Cost-benefit analysis of tree improvement in Ireland

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Abstract

The use of genetically improved trees usually results in better returns due to one or more of the following responses: higher growth rates, better timber quality and higher rates of carbon sequestration. Tree improvement is expensive, so it is important that available scarce resources are spent wisely. To this end, cost-benefit analysis (CBA), using the net present value approach, was used in this study to assess tree improvement investment possibilities for a large number of species of potential interest to Irish forestry, assuming that a 15% gain could be achieved and the costs of improvement were similar for all species. The CBA results showed that the conifer species with the greatest potential were (in order): (1) Sitka spruce and Douglas fir; (2) hybrid larch and Norway spruce; (3) Scots pine; and (4) lodgepole pine. The ranking for the broadleaved species were: (1) Eucalyptus; (2) ash; (3) red oak and sycamore. When issues such as availability of material from other programmes abroad, biological constraints (e.g. disease vulnerability, breeding and propagation problems), and the potential usage of species in a planting programme are also considered, the establishment of new breeding programmes are difficult to justify for most species, with the exception of Sitka spruce. The best approach for most species is to establish seed stands or seed orchards (with untested, or if available, tested material) to provide material for planting, but for some species it may also be possible to secure material from improvement programmes abroad.

Keywords: *Net present value, tested nursery material, breeding programme.*

Introduction

The reproductive material (seed, planting stock, etc.) used in afforestation and reforestation in Ireland must come from approved sources. The current regulations on the use of reproductive material, such as the EU Directive on Marketing of Forest Reproductive Material (FRM), provides for the identification of seed, with traceability from collection to production. Although these measures help safeguard the genetic quality of the material used, there is no requirement that only improved material should be planted, so there is a tendency to use the cheapest (often lowest quality) material that is permissible.

The EU FRM classifies reproductive material as (i) Source Identified, (ii) Selected, (iii) Qualified and (iv) Tested. The Source Identified category only confirms that the material has been collected from stands within a single seed zone (provenance). The Selected category refers to material from stands that appear superior (phenotypically).

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The Qualified category refers to material derived from seed orchards that have been established with phenotypically superior individuals. The amount of improvement that both the Selected and Qualified categories deliver is unknown because phenotypic superiority can be due to either environmental or genetic factors. For example, work in Scotland with Scots pine[1] showed that seed from a seed orchard containing phenotypically selected material (which would be considered as Qualified under the FRM Directive) provided a 2% increase in harvestable volume compared to seed from seed stands (Source Identified) (Gill 1983). However, if the parent trees in the seed orchard had been tested and only the genetically superior individuals had been retained in the orchard, a 10% increase in harvestable volume could be expected. Genetic improvement can only be guaranteed through the use of Tested material, which involves implementing a breeding programme, which is expensive.

Forest trees generally have a high degree of intraspecific variation for commercially important traits, but the amount of genetic control is low in some species, making improvement costly and inefficient. Furthermore, it is more difficult to justify an improvement programme for a species that has a long rotation because the payback is delayed (thus incurring higher costs). The first step in a tree improvement programme is to determine the best provenance, a step that has been completed for most tree species in Ireland (but climate change concerns may bring this into question for some species). Provenance selection may be the final step in the improvement process for some species, mainly because further returns on any investment are likely to be low (or even negative). In other species however, it may be economically worthwhile to select phenotypically superior plus trees and use them to establish seed stands or seed production areas. It may be difficult to justify going to the next step, which involves the evaluation (i.e. progeny testing) of these plus trees to determine their genetic worth. While a breeding programme may be difficult to justify for many species, the establishment of untested seed orchards may deliver sufficient gains, assuming that heritability is high enough to support the investment.

The use of genetically improved planting stock results in permanent changes in the growth and/or quality of trees. Improved trees are also likely to sequester carbon more quickly than unimproved material because they grow faster. Tree improvement efforts in Ireland have been underway since about the 1950s, with most of the early work focussing on provenance testing of conifers (Fennessy et al. 2012). Improvement work in later years was devoted to Sitka spruce, such that a relatively advanced programme is now in place for this species (Thompson 2013). There is a more limited improvement programme for other conifers, such as lodgepole pine and Scots pine. Much of the broadleaved tree improvement efforts commenced about 20-30 years ago. Coillte (the state-owned forestry company in Ireland) selected phenotypically

[1] See Table 1 for the botanical names of all species.

superior ash, oak, sycamore and cherry trees, which were established in gene banks and in an untested seed orchard near Ballyhea, Co. Cork (Fennessy et al. 2012). Teagasc (Agriculture and Food Development Authority in Ireland) commenced a birch improvement programme, establishing two seed orchards with phenotypically selected, untested material (O'Connor 2007). Teagasc have also established an untested alder seed orchard (O'Connor 2011).

Investment in tree improvement has resulted in increased forest productivity in Ireland (Fennessy et al. 2012, Thompson 2013). For example, improved Sitka spruce will on average result in at least one yield class (YC) improvement over unimproved Washington material in Ireland, equating with a 2010 value of €987 ha^{-1} (Phillips and Thompson 2010). However, rotation length has a large impact on the net present cost[2] of improvement, so the returns from improvement efforts are lower for some species, especially broadleaves. In addition, some species have complex inheritance patterns, making improvement strategies difficult to apply. Genetic gain estimates have not been calculated for most tree species in Ireland, but the results for Sitka spruce were similar to those achieved in the UK (a 15% increase in height growth, a 7% improvement in stem form and no significant loss in wood density). The expected gains for other species are likely to mirror those estimated elsewhere for the same species (but most often for a different provenance).

Background and objectives

With the exception of Sitka spruce (Pfeifer 1988, Phillips and Thompson 2010), no cost-benefit analysis (CBA) has been carried out on tree improvement programmes in Ireland. The decision as to whether or not improvement effort can be justified will depend far more on factors such as the inherent productivity of species, the likely availability of suitable sites for planting and rotation length, than on the costs of tree improvement.

All CBA methods have advantages and disadvantages, but the most widely used method is the net present value (NPV) approach (Anonymous 2011). The CBA approach used in this study focussed primarily in assessing the potential for improving a wide range of species of interest to Irish forestry. The NPV is the sum of discounted revenues minus discounted costs. The NPV method was used as it allows the ranking of project outcomes. In addition, the probable future use of the species was considered in the light of various issues, including the potential suitability (e.g. likely soil types), the inherent productivity of the species, estimated impact on the area planted for reforestation and afforestation and the inherent productivity of the species. It was assumed that a 15% gain in productivity could be achieved through tree improvement. The costs of improvement in this study were considered the same for

[2] See next section for explanation.

all species and were based on Coillte's information on file for Sitka spruce. The CBA was used to rank species, after which the optimal tree improvement strategy for those that ranked highest was considered, taking into consideration practical constraints and other issues (e.g. availability of improved material from programmes abroad, ease of breeding, disease issues, ease of propagation, disease threats etc.).

Materials and methods

NPV in CBA of forest genetics can be summarised using the following formula (Ahtikoski 2000):

$$NPV = \sum_{t_1}^{T_1} B_t^{diff} + (D_p)^t - \left[\sum_{t_2}^{T_2} C_t^{es} + (D_P)^t + \sum_{t_3}^{T_3} C_t^{diff} + (D_P)^t\right] \quad (1)$$

Where B^{diff} = Differential benefits i.e. increase in growth rate, volume outturn or timber quality; C^{es} = Cost of establishing the tree breeding programme, seed orchards etc.; Differential cost of improved material, i.e. annual management and administration was calculated as: $D_P = (1 + \frac{p}{100})^{-1}$ i.e. a discount factor with percentage rate p.

In the proposed framework, a time horizon of one rotation was assumed. The length of the rotation varied with species.

Costs

The additional costs arising out of the new research needed to deliver the predicted 15% gain and the subsequent management and administration costs were included. Based on the estimated costs of the improved Sitka spruce Washington provenance developed by Coillte and its predecessor the Forest and Wildlife Service, over the last 35 years, the investment cost of a tree improvement programme per species was €2.5 million over a 15-20 year period. The costs of grant aid for planting, road construction and other forestry support schemes were assumed to be the same whether improved or unimproved planting material was used. Similarly, the costs to the forest owners of maintenance, insurance, on-going management, a proportion of roading costs and reforestation following clearfell were not considered as these are incurred irrespective of whether improved or unimproved material is used.

Benefits

The categories of benefits considered were timber (including thinnings) and carbon sequestration. Other benefits (e.g. biodiversity, landscape enhancement) were excluded because of the paucity of data for all species. The impact on water quality was considered neutral on the basis that future planting complies with environmental guidelines and forestry measures under the Water Framework Directive.

The increase in timber volume yield arising from the use of the improved planting stock was the main benefit considered. A default increase of 15% was used, based on an average YC for each species. Estimates of volume increase were based on Forestry Commission yield models (Edwards and Christie 1981) rather than the Irish GrowFor dynamic models, mainly because GrowFor can only be applied to relatively few species and initial stand data input parameters are required (McCullagh et al. 2013). The additional carbon sequestered in the main stem was estimated from the volume increase data (Hawkins et al. 2012).

In calculating the impact on volume production, an average rotation length and YC was allocated to each species. Yield class, a measure of forest productivity, is the timber volume (m^3 ha^{-1} yr^{-1}) that the forest crop will produce on average over the rotation. The thinning and clearfell volumes over the assumed rotation were then discounted (5%) to present values and multiplied by 0.15 to provide the additional discounted volume (DV) attributable to the improved planting material. Forestry Commission yield tables were used to estimate volumes and where an appropriate model was not available, the most suitable substitute was used, in line with the routine protocol adopted in the private sector roundwood forecast (Phillips et al. 2009). The discounted volume multiplied by the average price for the particular species provided an estimate of the increase in NPV per hectare. The main difficulty in carrying out this task was the scarcity of reliable price information on conifer species, other than spruce, and the absence of any dependable information for broadleaved species. To overcome this, the average price for standing conifer sales by Coillte over the past 10 years was used as a baseline. For broadleaves there was little reliable information, so an estimate was made based on a combination of UK prices (Pryor and Jackson 2001) and anecdotal information on prices achieved in Ireland. Species that provide a wide range of timber and timber products, and those species with higher value timber products, had their timber price increased relative to the baseline in the absence of species-specific information. Likewise species with limited timber end uses and lower value timber products had their timber price reduced relative to the baseline.

Analysis process

A six-step process was followed in this analysis, as described below.

1. The species eligibility for planting was determined, based on the current list of approved species for grant aid under the current afforestation schemes as issued by the Forest Service. Species were categorised as: (a) approved (grant aided), (b) delisted (no longer supported; e.g. Japanese larch and ash), (c) tolerated (cannot be planted in pure blocks; e.g. birch), and (d) unapproved. A total of 47 species were considered.

2. The potential for using eligible species in reforestation and afforestation was estimated. The potential for species use in reforestation was estimated through

a combination of (a) range of soil types suited to the species, (b) existing planted area based on the National Forest Inventory (NFI) (Anonymous 2007) and (c) percentage area of suitable soil types in the forest estate. The range of suitable soil types was taken from Horgan et al. (2004). There was some subjectivity involved in this approach.

3. The potential to increase roundwood volume was assessed and was based on a combination of (a) the estimated impact on the area planted for reforestation and afforestation and (b) the inherent productivity of the species.

4. The increase in timber value from improved material was calculated. The potential increase in value was expressed in terms of NPV (€ ha^{-1}), assuming an average 15% increase in volume production.

5. Carbon sequestration was the only non-timber benefit included. A long-term price of €22 t^{-1} CO_2 was used in the sensitivity analysis (Phillips 2006).

6. The analysis to this point (steps 1 to 5) revealed that a number of species showed potential for improvement. Only those top-ranking species were considered further in this step. The other issues considered included the availability of material from other programmes abroad, biological constraints such as disease vulnerability, breeding and propagation issues.

Results

Suitability for planting, potential impact on roundwood production and timber value

Some species (e.g. Sitka spruce, Norway spruce, lodgepole pine) had a high potential for planting on many sites, others had more limited potential (e.g. Corsican pine, Monterey pine, *Eucalyptus nitens*, and rowan), while other species had little potential (e.g. hornbeam, lime, Macedonian pine) (Table 1).

Sitka spruce, Norway spruce, lodgepole pine, sycamore and oak were found to have the greatest potential to contribute to future roundwood volumes (Table 2). Other minor species, such as southern beech, hornbeam, lime and poplar, were considered unlikely to make a significant impact on future overall woodflows, given the low rates of planting.

The estimated net gain in NPV per hectare varied considerably for each species (Table 2). Sitka spruce (€629), Douglas fir (€615), western hemlock (€554), western red cedar (€516), hybrid larch (€504) and Norway spruce (€500) provided the highest returns. There was a longer list of species that provided more intermediate returns, which included ash (€429), the two lodgepole pine subspecies (ca. €350), sycamore (€341) and the three oak species (ca. €300). Many species yielded returns below €250, which included common alder (€214) and birch (€138). Because of the paucity of data, it was not possible to calculate reliable estimates for several species.

Proposed tree improvement approaches

The CBA (previous section) showed that some species provided similar returns (e.g. Sitka spruce and Douglas fir), in which case they were given equal ranking in the next CBA step.

The conifer species with greatest potential were:

(1) Sitka spruce and Douglas fir;

(2) hybrid larch and Norway spruce;

(3) Scots pine; and

(4) lodgepole pine.

The broadleaved species were ranked as follows:

(5) eucalyptus;

(6) ash;

(7) red oak and sycamore.

Beech and birch did not rank highly, but may have potential for improvement.

The current status of the tree improvement programme for the species that ranked highest is shown in Table 3. Currently Sitka spruce, Scots pine and lodgepole pine are the only species for which tested material is available. However, the amount of improved seed available is limited, especially for lodgepole pine. In most other cases no improvement has been carried out (e.g. Douglas fir), or plus tree selection is already underway. Progeny testing is underway for ash and Scots pine, but no tested material is available.

The recommended improvement approach for the ranked species is shown in Table 4. Tested material, that may be suitable for use in Ireland, may also be available in the market outside Ireland, so this option is suggested for Douglas fir and red oak. Sitka spruce is the only species that clearly warrants investment in a breeding programme. Norway spruce also showed potential for improvement. However, all current planting stock of Norway spruce is derived from seed collected from a single seed orchard in Denmark, which may provide improvement, but there is no information to confirm this.

The seed orchard option assumes that selection and testing must be done first, with exception of lodgepole pine where selection and testing has been completed (Table 4). In sycamore, selections have been made, but testing has not been initiated. The most promising broadleaved species for improvement are relatively minor components of the current national planting programme, so improvement options are limited, and ash has been delisted due to the dieback disease *(Chalara fraxinea)*.

Table 1: *Eligible species and potential of their use in afforestation / reforestation in Ireland (Horgan et al. 2004).*

				Soil type[c]																
Species		**FS[a]**	**Area[b]**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**
Alder, common	*Alnus glutinosa* (L.) Gaertn.	A	11.50																	
grey	*Alnus incana* (L.) Moench	N	n/a																	
Italian	*Alnus cordata* Desf.	N	n/a																	
Ash, common	*Fraxinus excelsior* L.	D	19.16																	
Beech, European	*Fagus sylvatica* L.	A	8.71																	
southern	*Nothofagus procera* (Poepp. & Endl.) Oerst.	A	0.14																	
Birch, downey	*Betula pubescens* Ehrh.	T	15.49																	
silver	*Betula pendula* Roth	T	14.20																	
Cherry, wild	*Prunus avium* L.	A	0.24																	
Chestnut, Spanish	*Castanea sativa* Mill.	A	0.20																	
Eucalyptus, nitens	*Eucalyptus nitens* (De & Ma) Ma	N	-																	
Hornbeam, common	*Carpinus betula* L.	N	0.50																	
Lime, common	*Tilia x europaea* L.	A	0.23																	
Maple, Norway	*Acer platanoides* L.	A	0.16																	
Oak, pedunculate	*Quercus robur* L.	A	7.34																	
red	*Quercus rubra* L.	T	-																	
sessile	*Quercus petraea* (Matt.) Leibl.	A	7.30																	
Poplar, black	*Populus nigra* L.	N	0.35																	
white	*Populus alba* L.	N	0.01																	
Rowan	*Sorbus aucuparia* L.	T	4.80																	
Sycamore	*Acer pseudoplatanus* L.	A	8.06																	
Willow, goat	*Salix caprea* L.	N	14.26																	
other	*Salix* spp.	N	17.96																	
Cypress, Lawson	*Chamaecyparis lawsoniana* (Murr.) Parlatore	A	0.41	x																
Leyland	*xCupressocyparis leylandii* (Jacks. & Dallim.)	A	-																	
Monterey	*Hesperocyparis macrocarpa* (Hartw.) Bartel	A	-																	
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco	A	10.20																	
Fir, grand	*Abies grandis* Lindl.	A	0.54	x																

noble	*Abies procera* Rehd.	A	2.60																	
silver	*Abies alba* Mill.	N	0.27																	
Hemlock, western	*Tsuga heterophylla* (Raf.) Sarg.	N	0.54																	
Larch, European	*Larix decidua* Mill.	A	0.53	x																
hybrid	*Larix x eurolepsis* Henry	A	n/a	x																
Japanese	*Larix kaempferi* (Lamb.) Carr.	A	21.51	x																
Pine, Austrian	*Pinus nigra* Arnold ssp. *nigra*	D	0.26	x	x															
Corsican	*Pinus nigra* ssp. *maritima* (Ait.) Melville	A	-	x	x		x													
lodgepole N.C.	*Pinus contorta* Dougl. ssp. *contorta*	A	12.69																	
lodgepole S.C.	*Pinus contorta* Dougl. ssp. *latifolia* Wats.	A	46.41																	
Macedonian	*Pinus peuce* Griseb.	A	n/a	x	x	x	x	x					x	x		x				
Monterey	*Pinus radiata* D. Don	N	0.23																	
Scots	*Pinus sylevestris* L.	A	7.34	x																
Redwood, coastal	*Sequoia sempervirens* (D. Don) End.	A	0.03	x																
Spruce, Norway	*Picea abies* (L.) Karst.	A	25.96																	
Serbian	*Picea omorika* (Pancic) Purkyne	A	-																	
Sitka	*Picea sitchensis* (Bong.) Carr.	A	327.83																	
Thuja, western red cedar	*Thuja plicata* D. Don	A	0.03																	
Yew, Irish	*Taxus baccata* L.	N	0.04																	
	Total Forest area		625.75																	
	% Forest area			2	13	1	3	4	3	1	3	2	12	9	3	11	20	1	11	1

The colours indicate the range in potential productivity: excellent (dark green), very good (light green), good (yellow), poor (dark orange) and very poor (red).

[a] Approved by Forest Service: A, approved; N, not approved; T, tolerated; and D, delisted. Species predisposed to coarse growth, poor form, instability or butt rot by the excessively favourable growing conditions and /or high pH provided under on particular soil types are indicated (x).

[b] Area under forest cover.

[c] Soil types listed are as follows: A. Alkaline brown earths and free draining, deep grey brown podzolics. B. Acid brown earth and brown podzolics. C. Rendzinas/ shallow brown earths/ shallow grey brown podzolics. D. Podsols/ peaty podsols ± weakly developed iron pan. E. Indurated iron pan podsol (organic layer or furze present). F. Indurated iron pan podsol (scrawed with heather). G. Peaty podsolized gleys (fertility class C) – organic layer present. H. Peaty podsolized gleys (fertility class C) – scrawed. I. Lithosols. J. Gleys/ peaty gleys (mottled profile) and grey-brown podsolics (fertility class A or B). K. Gleys/ peaty gleys (blue/ grey or yellow profile) (fertility class B). Gleys/ peaty gleys (fertility class C). M. Flushed and/or reclaimed blanket peat. N. Unflushed blanket peats and intact raised bogs. O. Cutaway blanket bogs (milled peat). P. Cutaway raised bogs (milled peat) post 1980 and fen peats. Q. Cutaway raised bogs (hand or machine sod) pre 1980.

Table 2: *Potential impact of species on predicted future roundwood volumes and estimated increase in timber value (€ ha^{-1}) from tree improvement.*

Species		Reforestation potential	Afforestation potential	YC range (m^3 ha^{-1} yr^{-1})	Mean YC (m^3 ha^{-1} yr^{-1})	Mean rotation (yrs)	Discounted vol. (m^3)	Price relativity	Average price (€)	NPV benefit (€ ha^{-1})	AE benefit (€ ha^{-1} yr^{-1})
Alder	common			4-10	8	45	9.7	0.60	22	214.45	12
	grey			4-10	8	45	9.7		NA	NA	NA
	Italian			4-10	8	45	9.7		NA	NA	NA
Ash	common	D	D	4-12	8	45	9.7	1.20	44	428.90	24
Beech	European			4-10	6	90	2.9	1.00	37	105.45	5
	southern			10-18	14	49	18.2		NA	NA	NA
Birch	downey		T	4-10	6	55	6.2	0.60	22	138.31	7
	silver		T	4-10	6	55	6.2	0.60	22	138.31	7
Cherry	wild			6-12	8	55	9.2		NA	NA	NA
Chestnut	Spanish			4-12	8	60	5.9		NA	NA	NA
Eucalyptus	nitens			20-36	26	15	27.7		NA	NA	NA
Hornbeam	common			4-10	6	90	2.9	0.90	33	94.91	5
Lime	common			4-10	6	90	2.9	0.90	33	94.91	5
Maple	Norway			4-10	6	55	6.2	0.90	33	207.46	11
Oak	pedunculate			4-10	6	85	4.1	1.20	44	183.37	9
	red		T	4-14	8	75	5.6	0.90	33	186.15	10
	sessile			4-10	6	85	4.1	1.20	44	183.37	9
Poplar	black			4-12	8	40	9.7	0.75	28	270.01	16
	white			4-10	8	40	9.7	0.75	28	269.73	16
Rowan			T	4-8	6	55	6.2		NA	NA	NA
Sycamore				4-12	8	55	9.2	1.00	37	340.77	18
Willow	goat			4-8	6	40	6.7	0.60	22	148.30	9
	other			4-12	6	40	6.7	0.60	22	148.30	9
Cypress	western red cedar			8-22	16	55	13.8	1.10	37	515.75	28
	Lawson			8-20	16	55	13.8		NA	NA	NA
	Leyland			8-22	16	55	13.8		NA	NA	NA
	Monterey			6-18	14	55	11.3		NA	NA	NA
Douglas fir				8-26	16	50	16.4	1.10	37	614.86	34
Fir	grand			8-32	18	45	17.8	0.60	20	363.73	20
	noble			8-24	16	50	13.6	0.70	24	322.73	18
	silver			8-24	16	50	13.6	0.70	24	322.73	18
Hemlock	western			8-24	18	45	18.1	0.90	31	554.17	31
Larch	European			4-12	8	45	8.3	1.00	34	280.50	16
	hybrid			6-20	12	40	15.6	0.95	32	503.88	29
	Japanese	D	D	6-14	10	45	12.1	0.85	29	349.69	20
Pine	Austrian			6-14	10	55	8.2		NA	NA	NA
	Corsican			6-20	12	55	10.9		NA	NA	NA
	lodgepole NC			6-16	12	45	12.1	0.84	29	344.72	19
	lodgepole SC			6-20	14	45	15.1	0.70	24	358.43	20
	Macedonian			4-12					NA	NA	NA
	Monterey			4-20	16	40	17.2		NA	NA	NA
	Scots			6-16	10	55	7.9	1.05	36	282.39	15
Redwood	coast			6-18	12	60	9.8		NA	NA	NA
Spruce	Norway			8-24	16	50	14.0	1.05	36	499.80	27
	Serbian			6-14					NA	NA	NA
	Sitka			8-34	18	40	18.5	1.00	34	629.00	37
Yew	Irish			4-6					NA	NA	NA

See Table 1 for explanation of colour codes regarding volume potential of reforestation and afforestation and discounted volume. The base timber prices assumed were €34 m^{-3} (conifers) and €37 m^{-3} (broadleaves). The estimated values indicated are: <€150 (dark pink), €150-249 (light pink), €250-374 (dark blue), €375-499 (blue) and ≥ €500 (light blue); Price relativity is the timber price (ratio) relative to the baseline (see Materials and Methods). AE is the NPV expressed as its annual equivalent. Blank boxes indicate data were unavailable.

Table 3: *Current improvement status of the species that ranked highest in the cost-benefit analysis*.

Species	Provenance testing	Plus tree selection	Progeny testing	Improved (tested) material available	Mass propagation (untested clones)	Mass propagation (tested clones)
Conifers						
SS	Completed	Completed	Completed	Yes	In use	Underway
DF	Completed	No	No	No	No	No
HL	Underway	No	No	No	No	No
NS	Complete	No	No	No	No	No
SP	Limited	Incomplete	Underway	Yes	No	No
LP	Completed	Completed	Completed	No	No	No
Broadleaves						
EU	No	No	No	No	No	No
AS	Underway	Limited	Initiated	No	No	No
RO	No	No	No	No	No	No
SY	No	Limited	No	No	No	No
BE	Underway	No	No	No	No	No
BI	Limited	Complete	Underway	No	No	No

Tree species abbreviations: SS, Sitka spruce; DF, Douglas fir; HL, hybrid larch; NS, Norway spruce; SP, Scots pine; LP, lodgepole pine; EU, *Eucalyptus*; AS, ash; RO, red oak; SY, sycamore; BE, beech and BI, birch.

Table 4: *Improvement option(s), relative costs of achieving gains, recommended approach, further work and recommendation for breeding programme.*

Species	Improvement option(s)	Predicted availability of improved material	Comments and recommended approach	Need for breeding programme
Conifers				
SS	Seed orchards and mass propagation of best tested genotypes	Available	Develop on-going programme. Low cost relative to returns.	Yes
DF	Seed orchards	30-35 years	Use improved material available elsewhere.	No
HL	Seed orchards	17-22 years	Exploit existing EU programmes and develop to suit Irish needs.	No
NS	Seed stands Seed orchards	20-25 years	Improved material available elsewhere.	No
SP	Seed stand Seed orchards	Available	Copious seed producer. Seed orchards provide good return. Need to replace ageing seed orchards with new material.	No
LP	Seed orchards	3-5 years	Copious seed producer. Seed orchards provide good return. More seed orchards of improved material need to be established.	No
Broadleaves				
EU	Species and provenance selection	N/A	Test species and provenances (if available).	No
AS	Seed stands Seed orchards	22-33 years	Difficult to justify improvement, especially due to disease issue.	No
RO	Seed stands Seed orchards	25-40 years	Difficult to justify improvement programme.	No
SY	Seed stands Seed orchards	22-28 years	Seed orchard option can be justified.	No
BE	Seed stands Seed orchards	30-43 years	Improvement programme difficult to justify.	No
BI	Seed stands Seed orchards.	Available	Copious seed producer so seed orchards should provide good return.	Yes, if improvements are verified and worthwhile

Tree species abbreviations: SS, Sitka spruce; DF, Douglas fir; HL, hybrid larch; NS, Norway spruce; SP, Scots pine; LP, lodgepole pine; EU, Eucalyptus; AS, ash; RO, red oak; SY, sycamore; BE, beech and BI, birch.

Discussion

The CBA approach used in this study assumed that a 15% gain could be achieved in one generation of improvement, whereas in reality it will be more difficult to achieve this in some species than in others, which might be reflected in higher costs per unit gain. Nevertheless, the costs of tree improvement tended to be influenced more by seed yield and rotation length than other factors (South 1991). Since many species form a minor component of forestry in Ireland, it is difficult to justify a tree improvement programme for these species beyond the EU FRM Qualified (untested seed orchards) category.

Conifers

The results of this study showed that excellent returns are likely to accrue from improvement efforts in Sitka spruce, in agreement with previous CBA findings (Phillips and Thompson 2010). If a total of €3,307,099 (€2.5 million, including interest) was invested in Sitka spruce research over a 15 year period, then a €629 ha^{-1} increase in NPV can be expected (Table 2). This would generate a potential annual benefit of €1.9 million, assuming an annual planting programme of 3,000 ha yr^{-1}. A minimum of 1,157 ha must be planted each year over five years to cover the cost of the investment. An annual planting level of 1,455 ha is needed to justify a similar investment for Norway spruce, based upon the cost assumptions and the AE returns estimated in this study (Table 2).

Sitka spruce performs exceptionally well on a wide range of sites in Ireland (Farrelly et al. 2011), so it is an ideal species for improvement. These results are also not surprising given that the Forestry Commission in Britain have also reported gains in Sitka spruce of more than 20% for some traits (Lee 2004). The current Sitka spruce programme in Ireland is relatively advanced in comparison with all other species. In addition to the establishment of conventional seed orchards, which will take about 10 years to produce seed, other options are being developed. Seed derived from specific crosses known to produce well above-average progeny are “multiplied” using vegetative propagation, thus allowing greater than average gains to be achieved (Thompson 2013). Nevertheless, further efforts are needed to advance the Sitka spruce improvement programme. Methods for early selection, approaches to screen families and individual trees for tolerance to stress and new ways to increase vegetative propagation yields are required. Bioassays to screen for tolerance and resistance to stress, pests and diseases are also needed.

Douglas fir produces high value wood and tree improvement efforts have delivered good returns at a modest cost and improved stock is widely used in the Pacific Northwest (Howe et al. 2006) and elsewhere. The species grows well on relatively sheltered sites with free-draining soil, but is prone to deer damage (Horgan et al. 2004). Therefore, it may be difficult to justify a tree improvement programme in Ireland, given the low availability of suitable planting sites. It may be preferable to source improved seeds for planting in Ireland from the Pacific Northwest or the UK.

The CBA results also showed that hybrid larch has potential to deliver improvement. The best approach to achieve improvements in a hybrid species may be quite different from the approach used to achieve improvement within a species. Most untested hybrid larch seed orchards yield gains of only about 5% (Lee 2004). Furthermore, seed orchards flower erratically with only about 20% of hybrid seed resulting. Results from trials of hybrid larch in Europe have shown that material from a Dutch programme performed best across a wide range of sites across Europe. This suggests that a common European hybrid larch breeding programme may be the optimal approach. However, the planting of hybrid larch needs to be considered in light of the current problems with *Phytopthora ramorum* that has affected Japanese larch; hybrid larch may succumb to this disease in the future.

Norway spruce is a relatively adaptable species, doing well on moderately fertile, moist mineral soils and the more fertile, shallow peats (Horgan et al. 2004). In particular, Norway spruce is often planted on sites that are considered unsuitable for Sitka spruce, especially where the risk of frost damage may be a factor. Heritability for many traits is high (Steffenremab et al. 2009). Trials to test this material have been established, but are still too young to provide conclusive results. Therefore, it is difficult to justify improvement work on this species until further information is available.

Because lodgepole pine is the only species suitable for planting on relatively low quality, wet sites in Ireland (Horgan et al. 2004), the demand for lodgepole pine stock is likely to continue. The high heritability for most economically important traits, the strong juvenile-mature genetic correlations, early sexual maturity, and ability to produce seed regularly, make this an ideal species for improvement (Xie and Ying 1996). To meet the demand for seed in Ireland, further seed orchards of the original Irish selections of south coastal material, as well as of an inter-provenance hybrid material, need to be established and managed, but it may be difficult to justify investment in a breeding programme given the limited potential for planting and the relatively low AE returns (Table 2).

Scots pine showed some potential for improvement also, but its low usage in Irish forestry makes it even less attractive than lodgepole pine as a potential species for improvement. Furthermore, the species is sometimes used in mixtures with oak and other broadleaves (Horgan et al. 2004), but the economics of using improved stock for use in mixtures may be difficult to justify. Material from Scottish clones has been propagated to establish two new seed orchards in recent years, which may provide sufficient material for future use.

Broadleaves

Broadleaf species planting accounts for about 35% of the current national afforestation programme (Anonymous 2013), so they are likely to form an increasingly important element in the national forest estate. There has been considerable debate about broadleaved tree improvement in Ireland and Britain (Savill et al. 2005). The long rotation (not true for all species), high establishment costs, low productivity, breeding and propagation difficulties and the low levels of genetic gain that are likely to accrue in many cases, make improvement work challenging. Although Palmer et al. (1998) showed that broadleaf improvement in Britain was resulting in significant gains, it was concluded that only simple mass selection and simple recurrent selection methods could be justified economically. Simple mass selection yielded the highest net returns. In particular, it may be difficult to justify the use of advanced methods for most broadleaved species, such as clonal propagation. It has been argued that the appropriate silvicultural practices may provide a greater improvement in a shorter period of time than classical breeding techniques in broadleaved species (Hubert and Lee 2005). Stem quality is far more important than yield for most broadleaved tree species, a trait that is very heavily influenced by the environment. It is highly unlikely that any improvements in tree form will be realised if broadleaves are planted on unsuitable sites and are not managed to a high standard. The best option may be to secure a supply of good quality seed, perhaps by establishing seed orchards with phenotypically selected, but untested (tested should of course be used if available) material (i.e. Qualified under EU FRM classification).

Several broadleaved species also ranked well in the CBA results, with *Eucalyptus* and ash providing the best returns. An annual planting programme of 1,696 ha would be needed to realise the returns from investing in a breeding programme in ash. In light of the uncertainty of the potential effect of the dieback disease on ash however, it is difficult to justify an improvement programme. It has been suggested that a programme to breed resistance to the disease should be initiated, but without a better understanding of the disease, this effort may be premature. Furthermore, breeding for resistance to the dieback disease may be difficult and expensive. In one study carried out in Denmark for example, only a small fraction of the ash trees were found to possess resistance, so it may not be possible to exploit this resistance without the risk of other adverse consequences (McKinney et al. 2011). Investing in a disease resistance breeding programme at national level is difficult to justify, but collaborating with other European countries on breeding efforts may be a more realistic approach.

While *Eucalyptus* showed good potential, this species forms only a minor part of the planting programme, predominantly for biomass production (Neilan and Thompson 2008). The main species of interest to Ireland have been identified by Neilan and Thompson (2008). While there may be considerable variation among provenances within species in *Eucalyptus* (King and Wilcox 1988), a limited number of provenances are likely to be suitable for Irish conditions. However, it is difficult to justify an improvement programme given the limited use of *Eucalyptus* species in Ireland. In addition, some improved seed is already available in the market for some species (e.g. *E. nitens*). It is likely that this improved material would be suitable for use in Ireland, but there is no scientific evidence to confirm this.

Although not native, sycamore has been naturalised in Ireland for several hundred years. No provenance testing has been undertaken to date with the species. Like ash, about 100 plus trees have been selected and used to establish one small seed orchard, but none of this material has been tested. More plus trees would have to be selected (500 to 1,000) and tested to provide enough material for an improvement programme, but the establishment of a breeding programme cannot be justified.

Beech and birch were deemed to have some potential for improvement. Results from Sweden for *Betula pendula* Roth have shown that significant improvement in yield can be achieved through breeding and selections can be made at an early age (Koski and Rousi 2005). The species also flowers regularly and profusely at an early age, making it an attractive species for improvement. There has already been substantial investment in birch improvement in Ireland. If improvements of 15% are achievable in birch, then it would require an annual planting level of 2,199 ha over the next 15 years to justify the estimated investment cost of €3,307,099. It is unlikely that birch planting levels will reach levels that are high enough to sustain the investment. Since a considerable amount of money has already been invested in this programme, it should be continued if significant improvement can be verified. Similar to many other species however, the most suitable improvement option might be to establish seed orchards with selected (untested and tested, as available) material.

Beech improvement efforts should focus initially on selecting appropriate provenances for use in Ireland. Information from provenance trials established in the 1990s should provide this information (Fennessy et al. 2012), but further work is difficult to justify given the low demand for planting stock. It is also difficult to justify improvement work in red oak for similar reasons. There are no other known breeding programmes that might provide suitable sources of improved material.

Conclusions and recommendations

After taking into consideration other issues (disease and other constraints, availability of improved material from other programmes abroad, etc.) in addition to the CBA data, it was difficult to justify a breeding programme for all species except Sitka spruce. Sitka spruce provides an excellent return on most site types in Ireland, but further investment in the programme is needed so that the species full potential can be realised. Since Douglas fir is a minor species, it may be preferable to source improved seeds from other countries. Improvement work beyond the establishment of seed orchards (i.e. Qualified category) is difficult to justify for all other conifer and all broadleaved species.

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