volume gain over unimproved plantation yields. Similarly, in an analysis of a Douglas-fir improvement programme in the Pacific Northwest, USA, benefits were again found to exceed costs, with a combination of first and second generation improvement, including the provision of seed orchards, as the most cost-effective of the nine options considered (Thompson *et al.*, 1989). McKenney *et al.* (1989) found that in the case of black spruce in Ontario, Canada, genetic gains of just 8 per cent enabled genetic improvement to be cost-effective. Clonal approaches to tree improvement were found to be less cost-effective than seed-based approaches, despite the higher genetic gains achieved, because of the higher multiplication costs associated with vegetative propagation.

In this paper, a Net Present Value (NPV) analysis of a genetic improvement programme currently in progress in the UK, which focuses on broadleaved trees, is described. The project is funded largely by the Ministry of Agriculture, Fish and Food (MAFF), and is being undertaken by a number of collaborating organizations, principally Horticulture Research International (HRI) and the Research Division of the Forestry Commission. The quality and growth rate of broadleaved timber trees in the UK is notoriously variable, but there have been few recent attempts to improve the genetic quality of the planting stock. The current MAFF programme was initiated in 1988, with funding provisionally committed up to the year 2000. The ultimate aim of the programme is to increase the value of the UK broadleaved timber crop, and hence encourage more land-owners to plant broadleaved trees, with a particular focus on planting on improved land. The programme encompasses two different approaches to tree improvement: (1) traditional selection and testing of material of seed origin, and (2) the use of clonal reproduction techniques for the development of superior cultivars. Tree improvement work is focusing primarily on four species, namely ash (*Fraxinus excelsior* L.), sweet chestnut (*Castanea sativa* Mill.), sycamore (*Acer pseudoplatanus* L.) and wild cherry (*Prunus avium* L.).

Current supply and demand conditions for hardwood timber in the UK are well documented (e.g. Venables, 1985; Whiteman, 1991; Kerr and Evans, 1993; Cahalan *et al.*, unpublished MAFF report 1995; Forestry Industry Committee of Great Britain, 1995). Although quality broadleaved timber produced in the UK has a high value, a low total percentage (23–29 per cent) of the UK hardwood consumption is currently supplied from home-grown timber; material harvested is generally of moderate to poor quality, with over 50 per cent of hardwoods from home-grown sources in the lowest value classes, namely mining timber, chip and firewood quality (Thompson, 1988). Although the high-quality British hardwood market is seen as one of great potential for home-produced timber, it is currently notably undersupplied from timber grown in the UK. There is no reason why British-grown timber could not compete with imports in the high-value market sectors, with quality oak, ash, sycamore, cherry, sweet chestnut and other minor species in considerable demand for joinery, furniture and veneer from timber merchants (Kerr and Evans, 1993). In fact, supplies of British timber to the UK hardwood market have contracted in recent years, mainly due to the loss of the mining timber market (Kerr and Evans, 1993).

It can be assumed that, in the foreseeable future, the market for quality hardwoods will remain strong and the price received for producers of quality hardwoods in the UK will remain independent of UK supply (Whiteman, 1991). However, it is important to note that high-value markets require timber within well defined size, form and other quality limits, and therefore a high genetic quality of planting stock. This suggests a clear need for tree improvement work to be undertaken on broadleaved species in the UK. The key question addressed in this paper is whether the current investment into such tree improvement work will be cost effective. A CBA, focusing on NPVs, of the present publicly funded broadleaved tree improvement programme was therefore undertaken in 1996 at MAFF's request to (1) assess the costs and benefits of the tree improvement work to the grower and (2) determine whether the tree improvement work being undertaken will provide value for money to the taxpayer.

Methods

Estimation of genetic gain

The standard approach to assessing the economic benefit of tree improvement programmes first involves the estimation of genetic gain (Lee, 1986, 1992; McKenney *et al.*, 1989; Thompson *et al.*, 1989; Porterfield *et al.*, 1975). Genetic gain is the key measure of the effectiveness of a tree improvement programme and may be defined simply as (Lee, 1986):

$$\text{Genetic gain} = \text{selection differential} \times \text{heritability}$$

The selection differential indicates the extent to which the mean of the selected population (for whatever trait is of interest) differs from that of the base population. The heritability is a measure of the extent to which a particular characteristic is genetically inherited and is usually estimated by analysis of variance of results from field trials testing material of different genetic origin (e.g. progeny tests). Narrow-sense heritability (h^2) relates to genetic improvement using seed-based approaches (progeny tests, seed orchards, etc.). In the case of genetic improvement using only clonal approaches, genetic gain is calculated using broad-sense heritability (H^2, the ratio of total genetic variation in a population to phenotypic variance). Values of H^2 tend to be significantly higher than h^2, leading to higher genetic gains at a given selection intensity.

A number of alternative strategies are available to tree breeders to achieve genetic gain (e.g. see Table 1). The magnitude of genetic gain obtained will vary according to the breeding strategy and multiplication technique used, the heritability of the characteristics being selected for, and the selection intensity adopted. To estimate genetic gain, the individual research and development projects being undertaken by the FC and HRI were related to one or more breeding strategies (see Table 1). Estimates of genetic gain were obtained on the basis of results of field trials in the minority of cases where this was possible (N. Cundall and C. Cahalan, personal communication). In all other cases, the genetic gains likely to be achieved were estimated using results from earlier tree improvement programmes, mostly undertaken with other species (e.g. Gill, 1983a, b; Zobel and Talbert, 1984; Gordon, 1992; Cornelius, 1994a; Cahalan *et al.*, unpublished MAFF report 1995).

Approach to CBA

The approach adopted in the CBA was to evaluate the total cost of achieving a given genetic gain via each of the breeding strategies considered. The benefits of that gain were then evaluated in terms of the increased value of timber output. The basis of the analyses is a series of cash flows, based on current estimated tree establishment costs (Mitchell *et al.*, 1994; Chadwick, 1995) and anticipated productivity (Edwards and Christie, 1981) of the four tree species included in the MAFF programme (*Fraxinus excelsior*, *Acer pseudoplatanus*, *Prunus avium* and *Castanea sativa*), if grown primarily for a timber crop.

These cash flows contain a number of assumptions relating to the husbandry and

Table 1: Estimated genetic gain for different breeding/multiplication strategies

Name of breeding strategy	Details of breeding strategy	Estimated genetic gain (%)
1. Simple Mass Selection	Involves phenotypic selection of 'plus' trees in selected stands on the basis of stem straightness, branching, health etc. Open pollinated seed is collected from selected trees and deployed without any genetic testing	0 to (6.2–10.7)*
2. Mass Selection with Testing	Trees are selected as (1) but with a much higher intensity of selection. Seed is tested in a progeny test. Genotypic selection is made on the basis of progeny means, the trial is rogued, and seed is collected from the remaining trees	0 to (15.5–22.1)
3. Simple Recurrent Selection	Trees selected as under (2) are grafted onto seedling rootstocks and established in a seed orchard. Seed is produced by cross-pollination between trees in the orchard. Genetic testing does not take place	0 to (18.8–32.6)
4. Selection with Mass Vegetative Propagation	Trees are selected as under (2), and are then propagated vegetatively to establish clonal hedges. Material for commercial production could then be produced directly from the hedges, as cuttings. No genetic testing of material takes place	0 to (37.7–46.1)
5. Mass Vegetative Propagation of tested clones	Trees selected and propagated as under (4). All clones are evaluated in clonal trials before deployment	0 to (60.7–65.8)

* Figures in parentheses represent the genetic gains that can be anticipated from tree improvement programmes which have genetic gain as the stated primary objective, and involve intensive early selection in the initial stages of the tree improvement programme. ***This intensive early selection has not occurred throughout the MAFF programme***, and therefore the chance of research success was estimated at 50% (i.e. genetic gain achieved has a 50% chance of falling within the anticipated values indicated in parentheses above, and a 50% chance of falling between zero and these values). (Following Cahalan *et al.*, unpublished MAFF report 1995).

productivity of the trees. Timber yields, breakdown of timber output into different grades of timber and returns from timber sales were all estimated using a combination of published information (e.g. Venables, 1985; Thompson, 1988; Hart, 1991; Whiteman *et al.*, 1991; Kerr and Evans, 1993; Nicoll, 1993) and information supplied by representatives of the timber industry (D. Anderson, personal communication; A. Scott, personal communication; C. Hind, personal communication). A recent 30-year review of the homegrown hardwood price index published by the Central Statistics Office (Whiteman *et al.*, 1991) confirmed no price trend, while Arnold (1991) has given evidence to suggest that, despite concerns over future shortages of timber on the world market, alternative supplies and substitutions within the timber market itself will counteract projected shortfalls. These conclusions support the use of current timber prices in the analysis. All timber production scenarios included anticipated grant payments under the Woodland Grant Scheme (WGS) (Anon., 1994) and the Farm Woodland Premium Scheme (FWPS); in the first instance it was assumed that all plantings take place on improved lowland areas, thereby maximizing grant income. However, inclusion of grant income has no effect on the overall ranking of the scenarios, because payments are presumed to be identical in all cases.

The benefits and costs were identified for each scenario and tree species, quantified over time and valued in real money terms. These were allocated to the time period in which they were expected to occur, to enable production of a cashflow for each scenario. The cash flows were then run, incorporating the predicted changes which result from genetic improvement strategies. The major benefit incorporated was the increase in percentage of high quality grade (Grades 1 and veneer) timber produced. Changes in costs included predicted increases in improved planting stock costs and a reduction in maintenance costs for scenarios which included the use of containerized stock. To allow for the fact that the costs and benefits arose at very different points in time, the annual cashflow estimates were discounted (HMSO, 1991).

Tree improvement work costs

Research and development (R&D) costs were allocated by improvement strategy and by tree species. R&D costs were treated as a capital cost. The tree improvement work costs were allocated to the time periods in which they occurred or are due to occur. In each scenario, there were differing lag periods between the end of the improvement work and the first potential planting occurrence. To compensate for this, the costs were compounded forward to year 0, namely the planting date, at the rate corresponding to the discount rate. In order to allow for legitimate comparisons between the cashflows and tree improvement work costs for each scenario, year 0 of the discounted cashflow was equated to year x of the compounded costs, where x is the equivalent end point of the tree improvement project and the first date for commercial release of planting stock. For ash the anticipated intervals between commencement of genetic improvement work and first commercial plantings are shown in Figure 1 for all the improvement strategies.

Uncertainty

Values assigned to future cashflows were made with varying degrees of uncertainty. To account for this, the CBA was carried out using the spreadsheet add-on program @RISK (Palisade Corp., 1992). This permitted a Monte Carlo simulation to be carried out and showed the distribution of the expected NPV, Benefit:Cost ratios (B:C) and the Internal Rate of Return (IRR) for all components of the breeding strategies (Hirst, 1988). The @RISK program deals with the uncertainty of a future cashflow by assigning a probability distribution to each stochastic variable, using a range of values that the variable may have and the probability of occurrence of each value in the range. It is assumed that the variables used in the analysis are unaffected by changes in other variables (Palisade Corp., 1992). To estimate the expected NPV, B:C and IRR, 1000 iterations were carried out for each scenario. More details of the estimation procedures can be found in Palmer *et al.* (1996).

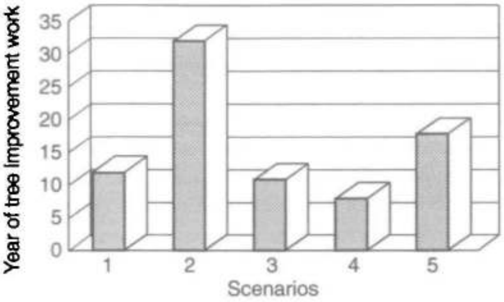

Figure 1. Anticipated interval between commencement of research and first commercial plantings of ash for the five different improvement strategies or scenarios in Table 1 (1, Simple Mass Selection; 2, Simple Mass Selection with progeny testing; 3, Simple Recurrent Selection; 4, Selection with Mass Vegetative Propagation; 5, Mass Vegetative Propagation with clonal testing).

Timber values

There were assumed to be four grades of hardwood timber within the market, namely veneer, first grade, second grade and third grade, in descending order of quality. Current timber prices were used for the analysis, based on information provided by sawmillers and timber merchants, which included minimum and maximum prices for each grade. The price range was used to estimate price variability.

Timber yield/quality

Since trees are not uniform it was assumed that there would be variation of yield within as well as between species. The interspecies variation was accounted for by taking the average timber yield per hectare for each species at given times within their life cycle. Yield variation within a species due to location and management factors was accounted for by assuming that timber yield per hectare was normally distributed around the average value with a standard deviation of 10 per cent. Account was also taken of the variation in timber quality achieved from each hectare. The average yield of all timber grades was calculated for the top three grades assuming that their yield would be normally distributed around the average with a standard deviation of 10 per cent. The quantity of third grade timber was then estimated residually. Finally, the per hectare value of timber was calculated by multiplying the sampled yield by the sampled price.

Tree improvement/scenario success

It was assumed that if the genetic improvement work being undertaken within the different breeding strategies was successful, it would increase the proportion of the higher grade timber. The improvement work was given a 50 per cent chance of being fully successful (i.e. that the genetic gain occurring would fall between the figures given in Table 1, with a 50 per cent chance of the genetic gain falling in the range between zero and the minimum anticipated genetic gain). This enabled the possibility of zero genetic gain to be included in the analysis. The estimates of the percentage change in genetic gain are derived by multiplying timber quality yield by gain to give the new (improved) timber yields. Using these new yields and the appropriate timber prices, the new per hectare value of the timber was then calculated for each scenario.

Results

The tree improvement work being carried out by HRI and the FC was evaluated in terms of its potential to achieve genetic gain within one of the improvement strategies identified. The results provide information on two aspects of the improvement work:

1. the relative NPV of timber crops to growers resulting from the use of improved stock—i.e. the potential financial benefits the grower can expect from using stock produced by the tree improvement programme; and
2. value for money from the viewpoint of society in terms of expenditure on tree improvement. Specifically, a calculation was made of the number of hectares of improved stock which needed to be planted if the benefits of increased timber output were to cover the costs of tree improvement expenditure.

In total, eight different scenarios were evaluated in the CBA, in an attempt to cover as much of the tree improvement work as possible. Scenarios were run for each of the five breeding strategies considered (see Table 1), with additional 'sub-scenarios' addressing (1) simple mass selection plus the use of containerized stock (Scenario 1b), and (2) mass vegetative propagation plus the use of genetic markers, with and without a progeny testing phase. As the work relating to the use of genetic markers was specific to wild cherry, it is not discussed further in this paper.

Benefits to the grower

For each of the four tree species (ash, wild cherry, sweet chestnut and sycamore), under each scenario, an NPV was calculated (Table 2). This is the anticipated financial outcome of utilizing improved planting stock produced by alternative improvement strategies. For comparison, the NPV of growing unimproved stock is included. In each case the benefits and costs were discounted at 6 per cent. As far as growers are concerned, the R&D costs are of historical interest and can be ignored, except that the price of planting stock will vary to some extent in relation to the price of the R&D. Accordingly, for growers the only costs considered were those for the purchase of tree stock and for planting, weeding, thinning and harvesting the timber. All the improvement strategies were ranked by NPV

Table 2: Net Present Value (NPV) (£/ha) of improved stock, and ranking of research scenarios

	NPV £ ha^{-1} (6% discount rate)							
	Ash		Sycamore		Wild cherry		Sweet chestnut	
Scenario	NPV ha^{-1}	(rank)	NPV ha^{-1}	(rank)	NPV ha^{-1}	(rank)	NPV ha^{-1}	(rank)
1	330	(3)	424	(3)	960	(2)	543	(1)
1b	175	(5)	264	(5)	804	(4)	385	(3)
2	350	(2)	446	(2)	n/a	–	n/a	–
3	368	(1)	465	(1)	1078	(1)	n/a	–
4	–250	(7)	–102	(7)	492	(6)	32	(5)
5	–217	(6)	–67	(6)	597	(5)	108	(4)
Base/ unimproved	312	(4)	402	(4)	898	(3)	492	(2)

Scenarios marked n/a are those for which no work is being carried out in the MAFF programme.

Scenario 1, Simple Mass Selection; Scenario 1b, Simple Mass Selection plus containerized stock; Scenario 2, Simple Mass Selection plus progeny testing; Scenario 3, Simple Recurrent Selection; Scenario 4, Selection plus Mass Vegetative Propagation; Scenario 5, Mass Vegetative Propagation plus progeny testing.

per hectare, including the (base) case involving unimproved stock and these are also given in Table 2.

In all cases, the most attractive financial option for the grower appears to be to use seed from a Simple Recurrent Selection system (Scenario 3). The genetic gain from this system was estimated to be up to 32.6 per cent. The Simple Mass Selection system (Scenario 1) was also consistently highly ranked. This option gives the lowest total estimated genetic gain (up to 10.7 per cent), but no increased cost for planting stock is anticipated or included in the analysis. Estimated benefits per hectare to the grower from using material generated through these two improvement strategies (i.e. difference between the NPV of improved stock and the NPV of unimproved stock) range from £56 ha^{-1} to £180 ha^{-1} for Simple Recurrent Selection, and £18 ha^{-1} to £62 ha^{-1} for Simple Mass Selection (see Table 3).

Where progeny testing is used after Simple Mass Selection (Table 2, Scenario 2) the NPV is greater than that for Simple Mass Selection alone. This is directly related to the increased genetic gain that can be anticipated from progeny testing (gains of up to 22 per cent can be anticipated with a carefully controlled progeny testing programme after initial mass selection). Overall, progeny testing increases the NPV of ash by a further £20 ha^{-1} and of sycamore by a further £22 ha^{-1}.

Scenarios 4 and 5—namely those focused on the use of material produced by Mass Vegetative Propagation (MVP) techniques—consistently ranked lowest. The key reason for this lay in the estimated cost of the planting stock produced by MVP techniques. At present all the indications are that the cost of vegetatively propagated stock will be around 250 per cent of that for unimproved stock (R. Ogilvie, personal communication). The impact of this high extra early cost is very significant when cash flows are discounted, and in all cases, the increased revenue from the improved stock is not enough to compensate for the extra early cost, despite the relatively high genetic gains achieved. The effect is particularly marked in species with a relatively low overall timber value (ash and sycamore) and a longer rotation length than, for example, cherry. Progeny testing, despite giving increased genetic gains and hence increased NPVs, still did not make enough difference to outweigh the high early costs of MVP planting stock.

The use of containers (Scenario 1b) was also evaluated. The additional cost of containerized stock was 10p per plant, based on current differentials in nurseries. The use of containerized stock is claimed to have many advantages, but for this analysis only a reduction of 50 per cent in beating up costs was included. The outcome of the discounted cash flows indicated that, at this level of saving, the use of containers could not be directly justified on financial grounds alone.

Value to society

The total compounded tree improvement costs financed both by MAFF and other contributing organizations (mainly the Forestry Commission) are given in Table 4. These enable an estimation to be made of what it has, or will cost, to achieve a certain estimated genetic gain at today's prices. The 'break-even area' (Table 4) gives an indication of the minimum additional area of farm woodland that would need to be planted with genetically improved trees to cover the tree improvement work costs associated with each improvement strategy. This figure is derived simply by dividing the tree improvement work costs by the mean NPV per hectare. The different improvement scenarios were also ranked in terms of the 'break-even areas', with the smallest increase in planting area ranked highest. Where the NPV per hectare of the improved stock was negative (e.g. MVP scenarios involving ash and sycamore), a 'break even area' has not been calculated, because it is assumed that no rational decision maker would plant improved stock in such circumstances.

Looking at the cost-effectiveness of the tree improvement work as measured by the additional area that would have to be planted to cover these costs, it is evident that Simple Mass Selection is the most cost-effective way of achieving genetic gain. Simple Recurrent Selection (i.e. untested clonal seed orchards) ranks second, because of the relatively high costs of seed orchard development compared with a Simple Mass Selection or 'plus' tree selection programme. Simple Mass Selection plus Progeny Testing (Scenario 2) also ranks well in this analysis, even though the additional costs and time taken to carry out progeny tests are quite significant. Evidently the extra genetic gain obtained by incorporating an element of testing is justifiable purely on financial terms, although a greater additional area of improved stock planting would need to be planted to cover the costs of tree improvement work.

Estimates of seed orchard productivity

However, it is important to consider the likely productivity of seed orchards, if the benefits of the Simple Recurrent Selection scenario (Scenario 3), are to be fully evaluated. If accurate seed orchard production data were available, then the number of years of seed production required to cover research and development costs could be estimated. However, there is little data available to assist with this evaluation because no seed orchards of any of the three species in question (ash, sycamore and wild cherry) exist in the UK. Nevertheless, estimates can be made of seed production from orchards (C. Cahalan, personal communication; R. Jinks, personal communication) (see Table 5). Although the mass of seeds produced per hectare of seed orchard is estimated to be the same (40 kg ha^{-1}), seed of different species weighs differently, so the total number of seeds produced per hectare of seed orchard will vary. Because only a certain percentage of seeds germinate to produce seedlings (Gordon, 1992), a figure is also given for the estimated annual seedling production per hectare of seed orchard

Table 4: Total research costs (6% compound/discount rate) and the 'break-even' areas of planting

	Ash			Sycamore			Wild cherry			Sweet chestnut		
Scenario	Total research costs	Hectares new planting	(rank)	Total research costs	Hectares new planting	(rank)	Total research costs	Hectares new planting	(rank)	Total research costs	Hectares new planting	(rank)
1	223 694	677	(1)	187 818	443	(1)	154 749	161	(1)	187 818	346	(1)
1b	368 333	2110	(3)	309 259	1172	(2)	283 764	353	(3)	309 259	803	(2)
2	1 535 670	4386	(4)	1 289 378	2892	(4)	n/a	n/a	–	n/a	n/a	–
3	656 623	1784	(2)	656 623	1411	(3)	320 117	297	(2)	n/a	n/a	–
4	817 369	*	*	445 923	*	*	1 104 703	2245	(4)	445 923	13 768	(4)
5	1 743 853	*	*	1 027 603	*	*	2 620 427	4389	(5)	1 027 603	9 500	(3)

* The outcome of the scenarios is a negative NPV—therefore they are assumed not to be a planting option.

Scenario 1, Simple Mass Selection; Scenario 1b, Simple Mass Selection plus containerized stock; Scenario 2, Simple Mass Selection plus progeny testing; Scenario 3, Simple Recurrent Selection; Scenario 4, Selection plus Mass Vegetative Propagation; Scenario 5, Mass Vegetative Propagation plus progeny testing.

Table 5: Estimated annual seed and seedling production from broadleaved seed orchards

Species	Estimated seed production (kg ha^{-1})	No. of seeds ha^{-1} total	No. of seedlings produced	Hectares planted @ 2000 trees ha^{-1}
Ash	40	500 000	300 000	150
Sycamore	40	350 000	150 000	75
Cherry	40	200 000	80 000	40

and the approximate total area per year which could be planted with these seedlings at recommended UK stocking densities (Anon., 1994).

Within the MAFF project, work towards the development of ash and sycamore seed orchards has been carefully considered by the Forestry Commission (A. Fletcher, personal communication), whereas proposals for establishment of wild cherry seed orchards are still in their early stages. Therefore, provisional conclusions are drawn only on ash and sycamore seed orchard productivity at this stage. Thus, Table 6 gives an indication of the number of hectares of ash and sycamore planting needed, given NPVs calculated in Scenario 3, to cover the estimated total cost of the seed orchard establishment and maintenance programme proposed by the Forestry Commission (A. Fletcher, personal communication). The figures include an allowance for the fact that ash flowers only once every 3–5 years on average, while sycamore flowers once every 1–3 years, reducing seed orchard productivity per unit area to 25 per cent and 50 per cent of its potential, respectively.

The total area per year of planting possible from the proposed ash and sycamore seed orchard programmes are below the current annual UK planting levels for both species (estimated at 1250 ha a^{-1} for ash, and 830 ha a^{-1} for sycamore), but it can be concluded that, if the proposed programmes were to go ahead, a significant area could be planted with the new improved stock. With the minimum estimated productive lifetime of a broadleaved seed orchard being an average of 25 years, then a minimum of 11 250 ha each of improved ash and sycamore could be planted.

Impact of the discount rate

The discount rate used is also likely to have a significant impact on the results obtained in long-term projects such as tree improvement. A 6 per cent rate was selected for the main analysis, as recommended in the Green Book (HMSO, 1991). However, all simulations were also run at 3 per cent and 9 per cent rates to show sensitivity to changes in this parameter. The results are illustrated in Figure 2 for all the improvement strategies in respect of ash.

Reducing the discount rate to 3 per cent has a marked impact on NPV results, and a lesser impact on the cost-effectiveness of different improvement scenarios. The NPVs of all scenarios become positive at the lower discount rate and the 'base', or unimproved scenario, is relegated to bottom ranking for all scenarios and all species. The impact of the high early costs of planting stock from the MVP scenarios is greatly reduced and, in fact, the MVP scenarios involving cherry—the species with the high-

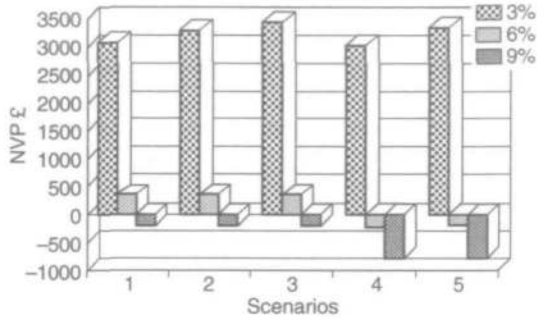

Figure 2. The NPV of ash, expressed in £ ha^{-1}, for the five different improvement strategies in Table 1 at 3, 6 and 9% discount rates. See Figure 1 for explanation of scenarios.

est timber value, now have the highest NPV of all, because of the much greater genetic gain associated with MVP techniques. Significantly, traditional private investment in forestry suggests that many growers use a discount rate closer to 3 per cent than 6 per cent (Kula, 1988). As a result, growers may be more prone than suggested to consider the use of MVP stock, in anticipation of the greater returns from a superior yield at the end of a rotation.

At a 9 per cent discount rate, the NPV per hectare in all scenarios and all species is negative, indicating that investment in tree planting is not a sensible option. Even the unimproved scenarios now result in a negative NPV, implying that no rational grower would plant trees for purely financial reasons.

In respect of the cost-effectiveness of the tree improvement work, as measured by the 'break-even' areas, reducing the discount rate had less impact. At a 3 per cent rate, the number of hectares of additional planting needed to cover tree improvement work expenditure was reduced in all scenarios and all species to less than one year's planting at current rates. On the other hand, at 9 per cent the tree improvement work would presumably not be justified, because all NPVs were negative. However, changing the discount rate did not affect the ranking of the improvement strategies with Simple Mass Selection and Simple Recurrent Selection remaining the most cost-effective. The lesser impact of changes in the discount rate on the ranking of improvement strategies from the perspective of the social returns ('value for money') was a result of the shorter timescale of the tree improvement work programmes compared with the timber rotations considered. The maximum time lapse between commencement of tree improvement work and first commercial release was projected to be 29 years, whereas the shortest timber rotation considered was 70 years.

Discussion

In terms of potential gains to growers, measured in terms of an increase in NPV of timber crops, the CBA analysis indicated that Simple Mass Selection and Simple Recurrent Selection breeding strategies were the most cost-effective of those considered. Planting stock sourced from a Simple Mass Selection programme was estimated to increase the NPV of a broadleaved timber crop by 5–10 per cent (£38 ha^{-1}), whereas the comparable figure for a Simple Recurrent Selection programme was 15–20 per cent (£100 ha^{-1}). Cherry produced both the highest NPV, and greatest increase in NPV relative to unimproved stock, in both scenarios.

In terms of the cost-effectiveness of the tree improvement work, as measured by the additional area of improved stock that would have to be planted to recoup the costs of an improvement programme, Simple Mass Selection ranked highest. Only one year of planting of improved stock produced by the programme, at current UK levels of planting, was apparently needed to justify the costs of tree improvement work. This is in line with previous suggestions that only a relatively small genetic gain is needed to justify basic tree improvement work (McKenney *et al.*, 1989; Porterfield *et al.*, 1975). Simple Recurrent Selection (i.e. the development of untested clonal seed orchards) was also confirmed as a cost-effective method of achieving genetic gain. Although the establishment and maintenance of seed orchards was projected to have a significant capital cost (estimated at between £22 780 ha^{-1} and £35 000 ha^{-1}), it is estimated that within 3 years of ash and sycamore seed production commencing under a recommended FC orchard development strategy, tree improvement costs would be justified.

Scenarios involving MVP to achieve genetic gain consistently ranked lowest in the analysis, whether measured in terms of NPV per hectare or the cost-effectiveness of the tree improvement work. These results closely mirror those of McKenney *et al.* (1989) with black spruce. The key reason lies in the fact that the estimated cost of planting stock produced by MVP is much higher than stock produced from seed. Because a high proportion of the costs of production of MVP stock is borne by the nursery rather than seed producers and collectors as with Simple Mass Selection and Simple Recurrent Selection, there is little doubt that these costs will have to be passed directly on to the customer. This has occurred in the case of 'Super Sitka' (Lee, 1992). As a result, MVP is particularly difficult to justify with ash and sycamore. These species have the lowest average timber values of the four species under consideration, and a significant increase in the costs of planting stock results in negative NPVs, despite high genetic gains.

The additional area which would be required to be planted to cover tree improvement costs varies considerably with the breeding strategy chosen. In general, the estimated required areas appear relatively low compared with current rates of new planting. It is estimated that approximately 1250 new ha of ash are currently being planted annually, 830 ha each of sycamore and wild cherry, and 415 ha of sweet chestnut (Palmer *et al.*, 1996). This suggests that the tree improvement expenditure may be justified, with the marked exception of the MVP work on ash and sycamore. The time required for MVP work on sweet chestnut to be matched by planting effort is also projected to be relatively long (19–26 years), because of the limited areas of this species currently being planted. However, as the NPV calculations indicate, investment decisions that are carefully considered will not result in the planting of improved stock until the price of that stock can be reduced, or farmers are given sufficient financial incentives in the form of grants to plant the stock.

The minimum estimated productive lifetime of a broadleaved seed orchard is 15–30 years, so the establishment of seed orchards as planned in Scenario 3 would eventually be highly rewarding in terms of increased quality timber output from improved planting stock. In theory, in a long-term tree improvement programme, new orchards will continually be being established as selection and testing progresses, so genetic gain is cumulative. Work towards the establishment of a clonal seed orchard for wild cherry is progressing, but is less readily assessable because of the very limited area of seed orchard being proposed within the MAFF project (K. Russell, personal communication).

Assumptions made and possible sources of error

These findings must clearly be viewed with caution because of the assumptions made in the analysis, and the possible sources of error. First, it must be emphasized that many of the individual tree improvement activities undertaken in this programme were not conceived as being part of integrated breeding strategies. The allocation of tree improvement projects (and their respective costs) to different strategy options was undertaken to enable these options to be compared in the CBA analysis. Furthermore, the achievement of genetic gain was not stated as an explicit objective in the majority of the tree improvement projects included, despite its central importance in traditional approaches to tree improvement.

Second, the magnitude of genetic gain achieved within any specific tree improvement activity will clearly vary depending on the selection intensity, the heritability of the trait being selected for and the efficiency of the experimental approaches adopted. For example, Cornelius (1994a), who reviewed results from 67 published papers describing the results of progeny tests (principally describing trials undertaken with conifers), concluded that for all traits assessed except specific gravity, narrow-sense heritability is usually less than 0.4 and most frequently in the range 0.1–0.3. In the case of specific gravity, heritability is almost always above 0.3, and usually in the range 0.2–0.7. Similar comments apply to the efficacy of 'plus' tree selection, which underpins all of the scenarios considered here. Cornelius (1994b) reviewed 24 published reports of different tree improvement trials, which indicated that gains of up to 15 per cent in height and diameter growth and of up to 35 per cent in volume per unit area can be achieved through 'plus' tree selection. However, as emphasized by Cornelius (1994b), the amount of gain from any 'plus' tree selection depends on the values of the parameters that determine the response to selection (selection intensity, heritability) and, in unfavourable situations, the gain could be close to zero.

Third, although non-zero probabilities of positive genetic gain were assumed in the analyses, it must be emphasized that there is no guarantee that any genetic gain will be actually achieved as a result of the current tree improvement programme, which is still on-going. The achievement of genetic gain is dependent on the breeding strategy being designed and executed properly, enabling heritabilities to be accurately estimated, and selections to be made effectively. Also, selections on growth and form parameters in forest trees are routinely made at around half rotation age (at least 15–20 years in the species involved in this programme). A firmer basis for genetic gain estimates awaits such results from field trials, which will not be available for some years.

Fourth, the potential gains in productivity which may be achieved with genetically superior planting stock will only be realized with appropriate establishment and maintenance techniques. It is assumed in the current analysis that all the improved material produced by this tree improvement programme will be planted and managed for timber production. However, there is little evidence to suggest that current broadleaved plantings have timber production as a primary objective (e.g. Crabtree, 1996), although those organizations funding the tree improvement work are apparently hopeful that more profitable timber production will underpin other objectives for planting broadleaved trees. The deployment of genetically superior material could have indirect benefits other than improved quality/quantity of the product, such as lower establishment/maintenance costs (e.g. weed control, fencing, pruning), or higher survival (e.g. through enhanced pest and disease resistance). These aspects were not explicitly addressed in the analysis.

Finally, as noted earlier, other critical assumptions included the use of current timber values and maximized current grant incomes, discount rates of 3–9 per cent and a normally distributed timber yield. The results of the CBA should clearly be viewed within the context of these assumptions and their intrinsic degree of error. Similarly, the benefit of genetic improvement was expressed in terms of the percentage increase in yield of higher quality timber. To what extent this is achieved in practice will depend partly on the traits being selected for in the tree improvement programme. The analysis carried out is based specifically on selection for improved form, and therefore increased proportions of the timber crop achieving veneer or Grade 1 quality. Growth may well be positively correlated with tree form, so the impact of the genetic gain achieved could well be underestimated in this analysis. In addition, timber properties (such as wood density and the absence of defects such as blackheart in ash, green vein in cherry and shake in chestnut) and resistance to pests and diseases (such as canker and black fly in cherry) may also need to be included as traits for selection. The extent to which these traits will actually be selected for in the operational programme will vary with the species and scenario adopted.

UK hardwood planting rates and sources of planting stock

The cost-effectiveness of tree improvement work depends critically on the areas to be planted. In recent years, there has been a significant increase in the areas of broadleaves planted, coinciding with improved incentives being made available under WGS and the FWPS. In the past six planting seasons an annual area of approaching 14 000 ha has been planted with broadleaves including restocking and new planting on Forest Enterprise sites (Forestry Commission, 1996). If grown for timber, broadleaved crops can be anticipated to produce 150–200 t ha^{-1} of quality timber at the end of a rotation. Planting at this level could therefore be expected to produce an average of 2.1–2.8 Mt a^{-1}, enough to supply the UK market.

Almost all planting stock used in Britain is sourced from UK nurseries. It is estimated that British nurseries produce over 25 million broadleaved transplants per year (Cahalan *et al.*, unpublished MAFF report 1995). Also, almost all broadleaved stock is produced in the form of transplants grown from seed in the nurseries. Only willows and poplars are regularly produced by vegetative propagation. Traditionally, nurseries have obtained their seed from a number of sources, both UK and imported. At present, seed from only two broadleaved species, oak and beech, is obtained from registered seed stands (i.e. trees which meet a certain minimum quality, as set by the Forestry Commission or similar registering organizations in other countries). Seed from all other species can be sourced from any quality of tree and imported from any country with few restrictions This implies that much of the planting stock currently deployed is likely to be of varying genetic quality and may be poorly adapted to the sites being planted.

Therefore, there is apparently good justification for a UK broadleaved tree improvement programme, such as that described in this investigation. In particular, there appears to be a strong, continuing demand for high quality broadleaved timber in the UK, a nursery sector already producing up to 25 million broadleaved transplants a year and a widespread acknowledgement that seedlings currently being planted are unlikely to produce the quality material in demand from the sawmilling sector because of either their poor, or inappropriate, genetic make-up. Based on the results of this CBA, growers would be advised to opt for planting stock which has been sourced from an approved seed orchard programme and has been well-screened via a series of progeny and provenance tests. Unfortunately, this option is not currently available to timber growers in the UK, so the best alternative is to source planting stock from certified stock or from a recognized 'plus tree' selection programme of known suitable provenance, if available.

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