Southern Beeches (*Nothofagus* species)

Rauli (*Nothofagus alpina* syn. *N. procera*), roble (*Nothofagus obliqua*) and related species.

Bill Mason, **Richard Jinks**, **Peter Savill** and **Scott McG. Wilson** review the current position and future potential of this interesting group of species that were widely promoted in the late 1970s and early 1980s but have since fallen out of fashion.

Foresters are giving much thought to alternative tree species that might be grown in Britain and Ireland if climatic change proceeds as predicted. There is also increasing awareness of the threats from novel tree pests and diseases, which have proliferated over the past two decades. Recently, the Wessex Silvicultural Group has considered this matter (Bladon and Evans, 2015), as have Forest Research (2017). There is an on-line network promoting novel species thought to have potential to grow well in Britain (SilviFuture, 2017), including nine high priority and 20 medium priority species. Read et al. (2009) suggested 49 'emerging' species (24 conifers and 25 hardwoods) with potential for adaptation of British forests to predicted climate change.

As noted in the last article in this series (Wilson et al., 2017), the debate about diversification has devoted less attention to alternative hardwoods than to alternative conifers. However, events such as the increasing incidence of ash dieback (*Hymenoscyphus fraxineus*) since 2012 and the awareness that species such as European beech (*Fagus sylvatica*) may prove vulnerable to drought in a warming climate in southern Britain (Ray et al., 2010) means that there is also a need to consider and evaluate alternative hardwoods. One group of species that has featured in previous discussions of alternative broadleaves for use in British forests are the southern beeches (*Nothofagus* spp.), which were operationally trialled in different parts of the country in the 1970s and 1980s (Tuley, 1980; Potter, 1987; Danby, 1991). However, widespread damage to and mortality of southern beeches following the cold winters of 1978/79 and 1981/82 (Murray et al., 1986), possibly aggravated by the planting of frost tender provenances (Potter, 1987), resulted in a decline in interest in these species. Given better understanding of appropriate provenance choice and silviculture as well as the probability of a warming climate, it is timely to re-evaluate the potential role of *Nothofagus* species in British forestry.

Introduction

The Nothofagaceae family comprises a group of some 40 evergreen and deciduous species confined to the southern hemisphere and found in regions such as New Guinea, New Caledonia, Australasia, Chile and Argentina. The taxonomy of this family has been much discussed in the last decades and there has been a recent proposal to divide it into four separate groups (Heenan and Smissen, 2013). This would result in a number of changes to the scientific names of species that have been grown in British forestry, for example rauli (*Nothofagus alpina*) would become known as *Lophozonia alpina*. However, since this new classification is not yet generally agreed, for the purposes of this article we have continued to use the traditional scientific names wherever possible. We will also use the Spanish names for the individual species since most have no common English names.

The first detailed summary report on the performance of

Nothofagus species as forest trees in Britain was provided by MacDonald et al. (1957). They noted that only Chilean species had proved successful in British forests and that those of particular interest were rauli (*Nothofagus alpina*) and roble (*N. obliqua*) (Figure 1). According to Elwes and Henry (1906), roble was first introduced to Britain in 1849 but subsequently died out. It was re-introduced by Elwes in 1902 and rauli was introduced around 1910; both species attracted considerable attention because of their rapid growth in various arboreta. Further seed collections in the 1920s resulted in plots of both rauli and roble being established in various parts of Britain and these were supplemented following further seed imports in 1953, which led to an extensive series of trial plantations (Nimmo, 1971). It was the good growth of some of these plots and plantations which led to the upsurge in interest in *Nothofagus* during the 1970s.

Rauli – *Nothofagus alpina* (Poepp. & Endl.) Oerst. (syns. *N. nervosa*, *N. procera*)

This fast-growing deciduous tree was first introduced into Britain in 1910 by F.R.S. Balfour of Dawyck in the Scottish Borders. It has excellent stem form with good self-pruning and a grey bark with widely spaced vertical fissures. The tallest tree recorded in Britain and Ireland (in 2010) was 33m tall at 82 years of age in County Wicklow in Ireland (www.treeregister.org). The ovate-lanceolate leaves can be up to 15cm long and 8cm wide, and have 15-18 pairs of veins – the larger leaf size and greater number of leaf veins are reliable ways of distinguishing rauli from roble. In 2015 there were about 70ha of this species on the public forest estate in Britain, over half of these stands being in Wales (Figure 2).

The natural range of rauli in southern Chile is from 35° to 41°30'S (roughly from the latitude of Curico to that of Llanquihue province) where it occurs both in the Andes and in the coastal mountains (Figure 1a). It can also be found in the Argentine Andes, but over a lesser range of latitude. It generally grows in mixed stands with both roble and coigue (*Nothofagus dombeyi*) as well as other tree species; in the central part of the natural range this mixed forest type can be found from close to sea level to over 1000m (Veblen et al, 1996). Here the dominant trees can reach over 40m in height and can live for up to 450 years. Rauli is generally dominant at intermediate elevations, while roble is more abundant lower down and coigue is more frequent higher up. Rauli is considered to have intermediate shade tolerance unlike most of the other *Nothofagus* species considered in this article that are light demanding (Donoso, 2006). Rauli typically grows on slopes with deep well drained volcanic soils and annual rainfall ranging from 1000 to more than 4000mm, although many sites can experience a dry summer period of up to three months. Perhaps more importantly for its potential in Britain, the species is not found in frost hollows in the native range.

Figure 2. Rauli (N. alpina) at 36 years near Machynlleth, west Wales. (Photo: W.L. Mason)

Climate and soil requirements

There are several site factors essential for successful growth of rauli in Britain. It requires a freely draining soil of 'fresh to slightly dry' soil moisture regime and 'poor to medium' soil nutrient regime defined using the Ecological Site Classification (ESC) (Pyatt et al., 2001). This suggests that rauli should preferably be planted on brown earths and on podzols, and also on ironpan soils, but only where the pan

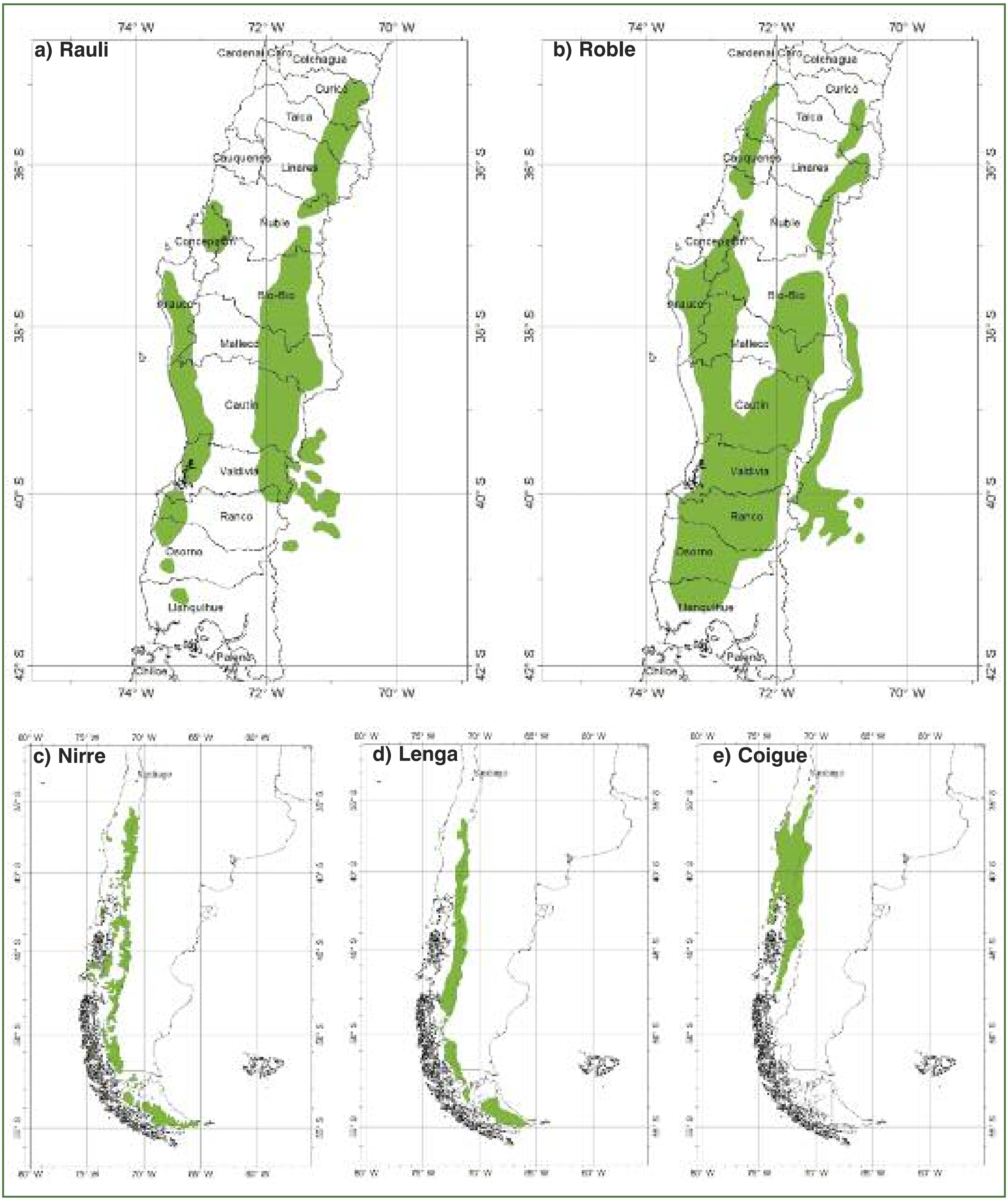

Figure 1. Natural ranges of a) Rauli (N. alpina), b) Roble (N. obliqua), c) Nirre (N. antarctica), d) Lenga (N. pumilio), and e) Coigue (N. dombeyi) in Chile and Argentina. a) and b) include provinces of Chile; distributions are redrawn from Amigo and Rodriguez-Guitian (2011). Note the different geographic scale for maps a and b compared to that for maps c-e.

has been broken to give access to more freely draining lower soil horizons. For satisfactory long-term growth moister soils such as gleys and especially those with peat layers should be avoided, as should shallow soils that could be prone to drought. Readers should note that this advice differs from previous reviews, which considered fairly heavy gleys as being suitable (Tuley, 1980). This revision recognises that in its native range rauli grows almost exclusively on deep volcanic soils that are naturally free draining. The main exception is in the coastal range where it occurs on brown earth soils with a loamy texture derived from metamorphic rocks but which are still free draining (Loewe et al., 1998). Since rauli naturally grows in temperate rainforest conditions (see above), favourable sites for this species in Britain are likely to be those receiving 1000mm of rainfall or more. This concurs with operational experience that growth of rauli has tended to be better in western Britain (Tuley, 1980; Danby, 1991). The species does not tolerate exposure to wind.

Most importantly, a major constraint upon the planting of rauli is its sensitivity to spring and autumn frosts plus its relatively low tolerance of winter cold. In a study of the cold hardiness of four provenances of rauli compared with European beech (*Fagus sylvatica*), Murray et al. (1986) showed that all rauli provenances set buds and hardened much later in the autumn than European beech, and that the trees dehardened earlier in spring, thus being at increased risk of frost damage. Furthermore, they also found that the maximum winter hardiness achieved was around -14°C, compared with values of well below -20°C for European beech. Combining these results with historic records (1941-1970) of minimum air temperatures in Britain, Murray et al. (1986) concluded that it was only in the milder coastal regions that rauli could be grown without experiencing damaging winter temperatures over a 50 year period (taken as being a likely rotation for this species). They also noted that, for a constant latitude and elevation, the rauli provenances tended to be slightly more cold hardy than roble, although French experience was that survival of roble was better than that of rauli following a cold winter in 1985 (Tessier du Cros and Laval, 1990).

Provenance selection

As shown above, a major risk in planting rauli in Britain is of severe damage from frost or winter cold and this can be reduced by careful provenance choice. Murray et al. (1986) found that more northerly provenances were less cold hardy than those from further south in the Chilean range, while Potter (1987) recommended the use of plants originating from Cautin or Malleco provinces (38-39° S) or from good quality mature stands in Britain.

This information was partly based upon early results from a series of provenance trials established in 1979 at 17 forests across Britain ranging north to south from Speymouth (Morayshire) to Arundel (West Sussex) and west to east from Ystwyth (Cardiganshire) to Thetford (Norfolk). This series involved comparison of 16 provenances collected from the natural range in Chile and covering nearly 4° of latitude. Most provenances were derived from stands growing below 1000m asl. Two British provenances of Chilean origin were also included. Results from these trials at the beginning of canopy closure (16 or 17 years after planting) are summarised in Table 1. Although overall survival may have been adversely affected by the cold winter of 1981/82, they clearly show the poorer performance of material of the most northerly Nuble provenance, which was also the most frost sensitive in the studies of Murray et al (1986). The best growth and survival tended to be found in plants of the more southerly Malleco and Cautin provenances as well as in those from Argentina. Across the different sites the best growth was found in the trials in the Forest of Dean, in west Wales and in maritime or milder parts of Scotland.

Table 1. Performance of different provenances of rauli at 16-17 years after planting on 17 experimental sites across Britain. Values are averages across all sites.

Region and average latitude of origin	Number of provenances tested	Survival (%)	Height (m)	Mean dbh (cm)
Nuble (36°40'S)	3	41	10.2	10.5
Arauco (37°15'S)	1	72	10.9	11.6
Malleco (38°S)	4	69	11.3	12.5
Cautin (38°50'S)	5	74	11.2	12.7
Valdivia (39°35'S)	1	47	10.3	10.8
Osorno* (40°15'S)	1	47	13.3	13.5
*Shortage of plants so only planted on a few sites.				
Argentina (39°25'S)	1	66	12.0	13.4
Britain**	2	69	12.0	11.3

**Material collected from British stands in southern England at Westonbirt and Weston Common. First provenance only planted at a few sites.

In recognition of the vulnerability of rauli to frost and winter cold in Britain, in the mid-1990s attempts were made to identify more cold hardy origins from higher elevations within the natural range in Chile. Seed collections were made from eight stands in both the Andes and in the coastal ranges (all at elevations of 1000m or more asl) (Ortega and Danby,

Table 2. Performance of different 'cold-hardy' provenances of rauli 17-18 years after planting in two experiments in south-west Wales (LL) and the central Highlands (GO).

Provenance	Survival (%) LL	Survival (%) GO	Top height (m) LL	Top height (m) GO	Basal area (m^2ha^{-1}) LL	Basal area (m^2ha^{-1}) GO	Notes
Malacahuello (38°29'S)	80.7	92.9	16.3	13.3	38.8	36.9	From Malleco. Average of four provenances.
Quilaletie (39°40'S)	76.5	93.4	15.7	12.6	29.9	29.8	From Valdivia province.
Pirihueico (40°0'S)	76.0	-	14.7	-	26.2	-	From Valdivia province. Insufficient plants for both experiments.
Neltume (39°46'S)	90.8	90.8	16.1	12.4	40.9	35.3	From Valdivia province.
Canete (37°42'S)	82.1	85.7	16.6	13.1	38.4	27.7	From Arauco in the coastal mountains.
Forest of Dean	78.1	30.1	16.4	9.9	38.1	5.7	From a first generation British stand of Malleco origin (latter located at around 800m asl).
Argentina	94.4	78.6	16.3	13.1	47.2	39.4	Little information available.

2000). The resulting seedlings (plus material from Argentina and from a home collection) were planted out in two trials near Haverfordwest (SW Wales) and in Glen Orchy (central Scottish Highlands) in 1998 and 1999. Summary results are shown in Table 2. While these data are not conclusive and no physiological cold hardiness testing has been carried out on this material, in general there is higher survival in these experiments than was found in the earlier provenance trials despite the material being exposed to the cold winters of 2010 and 2011. The poor survival of the home collected seedlot at the colder Scottish site is striking. The early growth rates are still very presentable being equivalent to Yield Class 18 at the Welsh site and Yield Class 14 at the Scottish one (based on tables in Tuley, 1980).

Taken overall, it is clear that careful provenance selection is a critical factor influencing the establishment and productivity of rauli in most of Britain. More northerly provenances (e.g. Nuble) should clearly be avoided, but the most recent trials also suggest that there could be benefits from trying to obtain seed from stands at higher elevations within the natural range. It appears that most existing mature stands of rauli in Britain were sourced from lower elevations within the natural range, and therefore may not be as cold hardy as the material that was tested in the recent trials.

Seed production, nursery practice

Under British conditions, rauli starts producing seed later than roble, and trees need to be around 40 years old before good quantities of seed can be expected. There are usually about 90,000 seeds per kg, which should provide about 20,000 germinable seeds per kg (Gordon and Rowe, 1982). Germination percentages are often low, at around 25%, and the seed will benefit from pre-chilling at 1-5°C for up to six weeks to break dormancy. Research trials have shown that germination can be enhanced by soaking seed for 12-24 hours in a 50 ppm GA 4/7 (gibberellic acid) solution (Rowe and Gordon, 1981), but this does not appear to have been used in operational nursery practice.

Plants can be produced either in containers as a one-year-old seedling or in bare-root nurseries as two-years old transplants or undercuts. In both types of production an important consideration is to adjust fertiliser regimes, particularly by reducing nitrogen top dressing, thus avoiding excessive top growth that could be vulnerable to frost. The tendency to set bud late in the autumn and to flush early in the spring could make cold storage of this species rather problematic. The best establishment success is likely to come from using 'hot-lifted' plants that are planted out between November and February.

Silviculture

Because of the potential vulnerability to frosts and winter cold, rauli was often planted under a light overstorey of birch or larch (50-100 stems ha^{-1}). However, it is very important to reduce or remove this top cover once the planted trees are more than 1.5m tall. Recommended planting spacing in Chile varies from 2m by 2m to 1.5m by 1.5m (Loewe et al., 1998). Once established early height growth is rapid with increments of around a metre per year being obtained on good sites. The silvicultural regime for use in pure stands should resemble that traditionally recommended for larch with first thinnings by 15-20 years and regular interventions to favour the best boles. On good sites dominant trees will reach 20-25m in height by 50 years and previous reviews (e.g. Tuley, 1980) have suggested that a rotation of 40-50 years could be envisaged for this species, similar to those used for many conifers. The species does coppice, but there is little practical experience in Britain of managing coppice

Table 3. Summary growth data from selected Forest Research sample plots of rauli and roble in England and Wales plus comparative data extracted from yield tables for *Nothofagus* (Tuley, 1980) and beech and oak at about 50 years (Edwards and Christie, 1981).

Species	Location	Age	Trees ha^{-1}	Top height (m)	Mean dbh (cm)	Standing basal area (m^{2}ha^{-1})	Standing volume (m^{3}ha^{-1})	Cumulative volume production (m^{3}ha^{-1})	General Yield Class
Rauli	Exeter	53	203	27.6	42.6	29.0	366	570	10
Rauli	Harlech	42	363	22.3	32.5	30.1	298	637	10
Rauli	Gwydyr	41	307	25.2	36.2	31.6	333	676	16
Roble	Bedgebury	47	262	26.1	34.6	24.6	265	539	12
Roble	Windsor	37	185	26.8	37.7	20.7	254	-	20
Nothofagus table		49	257	25.1	36.0	25.0	315	661	14
Beech table		50	766	21.0	20.3	24.7	189	336	8
Oak table		50	443	21.3	25.0	21.7	203	377	8

regrowth of rauli. Nevertheless, there has been speculation that such regrowth could form the basis of a short rotation forestry regime (Tuley, 1980) with a potential productivity of up to 10 odt ha^{-1}yr^{-1} on a 15 year rotation, which is higher than nearly all other species considered (McKay, 2011, Table 16).

Natural regeneration of rauli can be found in various parts of Britain, but is generally less common and less dense than that of roble. Hybrids between the two species can be found where mature stands of both species occur in close proximity. There is very limited experience in Britain of growing rauli in mixture with other species, except where it has been underplanted through mature larch or birch. The fast early growth can make it difficult to grow this species in intimate mixture with most native broadleaves since a two-storied structure dominated by rauli can often develop. However, its height growth is compatible with a number of conifers such as Douglas fir and it could theoretically be grown in mixture with such species as part of a diversification strategy. Growing rauli (and other southern beeches) in mixture could also be a means of reducing the hazard posed by the pathogen *Phytophthora pseudosyringae* (see below).

Yields and timber properties

As reported in previous reviews (e.g. Tuley, 1980), rauli is one of the faster growing broadleaves that has been trialled in Britain, with a maximum mean annual volume increment that can compare with some conifers on favourable sites (Figure 3). A number of sample plots were established in southern Britain and Wales, both with this species and with roble, but most were discontinued in the 1980s following the damage to operational plantings during the cold winters at the beginning of the decade. Table 3 lists summary data from the few plots that survived until close to rotation age, plus projections from published yield tables for *Nothofagus* (Tuley, 1980) and two native broadleaves. Published yield tables suggest that productivity of rauli can range from yield classes 10 to 18 in Britain, although higher values are reported from good sites (Table 3), and these yields exceed those obtained from most other broadleaves with the exception of *Eucalyptus* species and poplars.

Chilean rauli timber is said to be the best of all southern beeches, although it is much lighter than European beech (about 470-560kgm^{-3} at 15% moisture content compared with

Figure 3. Rauli (N. alpina) at Crarae, west Scotland at 50 years. (Photo: Scott Wilson)

720kgm^{-3} for beech). The densities recorded for rauli are similar to those reported for common alder and sycamore. It has a pinkish heartwood similar to cherry with very fine grain and a paler sapwood. Reports from Chile suggest that the heartwood is a prized timber for use in furniture, for doors, window frames, veneers, shingles and floors. Poorer quality timber is used for roof tiles, boards and pulp. One uncertainty is that the small amount of rauli timber tested in Britain came from fast-grown trees with relatively large amounts of sapwood and no distinctive features (Brazier and Moore, 1985). Although the samples had high stability and machined well, the boards had a tendency to split, possibly because of their fast growth. If rauli is to be grown for speciality timber markets, then it is probable that it will need to be grown on longer rotations to produce greater volumes of the more valuable heartwood.

Pests and diseases

Rauli is vulnerable to browsing by deer and bark stripping by grey squirrels has occurred, but experience is that it is not as preferentially attacked by squirrels as European beech and sycamore (Tuley, 1980). In some plots there has been damage to root systems by honey fungus (*Armillaria mellea*), which has made the trees more liable to windthrow.

A major issue in Britain is the incidence of stem cankers following cold winters, particularly on trees that have been planted in frost hollows or other low-lying sites. These cankers are caused by the death of the cambium due to low temperature; such cankers can girdle the stem and result in death or dieback of the plant above the point of damage. Where complete girdling does not occur, there can be splits in the bark or open wounds on one part of the stem, usually on the lower stem close to ground level. Even if the tree recovers from this damage, there can still be long-term weakness in the timber, including the occurrence of ring shake. The main way of avoiding this problem is to avoid planting rauli in areas prone to ponding of cold air and to use provenances that are likely to be less sensitive to frosts and cold temperatures (see above).

A more recent issue, and probably the most important current concern, is the damage to rauli (and other *Nothofagus* species) with bleeding cankers on stems and branches due to attack by *Phytophthora pseudosyringae* where both pole stage and mature trees have been killed (Scanu et al., 2012). This pathogen was previously known to attack roots of European beech, hornbeam, and common alder as well as damaging leaves of bilberry. The damage to *Nothofagus* was first reported from a stand of roble in Cornwall in 2009, and outbreaks of this disease have subsequently been confirmed from a number of sites in southern England, Wales and in western Scotland where both roble and rauli trees of up to 60 years of age have been killed. Limited studies (Scanu and Webber, 2016) have suggested that rauli may be less vulnerable to this pathogen than roble, but it remains a threat to the future use of both species, and expert advice should be sought for up-to-date information on pathogenicity and susceptibility.

Roble – *Nothofagus obliqua* (Mirb.) Blume.

Roble generally tends to have a coarser stem form than rauli (e.g. Figures 3 and 4), often with forking and heavy spreading branches; the bark is grey-brown and forms flaky plates in older trees, which can be a useful way of distinguishing it from rauli during the winter months. The tallest tree in Britain and Ireland (in 2013) was at Muncaster Castle in Cumbria, being 33m high and with a dbh of 67cm at about 80 years of age (www.treeregister.org). The lanceolate leaves are noticeably smaller than those of rauli and have around 7-11 veins. There were about 40ha of this species on the public forest estate in Britain, nearly all in England.

The natural distribution of roble is quite similar to that of rauli, except that it extends to latitudes slightly further to the north (Figure 1b). It can be found in both the coastal mountains and in the Andes, and also in the lowland regions (Central Depression) between the two mountain ranges, but these lowland forests have largely been cleared for agriculture (Loewe et al., 1998). It occurs in Argentina, but over a more restricted range from 36°50' to 40°15'S. As noted earlier, in the more southerly part of the natural range this species often grows in mixed forests with rauli and coigue, and it is the most abundant species at lower elevations and on warmer sites. It is more light demanding than rauli and is found on a wider range of mineral soils, including on shallow soils that could be prone to summer drought.

Climate and soil requirements

These are generally quite similar to those of rauli except that roble appears to be able to tolerate drier climates in Britain with annual rainfall as low as 600-800mm and this forms the basis of the general recommendation that it would be the preferred *Nothofagus* species for planting on lowland sites in eastern Britain (Tuley, 1980). Like rauli, roble does not tolerate exposure to wind.

Roble is sensitive to spring and autumn frosts, and does not tolerate severe winter cold. In their study of cold hardiness in *Nothofagus* species, Murray et al. (1986) found a similar trend to that reported for rauli with late bud set in the autumn and early flushing in the spring and a maximum winter cold hardiness of around -14°C. Their conclusion for roble was similar to that for rauli, namely that use of this species should be confined to milder regions, often near the coast.

Figure 4. Roble (N. obliqua) at Crarae, west Scotland at 50 years. (Photo: Scott Wilson)

Provenance selection

Provenance testing with roble was carried out in 1979 in parallel with that described above for rauli and used most of the 17 experimental sites mentioned previously. The range of roble provenances tested was less extensive than with rauli since the 1979 trials contained only nine seedlots, six of which originated from Chile covering three degrees of latitude from Malleco province in the north via Cautin to Llanquihue at just beyond 41°S. The other three seedlots were collections from mature British roble stands in Scotland and southern England. In 1981 a further smaller experimental series was planted that involved two Chilean provenances from Cautin and Llanquihue plus one from Nequen in Argentina as well as other *Nothofagus* species. Assessments of the roble provenance experiments during the late establishment and early pole stage were not systematic and a number were not measured after five years of age.

The influence of the harsh winter of 1981/82 is evident in the variable survival found in the 1979 series with less than 50% of trees alive in most provenances after five years on colder or less fertile sites such as Glentress (south Scotland), Inchnacardoch (north Scotland) or Speymouth (north-east Scotland). By contrast, on warmer and more fertile sites such as Wykeham (North York Moors) or Ystwyth (Wales) survivals of all provenances were between 80 and 95%. Possibly because the latitudinal range of roble provenances tested was less than in rauli, there was less striking variation between provenances with site effects being more important. Potter (1987) noted that the most southerly provenance from Llanquihue had performed well in many experiments and this was also the most productive in trials in Ireland (Lally and Thompson, 1998). The limited results available from the 1981 experiments (Table 4) show high survival and vigorous growth of the three roble provenances trialled, including excellent performance of the material originating from Argentina. One notable feature of these results was the much higher survival (over 90%) on the cold sites of plants originating from a mature roble stand in west Scotland. Murray et al. (1986) also found that the cold-hardiest seedlot of roble tested was from a British stand at Westonbirt (Glos.), originating from Malleco province, which suggests that it may be possible to identify more cold hardy material from mature stands growing in Britain and Ireland.

Figure 5. Dense natural regeneration of roble (N. obliqua) on the Morton estate, Nottinghamshire. (Photo: W.L. Mason)

Table 4. Comparative early growth and survival of three provenances of roble (*Nothofagus obliqua*) compared with two provenances of rauli (*N. alpina*) in two experiments in north-east England and west Scotland.

Provenance and latitude	Wykeham (north Yorkshire) Height (m) at 10 years	Survival (%)	Benmore (west Scotland) Height (m) at 13 years	Survival (%)
Roble				
Cautin (38°55'S)	5.9	98	7.2	98
Llanquihue (41°10'S)	5.7	91	7.4	92
Nequen, Argentina (40°11'S)	6.1	100	7.7	99
Rauli				
Malleco (38°S)	6.1	89	8.4	93
Cautin (39°15'S)	5.7	96	7.1	93

Seed production, nursery practice and silviculture

Much of what was presented for rauli also applies to roble, and only the main differences are highlighted in this section.

Seed production begins at a younger age in roble and reasonable seed crops can be found in stands of 25-30 years of age. Reported seed yields are higher at around 116,000 seeds per kg, which given a similar germination percentage, results in yields of about 25,000 germinable seeds per kg (Gordon and Rowe, 1982). Other aspects of seed pre-treatment and nursery practice are similar to rauli.

Silviculturally, the main difference from rauli noted in Britain is that the earlier and seemingly more regular production of seed can result in natural regeneration of roble being quite profuse in and around stands from 20-25 years of age (see Figure 5). Provided vegetation competition is light and browsing pressure is not severe, this regeneration can also develop as an understorey in adjacent stands of light demanding species such as pines and larches. Densities of several thousand seedlings and saplings per ha have been noted in some of the older 1950s plots and more recent operational plantings (WLM, pers. observation). The light demanding nature of roble means that the overstorey would need to be opened up rapidly once natural regeneration had established, suggesting that a shelterwood or seed tree system would be the most appropriate silvicultural system to use with this species, which is also practised in Chile (Loewe et al., 1998). Early and regular thinning is again desirable to maintain rapid growth and to improve crown and stem form.

Yields and timber properties

The limited sample plot data (Table 3) show the high productivities that can be obtained from roble, and these are the more striking for being from sites in relatively dry areas of south-east England. Brazier and Moore (1985) found samples of British roble timber to have a higher density ($600kgm^{-3}$) than rauli, but the heartwood had a greyish colour and was less visually attractive, which would limit its decorative potential. Roble timber had a higher tendency to split on drying and was not as stable as rauli. No specialist markets could be identified and the timber was best considered as a general purpose hardwood.

Pests and diseases

In general, the reported vulnerability of roble to pests and diseases in Britain is similar to that noted for rauli. The main exception is that roble is believed to be particularly susceptible to *P. pseudosyringae* and appears to be the first *Nothofagus* species to succumb to this pathogen in comparative species trials. Pathogenicity tests involving inoculation of logs and leaves have shown that this is an aggressive bark pathogen of roble and that foliar susceptibility is high with the potential for heavy sporulation in the field (Scanu and Webber, 2016). Lally and Thompson (1998) also report that planting roble on alkaline soils (not a recommended soil type) can lead to attack by Fomes butt rot (*Heterobasidion annosum*).

Other *Nothofagus* species

As noted by previous authors (e.g. MacDonald et al., 1957; Tuley, 1980) a number of other *Nothofagus* species can be grown in Britain, particularly those from South America and from New Zealand. However, few experimental plots have been established with these species so most evidence of potential under British conditions has been obtained from individual specimens in arboreta, often of unknown provenance. The only recent exception was a series of small experiments, planted in 1981, comparing performance of a number of South American *Nothofagus* species, sometimes with several provenances of certain species. The species tested included: nirre (*N. antarctica*), lenga (*N. pumilio*) and coigue (*N. dombeyi*), as well as *N. betuloides*, and *N. alessandri*. The last two species were only planted on a few sites and in very small plots (<5 plants) so are not considered further. Rauli and roble were also included in these experiments as standards.

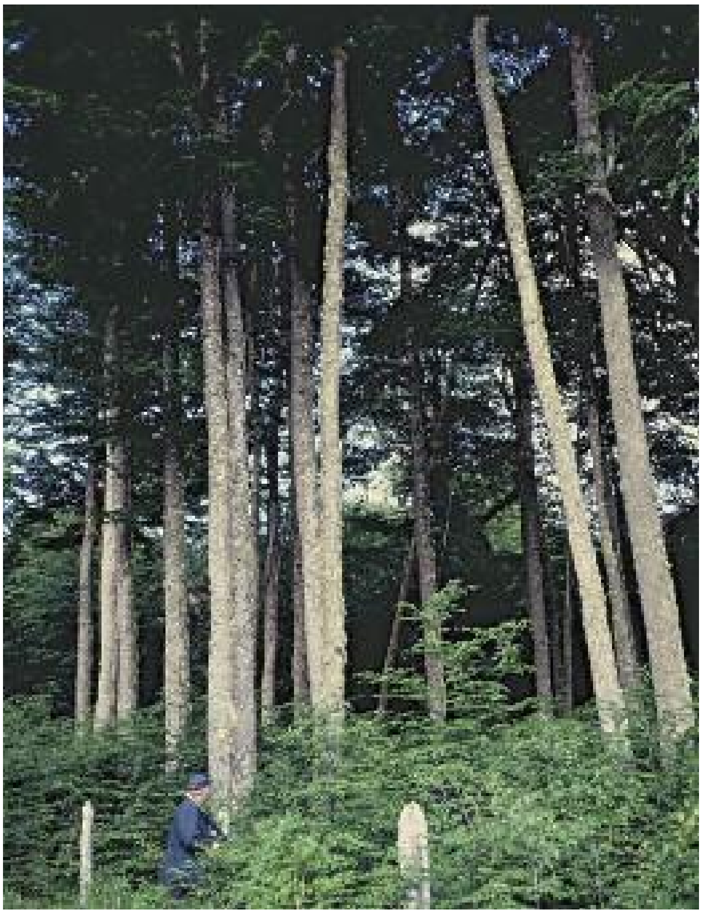

Figure 6. Mature lenga (N. pumilio) near Coyhaique in southern Chile. (Photo: W.L. Mason)

Nirre and lenga are deciduous species with extensive natural ranges extending from about 36° (nirre) or 37°S (lenga) all the way to the southern tip of South America at around 56°S (Figures 1c and 1d). In the more northerly part of their range these species are only found at higher elevations whereas they occur close to sea level in Tierra del Fuego. Lenga is reported to be of intermediate shade tolerance while nirre is light demanding (Peri et al., 2009), but the latter species can tolerate poorer site conditions such as dry or poorly drained soils. In southern Chile and Argentina, lenga is an important timber species managed primarily under shelterwood systems (Martinez Pastur et al., 2000) (Figure 6) while nirre is considered mainly as a firewood species. Nirre was first introduced into Britain in 1830 but lenga was not planted until about 1960 (Tuley, 1980). Both species are likely to be more tolerant of exposure and cold conditions than the other *Nothofagus* species considered in this paper. For instance, they were the most promising *Nothofagus* species trialled in parts of Norway and Denmark (Sondergard, 1997).

Coigue is an evergreen, shade intolerant pioneer tree occurring as a component of mixed forests with rauli and roble, and a distribution from about 34° to 48°S where it is generally found at higher elevations in both Chile and Argentina (Figure 1e). It grows on freely draining mineral soils, but is not tolerant of exposure. The species was first introduced to Britain and Ireland in 1916 and in 2013 trees of 34m and 32m tall were reported from Wicklow in Ireland and Muncaster in Cumbria respectively (www.treeregister.org). However, mature specimens often have forked stems with heavy crowns, which limits the potential for sawtimber production (Figure 7).

Figure 7. Coigue (N. dombeyi) at Kilmun, west Scotland at 60 years. (Photo: W.L. Mason)

Summary of the 1981 trials

Most species and provenances were only available in limited numbers, so treatments were planted in small plots (typically 10-30 plants) in an unreplicated design on a range of sites from southern England to Scotland. The provenances of nirre and lenga included in these experiments covered a natural range of up to 10° of latitude but plant shortages meant that not all provenances were planted at every site. A number of trials were badly affected by the cold winter of 1981/82 and subsequent monitoring was intermittent. Only a few experiments were assessed for longer than five years – results from three sites in northern England and Scotland where measurements were made for up to 10-17 years are shown in Table 5.

Nirre had the highest survival of the species trialled, with several provenances from southern Patagonia having no losses at the time of the last assessment. Lenga had high survival at the English site but had lower survival than nirre in the Dalmacallan experiment in south Scotland, which was a cold site at the bottom of a slope. Coigue had the poorest survival with no survivors of this species at the two sites where it was planted. Comparison of Tables 4 and 5 shows that, at the Wykeham and Benmore sites, the survival of rauli and roble was very similar to that of nirre and lenga. However, at the colder Dalmacallan site, rauli and roble (both of Cautin provenance) had only 25 and 47% survival respectively.

Height growth of nirre was quite similar to that of rauli and roble at the Wykeham experiment was but was appreciably less at Benmore. Lenga tended to be smaller than nirre at both these locations. However, one feature noted about both these species at all experiments was a high frequency of trees with multi-stemmed growth, which compared unfavourably with the straight, uniform stems characteristic of most rauli plots.

Conclusion

Unlike some other species considered in this series of papers, assessment of the potential role of different *Nothofagus* species in British forestry is based upon reasonable knowledge about their silvicultural characteristics combined with an understanding of the influence of provenance variation on performance. There is also much greater information available about the ecophysiology and silviculture of these species in their native habitats than was the case in the 1970s and 1980s (e.g. Donoso, 1993, 2006), which can be used to inform their deployment in Britain.

As concluded in previous reviews (e.g. MacDonald et al.,

Table 5. Survival and growth of different provenances of nirre (*N. antarctica*), lenga (*N. pumilio*), and coigue (*N. dombeyi*) in three experiments in northern England and Scotland. NP indicates 'not planted' at that site.

Species	Provenance (and approx latitude)	Wykeham (north Yorkshire) Height (m) at 10 years	Wykeham (north Yorkshire) Survival (%) at 10 years	Benmore (west Scotland) Height (m) at 13 years	Benmore (west Scotland) Survival (%) at 6 years	Dalmacallan (south Scotland) Dbh (cm) at 17 years	Dalmacallan (south Scotland) Survival (%) at 17 years
Nirre	Aysen, Chile (44°20'S)	6.5	88.9	NP	NP	13.6	97.2
	Isla Navarinmo, Chile (54°58'S)	5.7	100	6.7	85	10.1	55.6
	West of Ushuaia, Chile (54°80'S)	NP	NP	6.3	100	11.2	91.7
	West of Ushuaia, Chile (54°80'S)	NP	NP	NP	NP	10.9	100
	San Martin, Argentina (40°18'S)	NP	NP	NP	NP	12.5	85.0
Lenga	Coyhaique, Chile (46°45'S)	4.1	94.3	NP	NP	11.9	50.0
	Aysen, Chile (47°S)	5.4	90.0	5.3	76.0	12.3	61.1
	Magellanes, Chile (53°30'S)	4.4	93.0	5.2	88.0	12.1	61.1
	Ushuaia, Argentina (54°80'S)	NP	NP	NP	NP	12.5	85.0
Coigue	Bariloche, Argentina (41°13'S)	NP	NP	Dead	60.0	Dead	0.0

1957; Tuley, 1980; Danby, 1991), both rauli and roble have significant potential for wider use in the future, especially in a warmer climate. However, the risk of attack by *Phytophthora pseudosyringae* remains a real concern and more research is needed to understand the implications of this disease on the prospects for greater use of southern beeches. The fast growth and excellent stem form of rauli would make this the preferred species for future consideration, especially in western Britain. Roble remains a potential species of interest, especially on warmer and drier sites in lowland Britain. The growth rate of roble can be comparable to that of rauli, but its poorer stem form and lesser timber quality suggest that on sites where both species are suitable rauli would be preferred. For both species, it is essential to use seed from more southerly origins or from mature British stands in order to ensure that the planted material is as cold hardy as possible. It is equally important to pay attention to the characteristics of the site where these species are to be planted. Free draining soils will be essential for satisfactory long-term growth and potential frost pockets should be avoided, suggesting that the ideal sites will be on valley sides.

Given historic difficulties in obtaining adequate seed supplies of desired provenances of rauli and roble from Chile and Argentina, it will be important to maintain any existing mature stands and surviving experiments in Britain as future seed sources. Since the parent trees will have survived the 1981/82 and 2010/11 winters there should be some gain in cold hardiness from their progeny. However, it may also be helpful to renew contacts with South American researchers, not least because of the recent attempts to establish tree breeding programmes there with both rauli and roble (Ipinza et al., 2000). Where it occurs, natural regeneration of both species should be accepted and may provide some gain in hardiness, provided always that the regeneration is not affecting native woodland habitats of high conservation value.

The evidence from the limited trials of nirre and lenga suggests that, given their seemingly greater cold hardiness and exposure tolerance, both species could find a future role as broadleaved species for use in diversifying planted conifer forests in upland Britain. However, further trials would be necessary to test their precise site requirements, and also to determine whether material with better stem form could be identified. To date, there appears to be little evidence for advocating the use of any of the other *Nothofagus* species, although further trial plots could be established in arboreta and forest gardens.

In some ways the history of *Nothofagus* species in Britain can be considered a textbook example of how introduction of a non-native species can be seriously affected when the use of unsuitable (i.e. cold sensitive) provenances is combined with a severe winter, resulting in widespread damage and losses in operational plantings and a loss of confidence amongst growers. However, we hope that this article will help land owners and foresters understand the reasons for previous failures and will encourage them to consider further plantings of rauli and roble, provided they can find cold hardy provenances, have suitable sites, and have allowed for the possible disease risks.

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Dr Bill Mason was a silvicultural researcher at the Northern Research Station near Edinburgh for three decades before retiring in 2012. He is now a Research Fellow of Forest Research, is involved in an EU COST Actions on 'Non-Native Species' and is the current Chair of the Continuous Cover Forestry Group (CCFG).

Dr Richard Jinks is a project leader in the Centre for Sustainable Forestry and Climate Change, Forest Research, and is based at the Alice Holt Research Station in Surrey. He works on several research projects, including investigating potential species and provenances that might be useful for helping forests adapt to climate change.

Dr Peter Savill, since retiring from Oxford University in 2006, has been working as a trustee of three charities: Woodland Heritage, the Future Trees Trust and the Sylva Foundation. He has also written *The Silviculture of Trees used in British Forestry* (CABI, 2013) and edited *Wytham Woods - Oxford's Ecological Laboratory* (OUP, 2010).

Dr Scott McG. Wilson is an independent author on forestry and land-use, based in Aberdeen, Scotland. His research and consultancy interests over the past two decades have included selection of optimum species and silvicultural systems to realize multiple benefits from British forests.