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The potential of 44 native and non-native tree species for woodland creation on a range of contrasting sites in lowland Britain

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Summary

A series of species trials were set up to investigate the establishment and early growth (up to 14 years old) of 44 native and non-native tree species on a variety of different site types in lowland Britain. On good quality lowland afforestation sites, *Platanus* x *hispanica* (London plane) established and grew more successfully than the native trees tested, and may be an example of a species that could theoretically be established in anticipation of future climate change. Experiments on a variety of community woodland sites indicated that a range of exotic species, such as X *Cupressocyparis leylandii* (Leyland cypress), may have the potential for establishing a woodland cover on poorly restored land where few other trees would grow. However, on less challenging, better restored sites, a wide range of native species also grew successfully. Further long-term and larger scale trials on a wider variety of sites are required to confirm the potential of the species tested for British conditions. The results from these experiments also showed that relative growth rates of different species can vary through time, highlighting the danger in making premature judgements about species suitability based solely on very early tree growth.

Introduction

During the 20th century, much of the expansion of the forest area in Great Britain was driven by the objective of developing a strategic national reserve of timber. As the heathland, moorland and unimproved pasture that became available for large-scale afforestation was usually of relatively low soil fertility, and often located in the exposed uplands or northern and western parts of the country, exotic conifers such as *Picea sitchensis* (Bong.) Carrière (Sitka spruce), *Picea abies* (L.) H. Karst. (Norway spruce), *Pseudotsuga menziesii* (Mirb.) Franco (Douglas fir), *Larix kaempferi* (Lindl.) Carrière (Japanese Larch), *Larix decidua* Mill. (European Larch), *Pinus nigra* ssp. *laricio* Maire (Corsican pine), *Pinus contorta* Loudon (lodgepole pine) and the native *Pinus sylvestris* L. (Scots pine) became the species of choice on these sites where timber production was the primary aim (Macdonald *et al.*, 1957).

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In the late 1980s, the introduction of the Woodland Grant Scheme and in particular the Farm Woodland Scheme, followed in the early 1990s by the Farm Woodland Premium Scheme, provided increased government incentives for private landowners to convert surplus, better quality agricultural land into forests. Initially, the primary aim of many woodlands established under these schemes was timber production, and although more fertile sites potentially offered improved growth rates, there were also particular silvicultural challenges to address such as defining appropriate cultivation and weeding regimes and selection of appropriate species (Hibberd, 1988; Williamson, 1992; Willoughby and Moffat, 1996). Research into species selection for the afforestation of abandoned agricultural land has taken place in other countries (e.g. Michaud and Permingeat-Couty, 1994; Vares *et al.*, 2003). However, although some work has since taken place in the UK on a limited range of species, involving studies of yield potential (Matthews *et al.*, 1996), tree improvement (Cundall *et al.*, 2003; Savill *et al.*, 2005) and agroforestry systems (Incoll *et al.*, 1997; Hislop and Claridge, 2000), in the 1980s there was little contemporary British evidence on which to base comparisons of species performance on better quality, more fertile land recently converted from agriculture.

The instigation of initiatives such as the Community Forests, the National Forest and the National Urban Forestry Unit in Britain in the 1990s stemmed from an increasing recognition of the importance of providing multiple benefits to local urban communities when new woodlands are created (Countryside Commission, 1987; Forestry Commission, 1998, 2000, 2001). Most community woodlands have an emphasis on meeting the needs of local people, to be achieved in part through adopting a suitable planting design. Local demands on woodlands can include a requirement for recreational opportunities, landscape improvement, conservation and the provision of locally utilizable produce (Hodge, 1995). In recent years, the presumption of many practitioners has been that native species can best fulfil these needs. However, a wide range of generally untested, non-native species exist that may offer a similar or greater potential.

Many urban forests are characterized by the relatively poor quality of the sites that become available for woodland establishment. Particular opportunities exist to improve the local environment through woodland establishment, after suitable restoration, on brownfield sites such as landfills, colliery spoils, quarries and contaminated land (Moffat and McNeill, 1994; Hutchings, 2002). Recommendations for species choice on restored industrial sites exist (Dobson and Moffat, 1993; Moffat and McNeill, 1994; Kennedy and Moffat, 1999; Roots, 2005), and Rawlinson *et al.* (2004) have recently reported on the early growth of a wide range of species on poorly reclaimed sites. However, there appear to be few reports of comparative studies, particularly covering longer term growth and performance of native species both on poorly restored and on other challenging, non-man-made, urban woodland sites in the UK.

As the evidence for global climate change has increased, so has the concern over the future adaptability of tree species grown in the UK. Under the most extreme predictions of climate change, it is thought that much of southern England may become unsuitable for timber production using species such as *Fagus sylvatica* L. (beech) and *Fraxinus excelsior* L. (ash). In order to maintain a broadleaved woodland cover in the south of England, one approach that has been proposed is to plant non-native species that are better adapted for hotter and drier conditions (e.g. *Robinia pseudoacacia* L. (false acacia)) in advance of any climate change (Broadmeadow *et al.*, 2005). However, the authors also recommend that the performance of these alternative species under the oceanic climate of the UK should be determined before any widespread planting takes place.

Introduction of new species in the past has typically followed a pattern of initial establishment in gardens and arboreta, followed by small-scale plantings of promising species on estates or public land, before the most successful species are established in larger plantations 20–50 years later (Savill *et al.*, 1997). Of the wide variety of individual species growing in arboreta, most fail to progress to plantation scale establishment due to their unsuitability for the site or climate leading to poor growth or survival or difficulties in propagation. Others are rejected because they do not yield suitable timber products or otherwise fail to meet the objectives held for the woodland (Savill *et al.*, 1997). White (1996) estimated that ~2500 species of tree will grow and survive out of doors in some part of Britain, but probably only ~180 species have any potential for widespread plantation use (White, 1994). Of these, fewer than 60 species are currently growing as significant high forest components of British woodlands >2 ha in size (Forestry Commission, 2003). A significant factor in the current lack of enthusiasm of land managers for planting new exotic species probably results from the increasing appreciation of the wider environmental benefits of utilizing native species within more naturalistic woodland designs (Rodwell and Patterson, 1994), a practice also encouraged by government grants. However, many land managers may also be reluctant to establish alternative exotic species for which there is no proven volume market for any harvestable timber, even if tree growth rates are satisfactory. In addition, without significant numbers of managers taking a leap of faith and opting to plant a promising new species in order to establish a significant and sustainable supply, markets for new varieties of timber are unlikely to develop to any worthwhile extent. Hence, practitioners' concerns can become self-fulfilling.

In the work reported here, a series of species trials were set up in an attempt to address some of the issues outlined above. In the first experiment at Boxworth (Cambridgeshire) (see Figure 1 for a location map), five native and four commonly used exotic species were trialed on a site similar to those which were at the time being targeted for planting under the newly introduced Farm Woodland Scheme. The second experiment was replicated on two good quality agricultural sites, Fritton (Norfolk), and Shutebridge (Devon). Nine exotic species were selected with the aim of identifying species that might outperform *F. excelsior* and *Quercus robur* L. (pedunculate oak), common species choices for such sites. In addition, tree species were chosen for their potential to produce timber that might be valuable, and hence readily marketable, even if produced in relatively small quantities. The third experiment was replicated at four sites, Aldewood (Suffolk), Bagworth Heath (Leicestershire), Rockbeare (Devon) and St Neots (Cambridgeshire), and used 17 mainly exotic species, judged to have potential for establishing woodland cover, and producing timber, on difficult and degraded Community Woodland sites. The fourth experiment, repeated on three sites at Barton-under-Needwood (Staffordshire), Bagworth Heath (Leicestershire) and Church Gresley (Derbyshire), was set up to investigate the performance of 17 native species on a range of both good quality, and poor quality degraded sites, within the National Forest area (Countryside Commission, 1987).

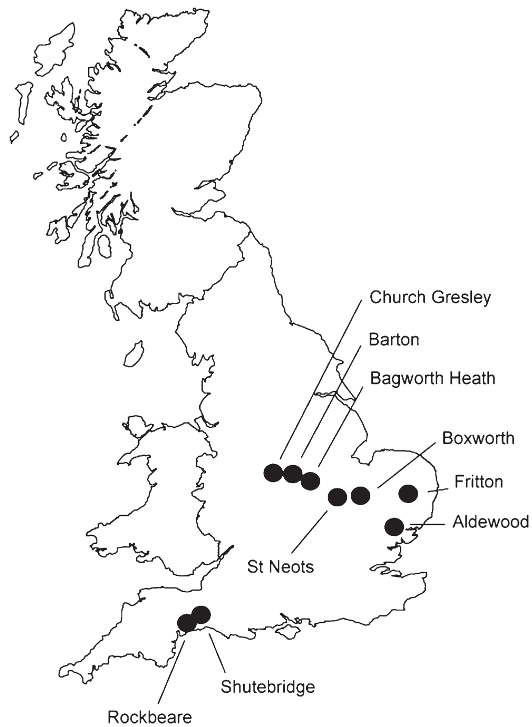

Figure 1. Location map for species experiments.

Materials and methods

Experiment 1 – Boxworth

The experiment was located at Agricultural Development and Advisory Service (ADAS) Boxworth Experimental Husbandry Farm and was chosen as typical of the type of farmland that was anticipated would become available for afforestation under new grant schemes. Site and establishment details are given in Table 1, and species used and initial plant size are shown in

Table 5. Two-year-old bare root-planting stock was used, except for *P. nigra* ssp. *laricio* Maire (Corsican pine) which was planted as 1-year-old containerized stock grown in Japanese paper pots (F308 size), and *Populus* x *canadensis* cv. Gibecq Moench (hybrid black poplar) which was planted as cuttings. All stock was purchased from reputable nursery suppliers. Trees were planted at 2 × 2 m spacing, except for the *P.* x *canadensis* cuttings which were inserted at 4 × 4 m spacing. Each 30 × 32 m plot contained 240 trees (64 for poplar), with assessments carried out only on the central 5 × 5 trees. There were two replicates of each of the nine species, laid out in two randomized blocks, giving 18 plots in total. Herbicides were used to keep a 1-m^2 area weed-free around each tree from April to August for the first 6 years after planting, and the inter-row areas were regularly mowed. Any tree deaths were replaced with individuals of the same species, but these were not subsequently assessed. Height (to the nearest 0.1 cm), stem diameter (to the nearest 0.1 mm) at 10 cm above ground level and survival were recorded after planting and at the end of the growing season periodically over the 14-year period the experiment was maintained.

Experiment 2 – Fritton and Shutebridge

This experiment was partially replicated on two good quality ex-agricultural sites at Fritton and Shutebridge – see Table 1 for site and establishment details and Table 6 for species used and initial plant size. Species were selected for their potential to outperform more traditional choices for such sites (represented by *F. excelsior* and *Q. robur*), and for their potential to produce high value timber that might be readily marketable even in small quantities. A detailed rationale for individual species choice is given in Table 2. Two-year-old bare root-planting stock was used. Stock was sourced from reputable supplies, or grown from seed at Headley Research Nursery, UK (51° 08′ N, 1° 51′ W). Trees were planted at 2 × 2 m spacing, and each 22 × 22 m plot contained 121 trees, with assessments carried out only on the central 7 × 7 trees. There were two replicates of each of the 11 species at Fritton, six at Shutebridge, laid out in two randomized blocks, giving 22 plots at Fritton and 12 plots at Shutebridge. A three-row buffer of *F. excelsior* was planted round the outside of both experiments. Herbicides were used to keep a 1-m^2 area weed-free around each tree from April to August for the first 4 years after planting, and any dead trees were replaced but not assessed. Height (to the nearest 0.1 cm), stem diameter (to the nearest 0.1 mm) at 5 cm above ground level and survival were assessed after planting and at the end of the growing season periodically over the 9-year experiment. Tree form was assessed at Fritton in May 2004, by visually ranking trees on a scale of 1–3, where 1 was a potentially excellent timber tree of high commercial value, 2 was a potential timber tree with some flaws and 3 was a tree that was not 1 or 2 and was a candidate for early thinning.

Experiment 3 – Aldewood, Bagworth Heath, Rockbeare and St Neots

The experiment was replicated on four poor quality or challenging sites for tree establishment at Aldewood, St Neots, Rockbeare and Bagworth Heath – see Table 3 for details and Tables 7 and 8 for initial plant size and species used. Non-native species were selected for their potential to establish a woodland cover and produce timber on difficult and degraded sites – see Table 2 for the detailed rationale for individual species. The native species *Q. robur* was included for comparison. One- to two-year-old bare root plants were used, except for *P. nigra* which was cell grown. Stock was sourced from reputable supplies or grown from seed at Headley Research Nursery, UK (51° 08′ N, 1° 51′ W). *Platanus* x *hispanica* Münchh. (London plane) and *Quercus* x *turneri* Willd. (Turner's oak) were not planted at Bagworth Heath until February 1995 and December 1995, respectively, due to supply problems. Trees were planted at 1.8 × 1.8 m spacing, and each 14.4 × 14.4 m plot contained 64 trees, with assessments carried out on all trees. There were three replicates of each of the 17 species, laid out as three randomized blocks, giving 51 plots in total. *Acer campestre* L. (field maple) was planted around any plot edges not abutting other treatments. *Acer campestre* was also used to replace any dead trees in all the species plots, to maintain conditions of even competition. Herbicides were

Table 1: Site details for the species trials at Fritton and Shutebridge, and for Boxworth

	Boxworth	Fritton	Shutebridge
Planting date	March 1989	March 1995	December 1994
UK grid reference	TL 343622	TM 403979	SY 020928
Latitude/longitude	52.24° N, 0.03° W	52.53° N, 1.54° E	50.73° N, 3.39° W
Elevation (metre above sea level)	50	20	40
DAMS*	12	12	12
WHC†	2	2	2
Continentality‡	11	10	8
Annual average rainfall (mm)§	555	600	950
Annual average growing degree days (>5°C)§	1778	1784	1999
Annual average soil moisture deficit (mm)§	206	233	173
Ecological site classification¶	Moist, very rich	Slightly dry, medium	Moist, rich
Topography	Slightly undulating	Slightly undulating	Slightly undulating
Underlying geological formation	Glacial deposits over Oxford clay	Norwich Crag, Red Crag and Chillesford clays	Permian Marl
Soil#	411d Hanslope slowly permeable, calcareous clayey soil	572n Burlingham 1 deep sandy loam	572f Whimple 3 heavy gleyed brown earth and loam over clay
Previous land use and vegetation	1930–1940 abandoned land; managed grassland until 1980, heavy arable land since with crops of winter wheat, beans and winter oilseed rape	Arable for many years, set-aside in 1992; vegetation grass and thistle	Ex-arable, last crop was barley, removed in September 1994; little vegetation remained on site
Protection	Rabbit fence	Rabbit fence	Rabbit fence
Initial site preparation	Sprayed with contact herbicide, ploughed, then re-sprayed with contact herbicide	Uncultivated; pre-planting application of contact herbicide	Deep tine ripped at 1-m centres, ploughed and harrowed

* Total windiness score, using DAMS (Detailed Aspect Method of Scoring) for measuring the exposure of a site following Quine and White (1993) from Pyatt *et al.* (2001) and field assessment. Measure includes components for wind zone, elevation, topex and aspect, but not soil.
† WHC (windthrow hazard class) following Quine and White (1993) adds effect of soil type to total windiness score.
‡ Continentality – based on the Conrad Index, from Pyatt *et al.* (2001).
§ From Pyatt *et al.* (2001).
¶ Ecological Site Classification (Pyatt *et al.*, 2001) giving soil moisture and soil nutrient regimes.
\# Soil Association from Avery (1980).

used to keep a 1-m^2 area weed-free around each tree from April to August for each of the 5 years the experiment was maintained. Height (to the nearest 0.1 cm), stem diameter (to the nearest 0.1 mm) at 5 cm above ground level and survival were assessed after planting and at the end of each growing season.

Experiment 4 – Barton, Bagworth Heath and Church Gresley

The experiment was replicated on three varying quality sites, Barton-under-Needwood, Bagworth Heath and Church Gresley, see Table 4 for details, and Tables 9 and 10 for initial plant size

Table 2: Rationale for the species choice for Experiments 2 and 3, showing summary of site characteristics, with potential species characteristics based on experience of field and arboreta studies, as reported by Hibberd (1989) and White (1994, 1996)

Species	Acid soil	Alkaline soil	Dry soil	Moist soil	Heavy clay soil	Compacted/ anaerobic soil	Other characteristics
Ailanthus altissima	X	X	X		X	X	Rapid cover on very poor sites, volume, low quality timber
Alnus cordata			X	X	X		Best dry site alder in Britain, good nurse and site improver, amenity, soil enrichment, low quality timber
Alnus incana	X			X	X	X	Nurse to more valuable species, cover, shelter, soil enrichment
Acer saccharinum	X				X	X	Amenity, quality timber
Betula papyrifera	X		X				Amenity, timber
Corylus colurna		X	X	X	X	X	Hardy amenity tree, quality timber*
X *Cupressocyparis leylandii*	X	X	X	X	X	X	Fast growing, shelter, timber, volume, low quality timber
Catalpa speciosa					X	X	Amenity, wood products
Fraxinus excelsior	X	X		X	X		Good quality fertile, moist, well-drained sites, quality timber
Fraxinus pennsylvanica	X		X	X		X	Amenity, pioneer, cover, timber
Ginkgo biloba			X		X	X	Urban tolerant, amenity
Juglans nigra				X	X		Good quality, fertile, moist, well-drained, sheltered low elevation sites, quality timber*
Juniperus virginiana		X	X				Low elevation, quality timber*
Laburnum alpinum	X	X	X				Thin and rocky soils, ornamental, amenity, quality timber*
Laburnum anagyroides	X	X	X				Thin and rocky soils, ornamental, amenity, quality timber*
Liriodendron tulipifera		X	X	X	X		Low elevation sites, tolerant of air pollution, amenity, quality timber*
Platanus x *hispanica*	X	X	X	X	X	X	Fast growing, tolerant of air pollution, shelter, amenity, quality timber*
Populus alba	X		X	X	X		Hardy pioneer, shelter, cover, site protection, wood products
Pinus nigra ssp. *laricio*	X	X	X	X	X		Shelter, timber
Pyrus communis				X			Good quality, fertile, well-drained, low elevation sites, amenity, quality timber*
Quercus robur	X		X		X		Amenity, quality timber
Quercus rubra	X		X		X		Amenity, quality timber
Quercus x *turneri*	X						Amenity, quality timber
Robinia pseudoacacia	X		X		X	X	Tough, good growth on poor sites, tolerates city conditions, cover, amenity, quality timber*
Site							
Fritton	X		X				
Shutebridge	X			X	X		
Aldewood	X		X				
Bagworth Heath					X	X	
Rockbeare					X	X	
St Neots		X		X	X		

* Potentially high value, decorative timber that might be readily marketable even in small quantities.

Table 3: Site details for the Community Forest species trials series

	Aldewood	Bagworth Heath	Rockbeare	St Neots
Planting date	December 1993	March 1994	February 1994	February 1994
UK grid reference	TM 356477	SK 456072	SY 062945	TL 231594
Latitude/longitude	52.08° N, 1.44° E	52.66° N, 1.33° W	50.74° N, 3.33° W	52.22° N, 0.20° W
Elevation (metre above sea level)	13	144	159	50
DAMS*	13	13	13	12
WHC†	2	4	4	2
Continentality‡	10	11	8	11
Annual average rainfall (mm)§	600	750	950	550
Annual average growing degree days (>5°C)§	1850	1524	1747	1783
Annual average soil moisture deficit (mm)§	237	155	143	204
Ecological site classification¶	Slightly dry, poor	Not applicable	Not applicable	Moist, very rich
Topography	Level	Artificial plateau raised above surrounding level topography	Gentle slope, artificially raised above surrounding land	Level
Underlying geological formation	Pleistocene, Red Crag	Drift over Permo-Triassic and Carboniferous reddish mudstone	Mesozoic and Palaeozoic siltstone and shale	Upper Jurassic, Oxford clay
Soil#	551g Newport 4 deep well-drained sandy soil with flints	Coal-washed spoil overlain by 15–40 cm of brown silty clay loam topsoil, pH 6.6	Old capped silt pond. Inert material to an unknown variable depth, heavy clay/sand, thin loam topsoil	411d Hanslope slowly permeable, calcareous clayey soil
Previous land use and vegetation	Scots pine, clear felled 1992; vegetation bracken, bramble and gorse	Colliery spoil tip with low-grade restoration by land forming; fescues with 5% wild flower mix sown	Working silt lake for nearby quarry for over 20 years; capped with landfill and 2–5 cm topsoil; very little vegetation, nearby vegetation is gorse, birch, uddleia, rush, annual grasses	Arable land for many years; recently harvested oilseed rape, few typical agricultural weeds
Protection	Rabbit and roe deer fence, vole guards where necessary	Rabbit and roe deer fence, vole guards where necessary	Rabbit and roe deer fence, vole guards where necessary	Rabbit and roe deer fence, vole guards where necessary
Initial site preparation	De-stumped and windrowed by March 1993	Fertilized with 600 kg ha^{-1} of NPK and 600 kg ha^{-1} of triple super phosphate; coarse limestone spread at 12 $tonneshectare^{-1}$ to buffer rising acidity caused by presence of iron pyrites; wing tine ripped	Wing tine ripped to a depth of 0.5–1 m; rabbit and deer fenced	None

* Total windiness score, using DAMS (Detailed Aspect Method of Scoring) for measuring the exposure of a site following Quine and White (1993) from Pyatt *et al.* (2001) and field assessment. Measure includes components for wind zone, elevation, topex and aspect, but not soil.
† WHC (windthrow hazard class) following Quine and White (1993) adds effect of soil type to total windiness score.
‡ Continentality – based on the Conrad Index, from Pyatt *et al.* (2001).
§ From Pyatt *et al.* (2001).
¶ Ecological Site Classification (Pyatt *et al.*, 2001) giving soil moisture and soil nutrient regimes.
# Soil Association from Avery (1980).

and species used. All species were native to the region except *Acer saccharinum* L. (silver maple) and *Alnus incana* (L.) Moench (grey alder) which were included for comparison with Experiment 3. Two-year-old planting stock was used. Some stock was sourced from reputable supplies, some grown from seed at Headley Research Nursery, UK (51° 08′ N, 1° 51′ W). Experiment 4 was maintained for five growing seasons at Barton-under-Needwood and Bagworth Heath and for four growing seasons at Church Gresley, which was planted 1 year later. All other methods were as for Experiment 3.

Statistical analysis

Within each series of experiments, the sites were analysed separately, as Bartlett's test for homogeneity of variance showed significantly different variances at the different sites, and in addition, there were no clear patterns to explain site × species interactions. Growth increment was analysed by analysis of variance (GenStat, 2005), initially using a covariate of initial height or stem diameter to determine whether this influenced increment. If the covariate was non-significant was removed from the model and the analysis of variance repeated. Comparisons were also made between each species and the overall population mean (the mean of all species and all plots at the site), by calculating a level above which species were performing significantly better than average, defined as the standard error of the effects × 5 per cent level of the *t* distribution for a one-sided comparison. Analysis of survival was carried out using a generalized linear model with a logit-link and assuming a binomial distribution (GenStat, 2005). Initial height and stem diameter were included in the model as possible explanatory variables. Data were transformed to a log scale prior to analysis to homogenize the variances, before using analysis of variance of repeated measures and fitting an appropriate curve (exponential – Boxworth and Shutebridge, linear/quadratic – Fritton) (GenStat, 2005). For the Fritton-site only, form scores were subject to analysis of variance. For the Boxworth-site only (the longest running experiment), top height was also calculated by taking the average height of the largest diameter trees in each replicate, to allow the use of the yield curves in Edwards and Christie (1981) to estimate yield class, and allow comparisons with the yield class that might be predicted using site characteristics as proposed by Matthews *et al.* (1996).

Results

Experiment 1 – Boxworth

Table 5 shows mean survival, height and stem diameter increment after 14 years for each species. Survival varied significantly between species. Although overall survival across the site was good (>90 per cent), *P. nigra* (82 per cent) and *F. sylvatica* (70 per cent) had significantly lower survival after 14 years than the other species.

Initial height was found to be non-significant as a covariate, but initial diameter was significant ($P = 0.03$) and included in the model for diameter increment. Analysis of variance showed significant growth differences between species. *Populus* x *canadensis* formed the largest trees, on average reaching ~1100 cm in height and 190 mm in diameter after 14 years of growth. *Fraxinus excelsior*, *P. canadensis* and *Thuja plicata* D. Don (western red cedar) all had height increments significantly larger than the average for the site. Stem diameter increment showed a similar pattern, with *P. canadensis* and *T. plicata* again having above average increment for the site, along with *P. nigra*.

Analysis of variance of repeated measures showed significant ($P < 0.001$) differences in growth rate between species over the lifetime of the experiment – see Figure 2. Although *P. avium* showed rapid early growth, its relative growth rate compared with other species had slowed by the end of the experiment. *Pinus nigra* showed the fastest early growth rate but after 5 years had slowed to show a similar relative growth rate to the other species.

Experiment 2 – Fritton and Shutebridge

Table 6 shows mean survival, height and stem diameter increment after 9 years. Survival varied significantly between species at both sites. Overall survival was good at ~90 per cent for both

Table 4: Site details for the National Forest native species trials series

	Barton	Bagworth Heath	Church Gresley
Planting date	April 1994	April 1994	February 1995
UK grid reference	SK 201182	SK 456073	SK 296174
Latitude/longitude	52.76° N, 1.70° W	52.66° N, 1.33° W	52.75° N, 1.56° W
Elevation (metre above sea level)	52	136	110
DAMS*	11	13	11
WHC†	2	4	3
Continentality‡	11	11	11
Annual average rainfall (mm)§	680	750	700
Annual average growing degree days (>5°C)¶	1734	1524	1627
Annual average soil moisture deficit (mm)¶	180	155	167
Ecological Site Classification¶	Moist, rich	Not applicable	Moderately dry, medium
Topography	Even	Artificial plateau raised above surrounding level topography	Gently sloping to south-west
Underlying geological formation	Triassic Keuper Marls	Drift over Permo-Triassic and Carboniferous reddish mudstone	Carboniferous shale with coal measures and beds of sandstone
Soil#	831c Wigton Moor, fine and coarse loamy soil	Coal-washed spoil overlain by 15–40 cm of brown silty clay loam topsoil, pH 6.6	572c Hodnet, fine to coarse reddish loam
Previous land use and vegetation	Good quality agricultural land; arable stubble	Colliery spoil tip with low-grade restoration by land forming; fescues with 5% wild flower mix sown	Restored low-grade agricultural pasture; previously subject to China clay workings
Protection	Rabbit fence, vole guards where necessary	Rabbit fence, vole guards where necessary	Rabbit fence, vole guards where necessary
Initial site preparation	Left uncultivated	Fertilized with 600 kg ha^{-1} of NPK and 600 kg ha^{-1} of triple super phosphate; high levels of iron pyrites in spoil; coarse limestone spread at 12 tonnes $hectare^{-1}$. Wing-tine ripped	Ripped using agricultural subsoiler to a depth of 50 cm with 125 cm between lines

* Total windiness score, using DAMS (Detailed Aspect Method of Scoring) for measuring the exposure of a site following Quine and White (1993) from Pyatt *et al.* (2001) and field assessment. Measure includes components for wind zone, elevation, topex and aspect, but not soil.

† WHC (windthrow hazard class) following Quine and White (1993) adds effect of soil type to total windiness score.

‡ Continentality – based on the Conrad Index, from Pyatt *et al.* (2001).

§ From Pyatt *et al.* (2001).

¶ Ecological Site Classification (Pyatt *et al.*, 2001) giving soil moisture and soil nutrient regimes.

\# Soil Association from Avery (1980).

Table 5: Size at planting, height and stem diameter increments and survival after 14 years at Boxworth

Species	Boxworth					
	Initial height (cm)	Initial diameter (mm)	Height increment (cm)	Stem diameter increment (mm)	% survival	Indicative general yield class
Acer platanoides L. (Norway maple)	48.3	5.6	520.1	103.3	92.0 ab	6
Fagus sylvatica L. (beech)	38.6	3.2	423.1	71.4	70.0 c	8
Fraxinus excelsior L. (ash)	35.8	4.4	**989.2**	118.3	100	8
Pinus nigra ssp. *laricio* Maire (Corsican pine)	10.1	2.2	676.6	**165.5**	82.0 bc	16
Populus x *canadensis* cv. Gibecq Moench (hybrid black poplar)	0*	0*	**1097.5**	**190.5**	96.0 a	12
Prunus avium L. (wild cherry)	43.2	5.2	544.6	96.7	92.0 ab	10
Quercus robur L. (pedunculate oak)	55.1	5.7	529.9	112.2	92.0 ab	6
Thuja plicata D. Don. (western red cedar)	34.2	3.2	**827.3**	**202.3**	94.0 ab	24
Tilia cordata Mill. (small leaved lime)	48.1	8.4	537.6	110.1	96.0 a	4
Average	–	–	683.0	130.0	–	–
s.e.d.	–	–	54.55	9.19	n/a	–
Residual d.f.	–	–	8	8	7	–
l.s.d. ($P \leq 0.05$)	–	–	125.84	21.19	n/a	–
P	–	–	<0.001	<0.001	<0.001	–

s.e.d., standard error of difference of means; l.s.d., least significant difference. Mean survival percentages sharing the same letter are not significantly different at the $P \leq 0.05$ level. Species for which all survival observations were 100% were excluded from the analysis, as in this case the contribution to the deviance is zero, and hence the corresponding parameter estimate would be infinite. Height increment and stem diameter increment values shown in bold performed significantly better than the average (as shown) for the site.

* Planted as unrooted cuttings with one live bud above ground, giving effectively zero initial height, and hence zero initial diameter at 10 cm. Yield classes are calculated using height of largest diameter tree per plot to calculate top height, then using yield curves in Edwards and Christie (1981), but are indicative only as yield class data for the early growth of trees is sparse.

Fritton and Shutebridge. However, *Liriodendron tulipifera* L. (tulip tree) had a significantly lower survival than other species at Fritton (49 per cent), as did *Juglans nigra* (61 per cent) and *Juniperus virginiana* (87 per cent) at Shutebridge. No species had a significantly better survival than *Q. robur* or *F. excelsior*.

Initial height and stem diameter covariates were not significant at both sites, and subsequent analysis showed significant growth differences between species. Overall growth was similar at both sites, with the trees of the largest species reaching on average ~760 cm in height and 110 mm in diameter after 9 years. At both sites, *P.* x *hispanica* showed greater than average increases in height, as did *F. excelsior* and *Pyrus communis* L. (pear) at Shutebridge and *Betula papyrifera* Marsh. (paper birch) and *R. pseudoacacia* L. (false acacia) at Fritton. *Platanus* x *hispanica* and *P. communis* at Shutebridge, and *B. papyrifera* at Fritton had higher than average stem diameter increment, corresponding to height increment. However, aside from this diameter increment did not vary greatly. Poorest growth was shown by *J. nigra* L. (black walnut) and *J. virginiana* L. (pencil cedar) at Shutebridge. The comparison species *Q. robur* was only significantly outgrown at both sites by *P.* x *hispanica*. However, *B. papyrifera,*

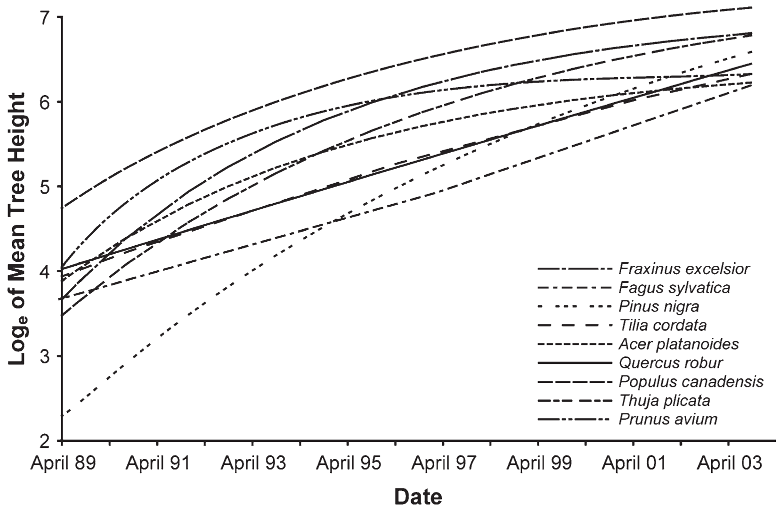

Figure 2. Mean height over 14 years for trees at Boxworth.

and *R. pseudoacacia* at Fritton, and *P. communis* at Shutebridge, had a better height or diameter increment. *Fraxinus excelsior* was not outgrown by any species at Shutebridge, but at Fritton all species except *J. nigra* and *Laburnum anagyroides* Medik. (laburnum) had a greater diameter increment. *Pyrus communis*, *L. anagyroides* Medik. (laburnum) and *R. pseudoacacia* had significantly poorer form than the other species (Table 11).

At both Fritton (Figure 3) and Shutebridge (Figure 4) significant ($P < 0.001$) differences in relative growth rate between species were observed over the lifetime of the experiments. At Fritton, all species showed a fairly constant relative growth rate throughout the trial, except *R. pseudoacacia* and *B. papyrifera*, whose growth rate slowed after 4–5 years. At Shutebridge, *P.* x *hispanica* and *J. nigra* showed a constant relative growth rate over 9 years, whereas the relative growth rates of the remaining species, *F. excelsior*, *Q. robur*, *P. communis* and *J. virginiana*, slowed after 4–5 years.

Experiment 3 – Aldewood, Bagworth Heath, Rockbeare and St Neots

Table 8 shows mean survival, height and stem diameter increment after 5 years for each species. Survival varied significantly between the species on all four sites. Overall survival was greatest at St Neots (71 per cent), followed by Rockbere (68 per cent) then Aldewood (47 per cent), and poorest at Bagworth Heath (21 per cent). X *C. leylandii* generally had the best survival, and on the most challenging site at Bagworth Heath, it was the only species to give anything approaching acceptable survival, with over 75 per cent of the trees being alive at year 5. Survival of species such as *Ailanthus altissima*, *Catalpa speciosa*, *Ginkgo biloba*, *Q. turneri*, *R. pseudoacacia*, *P.* x *hispanica* was very poor throughout, even on the better quality sites at St Neots and Aldewood. Only X *C. leylandii* and *Fraxinus pennsylvanica* at Bagworth Heath, and *Populus alba* at St Neots had significantly better survival than *Q. robur*.

Initial height and stem diameter covariates were non-significant at all sites, and subsequent analysis of variance showed significant growth differences between species. Overall growth was greatest at Rockbere and St Neots with the largest trees being on average ~450 cm in height and 60 mm in diameter after 5 years, and poorest at Bagworth Heath where the largest trees were on average just over 170 cm in height, with a stem diameter of 30 mm. Height increment of X *C. leylandii* cv. Leighton Green (A.B.Jacks. & Dallim.) Dallim. (Leyland cypress) was better than average at all sites, and *Alnus cordata* (Loisel.) Duby (Italian alder) and *P. alba* L. (white poplar)

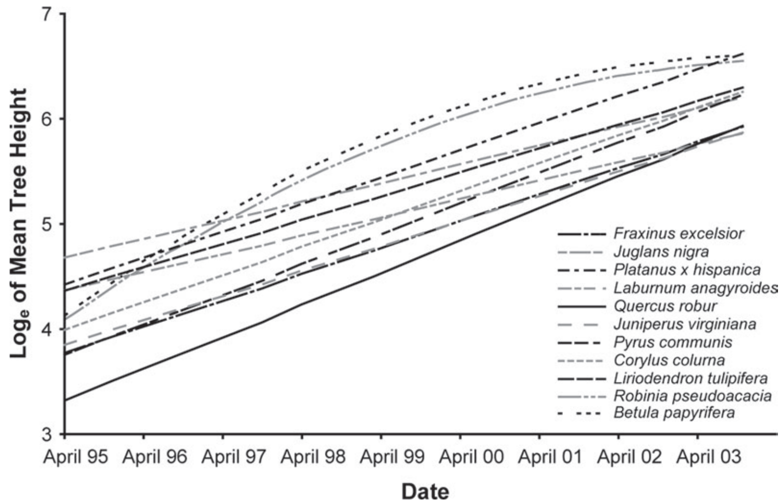

Figure 3. Mean height over 9 years for trees at Fritton.

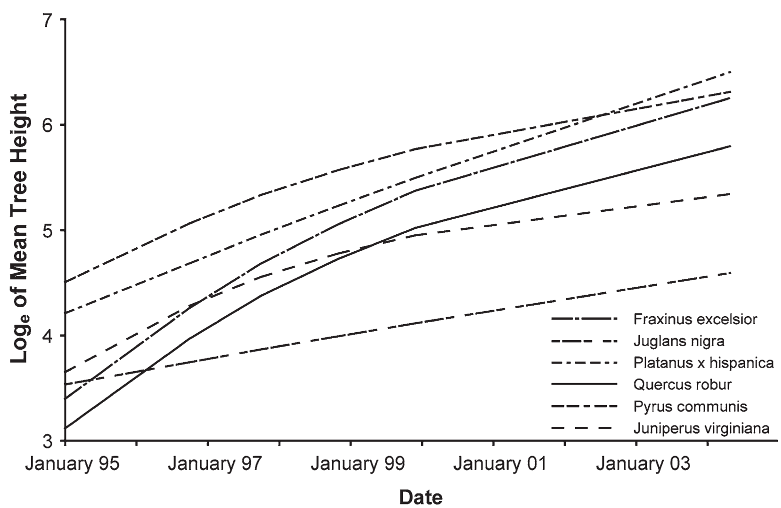

Figure 4. Mean height over 9 years for trees at Shutebridge.

grew taller than average at all sites except Aldewood. *Acer saccharinum*, *P. nigra*, *Q. robur* and *Quercus rubra* L. (red oak) grew taller than average at Aldewood only. *Ailanthus altissima* (Mill.) Swingle (tree of heaven), *Corylus colurna* L. (Turkish hazel), *C. speciosa* Engelm (western catalpa), *F. pennsylvanica* Marsh (green ash), *G. biloba* L. (maidenhair tree), *Laburnum alpinum* (Mill.) J. Presl (Scottish laburnum), *P.* x *hispanica* and *Q.* x *turneri* grew relatively poorly compared with the average on all four sites. Negative height increment for *C. colurna* at Bagworth Heath was the result of wind snap. Stem diameter increment showed a very similar pattern to height increment, with *C. leylandii* again growing better than average at all sites, as well as *P. nigra*. On all sites except Aldewood, *A. cordata* and *P. alba* also had better than average diameter

Table 6: Size at planting, height and stem diameter increments and survival after 9 years at Fritton and Shutebridge

Species	Fritton					Shutebridge				
	Initial height (cm)	Initial diameter (mm)	Height increment (cm)	Stem diameter increment (mm)	% survival	Initial height (cm)	Initial diameter (mm)	Height ncrement (cm)	Stem diameter increment (mm)	% survival
Betula papyrifera Marsh. (paper birch)	56.3	7.2	**702*** $	**100.0*** $	93.9 a	–	–	–	–	–
Corylus colurna L. (Turkish hazel)	75.9	7.9	431	87.6 $	93.9 a	–	–	–	–	–
Fraxinus excelsior L. (ash)	39.8	6.5	298	45.7	96.9 a	32.4	7.2	**469**	89.5	94.9 ab
Juglans nigra L. (black walnut)	39.9	7.7	465	64.1	99.0 a	41.0	4.8	54	19.1	61.2 c
Juniperus virginiana L. (pencil cedar)	41.8	8.3	262	85.9 $	86.7 a	40.1	5.3	170	58.0	86.7 b
Laburnum anagyroides Medik. (laburnum)	63.2	8.8	232	61.9	93.9 a	–	–	–	–	–
Liriodendron tulipifera L. (tulip tree)	96.2	13.9	486	84.7 $	49.0 b	–	–	–	–	–
Platanus x *hispanica* Münchh. (London plane)	88.1	11.8	**619*** $	89.9 $	90.8 a	77.1	9.3	**567***	**95.7**	98.0 a
Pyrus communis L. (pear)	106.9	14.5	353	88.7 $	98.0 a	97.6	12.4	**432***	**108.2**	100
Quercus robur L. (peduinculate oak)	26.6	6.9	309	69.7	91.8 a	25.4	4.3	291	82.9	98.0 a
Robinia pseudoacacia L. (false acacia)	58.9	6.5	**643*** $	89.6 $	83.8 a	–	–	–	–	–
Average	–	–	436	78.9	–	–	–	331	75.5	–
s.e.d.	–	–	116.7	12.71	n/a	–	–	36.0	11.05	n/a
Residual d.f.	–	–	10	10	10	–	–	5	5	4
l.s.d. ($P \leq 0.05$)	–	–	260.1	28.33	n/a	–	–	92.5	28.40	n/a
P	–	–	0.021	0.040	0.010	–	–	<0.001	0.004	0.027

s.e.d., standard error of difference of means; l.s.d., least significant difference. Only six species were planted at Shutebridge. Within a site, * or $ indicates significantly better growth than the comparison species, *Q. robur* (*) or *F. excelsior* ($), using an l.s.d. test. Within each site, mean survival percentages sharing the same letter are not significantly different at the $P \leq 0.05$ level. Species for which all survival observations were 100% were excluded from the analysis, as in this case the contribution to the deviance is zero, and hence the corresponding parameter estimate would be infinite. Height increment and SD increment values shown in bold performed significantly better than the average (as shown) for the site.

Table 7: Initial plant size at the Community Forest species trial sites at Aldewood, Bagworth Heath, Rockbeare and St Neots

	Aldewood		Bagworth Heath		Rockbeare		St Neots	
Species	Initial height (cm)	Initial diameter (mm)	Initial height (cm)	Initial diameter (mm)	Initial height (cm)	Initial diameter (mm)	Initial height (cm)	Initial diameter (mm)
Ailanthus altissima	26.1	2.9	21.0	2.2	13.8	3.1	22.6	3.4
Alnus cordata	52.1	4.8	50.2	4.8	30.2	3.6	35.3	4.3
Alnus incana	55.6	5.0	56.9	5.2	64.3	5.1	60.8	5.8
Acer saccharinum	44.9	3.2	40.0	2.9	45.3	3.6	42.9	3.9
Corylus colurna	78.3	6.9	72.7	5.5	74.5	5.4	79.9	7.0
X *Cupressocyparis leylandii*	60.1	5.8	43.4	5.1	53.7	4.3	44.4	4.7
Catalpa speciosa	36.9	3.9	31.9	3.2	19.6	3.2	33.0	4.3
Fraxinus pennsylvanica	24.8	3.1	20.3	3.7	15.5	3.3	16.3	3.4
Ginkgo biloba	14.3	3.5	11.9	2.9	13.2	3.4	12.1	3.8
Laburnum alpinum	14.7	3.0	14.1	2.4	10.6	2.8	12.4	3.3
Platanus x *hispanica*	53.8	5.5	67.2	5.4	48.4	5.5	62.9	7.5
Populus alba	100.7	7.4	90.2	6.6	89.5	6.5	91.2	7.7
Pinus nigra ssp. *laricio*	12.4	2.5	9.9	2.8	9.8	3.0	9.9	3.2
Quercus robur	25.7	3.4	30.0	3.7	22.2	3.2	23.7	4.0
Quercus rubra	16.8	2.9	11.0	2.4	13.8	3.0	14.9	3.3
Quercus x *turneri*	30.8	4.5	$	$	23.6	4.1	30.4	5.0
Robinia pseudoacacia	43.0	2.9	34.1	2.3	39.8	3.3	38.9	3.3

$, no data.

growth. The comparison species *Q. robur* was only consistently significantly outgrown by X *C. leylandii* at all four sites. However, *A. incana*, *A. saccharinum* and *F. pennsylvanica* and *R. pseudoacacia* outgrew it at Rockbere and St Neots; *P. nigra*, at Rockbere, Aldewood and St Neots and *P. alba* and *A. cordata* at Bagworth Heath, Rockbere and St Neots.

Experiment 4 – Barton, Bagworth Heath and Church Gresley

Table 10 shows mean survival, height and stem diameter increment after 5 years (four for Church Gresley) for each species. Survival varied significantly between the species on all three sites. Overall survival was greatest at Barton (80 per cent), followed by Bagworth Heath (43 per cent) then Church Gresley (38 per cent). *Acer campestre* generally had the best survival across all sites. At the good quality site at Barton, only *Alnus glutinosa*, *Salix caprea* and *A. incana* had less than 70 per cent survival, in the latter case dropping to 17 per cent. Survival of *A. glutinosa*, *A. incana*, *Corylus avellana*, *Populus tremula* and *S. caprea* was very poor at both Bagworth Heath and Church Gresley. In addition, *P. avium* had poor survival at Bagworth Heath, and *A. saccharinum*, *Betula pendula* and *Cornus sanguinea* L. (dogwood) at Church Gresley.

Initial height and stem diameter covariates were non-significant except for initial height at Church Gresley ($P = 0.04$), where it was subsequently included in the model for height increment. At all sites, analysis of variance showed significant growth differences between species. Overall growth was greatest at Barton with the largest species being ~390 cm in height and 55 mm in diameter after 5 years, and poorest at Bagworth Heath where the largest trees were on average ~190 cm in height, with a stem diameter of 25 mm. Height increment of *A. incana*, *B. pendula* (Roth.) (silver birch) and *P. tremula* L. (aspen) was better than average at all sites. *Prunus avium* L. (wild cherry) grew taller than average at

Table 8: Survival, height and stem diameter increments after 5 years at the Community Forest species trial sites at Aldewood, Bagworth Heath, Rockbeare and St Neots

Species	Aldewood			Bagworth Heath			Rockbeare			St Neots		
	Height increment (cm)	Stem diameter increment (mm)	% survival	Height increment (cm)	Stem diameter increment (mm)	% survival	Height increment (cm)	Stem diameter increment (mm)	% survival	Height increment (cm)	Stem diameter increment (mm)	% survival
Ailanthus altissima (Mill.) Swingle (tree of heaven)	$	$	0	–	–	0	15.4	5.4	10.9 e	54.3	12.3	60.9 g
Alnus cordata (Loisel.) Duby (Italian alder)	15.2	6.1	45.8 bc	**100.8***	**28.1***	17.2 cd	**336.9***	**69.6***	89.1 abc	**191.9***	**37.2***	79.2 def
Alnus incana (L.) Moench (grey alder)	111.3	19.1	87.0 a	37.7	10.6	2.1 d	**292.2***	**74.9***	85.4 abc	**179.6***	**29.9***	88.5 bcd
Acer saccharinum L. (silver maple)	**157.1**	27.0	92 .2 a	55.4	10.0	38.0 bc	117.1*	18.8*	82.3 bc	128.0*	18.2	85.4 cde
Corylus colurna L. (Turkish hazel)	−31.0	−0.9	8.9 e	−46.5	0.2	5.7 d	−8.4	7.2	85.9 abc	14.6	10.5	79.7 def
X *Cupressocyparis leylandii* cv. Leighton Green (A.B.Jacks. & Dallim.) Dallim. (Leyland cypress)	**287***	**78.4***	98.4 a	**128.1***	**25.9***	78.6 a	**179.8***	**52.8***	96.9 a	**294.3***	**70.1***	100
Catalpa speciosa Engelm (western catalpa)	10.0	2.5	14.1 de	–	–	0	35.7	9.4	24.0 e	47.4	11.2	28.6 h
Fraxinus pennsylvanica Marsh (green ash)	45.9	8.2	58.3 b	54.0	8.5	72.4 a	87.8*	13.6*	92.7 ab	106.2*	14.3	92.7 abc
Ginkgo biloba L. (maidenhair tree)	–	–	0	18.7	0.8	2.6 d	7.4	0.3	48.4 d	9.4	0.2	38.0 h
Laburnum alpinum (Mill.) J. Presl (Scottish laburnum)	28.3	8.9	41.7 bcd	16.1	3.8	29.2 bc	9.0	3.7	20.8 e	54.5	9.7	72.9 efg
Platanus x *hispanica* Münchh. (London plane)	27.5	5.8	20.8 cde	–	–	0	74.9*	16.6*	52.1 d	78.3	13.4	66.7f g
Populus alba L. (white poplar)	−35.8	2.4	26.6 cde	**105***	**22.9***	40.6 b	**246.0***	**40.4***	96.4 a	**425.7***	**57.8***	98.4 a
Pinus nigra ssp. *laricio* Maire (Corsican pine)	**170.0**	**58.6***	97.4 a	66.3	**18.8**	30.7 bc	102.9*	**37.4***	97.4 a	110.8*	**29.5***	96.4 ab
Quercus robur L. (pedunculate oak)	**130.3**	**29.0**	94.8 a	46.5	9.0	35.4 bc	27.5	6.4	83.9 abc	32.1	7.6	87.0 bcd
Quercus rubra L. (red oak)	**139.7**	20.9	91.7 a	25.0	3.6	2.6 d	23.0	4.1	73.4 c	5.7	0.8	65.1 fg
Quercus x *turneri* Willd. (Turner's oak)	12.9	3.4	14.6 de	–	–	0	13.0	3.9	75.0 bc	−5.3	2.3	25.0 h
Robinia pseudoacacia L. (false acacia)	**200.9**	**37.0**	56.8 b	–	–	0	118.6*	26.4*	49.5 d	**201.1***	**42.1***	35.4 h
Average	84.6	20.4	–	50.6	11.9	–	98.7	23.0	–	113.4	21.6	–
s.e.d.	35.68	5.93	n/a	24.72	5.18	n/a	16.69	3.59	n/a	24.95	3.75	n/a
Residual d.f.	27	27	28	17	17	22	32	32	32	32	32	30
l.s.d. ($P \leq 0.05$)	73.20	12.16	n/a	52.16	10.92	n/a	33.99	7.31	n/a	50.81	7.64	n/a
P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

s.e.d., standard error of difference of means; l.s.d., least significant difference. $, only two trees survived, not included in analysis; –, no survival or not applicable; *, Within a site, significantly better growth than the comparison species, *Q. robur*, using an l.s.d. test. Within each site, mean survival percentages sharing the same letter are not significantly different at the $P \leq 0.05$ level. Species with 100% survival are not included in the survival analysis. Species for which all survival observations were either 100% or 0% were excluded from the analysis, as in both these cases the contribution to the deviance is zero, and hence the corresponding parameter estimates would be infinite. Height increment and SD increment values shown in bold performed significantly better than average (as shown) for the site.

Table 9: Initial plant size at the National Forest native species trial sites at Barton, Bagworth Heath and Church Gresley

	Barton-under-Needwood		Bagworth Heath		Church Gresley	
Species	Initial height (cm)	Initial diameter (mm)	Initial height (cm)	Initial diameter (mm)	Initial height (cm)	Initial diameter (mm)
Acer campestre	53.6	4.1	–	–	42.4	2.4
Alnus glutinosa	30.5	3.0	29.7	2.3	46.4	4.4
Alnus incana	16.6	4.5	21.5	3.7	54.7	8.2
Acer saccharinum	37.8	3.5	38.7	2.8	50.6	4.1
Betula pendula	32.3	3.2	62.4	3.2	37.7	2.9
Corylus avellana	57.9	4.4	59.5	3.7	37.9	5.5
Crataegus monogyna	35.0	4.1	35.8	3.2	46.2	3.6
Cornus sanguinea	45.2	3.2	43.3	2.4	28.6	2.3
Euonymus europaeus	54.3	5.5	56.8	4.8	41.5	5.0
Fraxinus excelsior	30.1	3.9	30.3	3.3	43.4	5.4
Malus sylvestris	41.3	4.2	43.8	3.7	62.2	5.6
Prunus avium	41.1	7.3	51.5	6.1	30.9	3.4
Populus tremula	66.4	4.9	70.5	3.7	54.6	8.3
Quercus robur	26.0	3.5	20.2	2.6	29.0	3.4
Rhamnus cathartica	46.9	4.3	47.0	3.3	50.4	3.9
Salix caprea	102.3	11.1	87.9	8.5	21.6	9.9
Tilia cordata	65.7	7.7	70.0	5.6	32.8	3.6

Barton only, *A. glutinosa* (L.) Gaertn. (alder) at Bagworth Heath only, and *S. caprea* L. (goat willow) performed well at Bagworth Heath and Church Gresley but not at Barton. *Acer campestre*, *C. avellana* L. (hazel), *P. avium* and *Tilia cordata* Mill. (small leaved lime) grew relatively poorly on the most challenging site at Bagworth Heath and *A. glutinosa* grew poorly at Church Gresley. Negative height increment for *C. colurna* and *T. cordata* at Bagworth Heath was the result of wind snap. Generally, stem diameter increment showed a similar pattern to height increment, although there were some variations between sites.

Discussion

As already noted, although some of the minor species reported here have been subject to investigation in arboreta or nurseries, or in field-based provenance trials (Cundall *et al.*, 2003; Savill *et al.*, 2005) or agroforestry experiments (Incoll *et al.*, 1997; Hislop and Claridge, 2000), only a limited number of the published studies report direct measurements of survival or growth increment for individual species. Yield models exist based on extensive records of forest growth and yield from permanent sample plots throughout Britain (Edwards and Christie, 1981; Matthews *et al.*, 1996), but the models only cover a limited range of species and are not generally applied to trees less than 10 years old due to limited data on early tree growth. Therefore, for many of the species investigated in our work, there appear to be few published studies on which to make direct comparisons of growth in British conditions.

On average across the species, at Boxworth, Shutebridge, Aldewood and St Neots, ~10–30 per cent of the total survival loss at the end of the each experiment occurred in the first year. At Bagworth Heath, Church Gresley and Rockbeare, 50–90 per cent of losses occurred in the first year. Initial stock size was not consistently significant as a covariate for final survival and hence removed from the model for analysis (data not presented). However, for Bagworth Heath, Church Gresley and Rockbeare in particular, survival of the species used may have been more affected by the incomplete restoration of these previously industrial sites, rather than any inherent inability to cope with the prevailing climatic conditions. Judgements on suitability must

Table 10: Survival, height and stem diameter increments at the National Forest native species trial sites at Barton (5 years), Bagworth Heath (5 years) and Church Gresley (4 years)

Species	Barton-under-Needwood			Bagworth Heath			Church Gresley		
	Height increment (cm)	Stem diameter increment (mm)	% survival	Height increment (cm)	Stem diameter increment (mm)	% survival	Height increment (cm)	Stem diameter increment (mm)	% survival
Acer campestre L. (field maple)	138.4	24.8	98.4 a	$	$	$	37.8	7.3	70.3 abc
Alnus glutinosa (L.) Gaertn. (alder)	197.0	33.6	55.7 c	**107**	**27.2**	35.9 cdef	5.8	1.2	3.6 g
Alnus incana (L.) Moench (grey alder)	**208.1**	29.2	17.2 d	**79**	**22.7**	27.6 cdef	**155.7**	**25.7**	6.3 g
Acer saccharinum L. (silver maple)	175.4	28.7	80.2 abc	26.6	5.3	53.6 abcd	55.4	7.7	26.6 efg
Betula pendula (Roth.) (silver birch)	**274.0**	**49.8**	72.4 abc	**83.5**	**18.0**	53.1 abcd	**112.2**	**17.5**	14.1 fg
Corylus avellana L. (hazel)	72.7	13.1	80.7 abc	−22	0.6	11.5 cdef	35.3	6.6	33.9 def
Crataegus monogyna Jacq. (hawthorn)	138.8	26.3	89.6 ab	62.6	10.2	45.8 bcde	39.3	6.3	80.7 ab
Cornus sanguinea L. (dogwood)	91.2	15.0	87.5 ab	27.8	5.9	39.1 bcde	32.7	4.8	8.9 g
Euonymus europaeus L. (spindle)	135.9	28.6	97.4 a	34.7	7.9	77.1 a	27.8	2.2	61.5 abcd
Fraxinus excelsior L. (ash)	152.5	26.6	78.6 abc	24.3	8.5	67.2 ab	30.3	7.0	85.9 a
Malus sylvestris (L.) Mill. (crab apple)	166.3	33.7	89.6 ab	60.6	12.3	45.8 bcde	79.8	12.9	57.8 bcd
Prunus avium L. (wild cherry)	**230.0**	**49.4**	79.7 abc	17.2	6.0	12.0 cdef	40.0	7.6	43.2 cde
Populus tremula L. (aspen)	**327.1**	**50.0**	84.4 ab	**118.8**	**20.3**	27.6 cdef	**95.5**	7.1	1.0 g
Quercus robur L. (pendunculate oak)	134.2	26.3	94.8 a	49.8	9.4	60.9 abc	67.7	**15.9**	45.8 cde
Rhamnus cathartica L. (buckthorn)	109.1	20.6	91.7 a	36.3	7.5	41.7 bcde	40.6	5.6	50.5 cde
Salix caprea L. (goat willow)	138.1	32.9	63.5 bc	**90.1**	**21.3**	21.9 cdef	**139.1**	**19.1**	16.1 fg
Tilia cordata Mill. (small leaved lime)	95.7	23.8	92.2 a	−10.5	4.8	41.1 bcde	22.5	6.5	36.5 def
Average	163.8	30.1	–	49.1	11.7	–	59.9	9.5	–
s.e.d.	29.03	5.41	n/a	21.93	3.90	n/a	20.19	3.06	n/a
Residual d.f.	32	32	32	30	30	30	29	30	32
l.s.d. ($P \leq 0.05$)	59.14	11.02	n/a	44.79	7.96	n/a	41.30	6.254	n/a
P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

s.e.d., standard error of difference of means; l.s.d., least significant difference. Values recorded after five growing seasons at Barton-under-Needwood and Bagworth Heath and after four growing seasons at Church Gresley. Within each site, mean survival percentages sharing the same letter are not significantly different at the $P \leq 0.05$ level. Height increment and SD increment values shown in bold performed significantly better than average (as shown) for the site. $, not planted at Bagworth Heath.

Table 11: Mean form scores for Fritton species trial

Species	Mean form score
Betula papyrifera	1.8
Corylus colurna	2.1
Fraxinus excelsior	2.1
Juglans nigra	2.1
Juniperus virginiana	2.3
Laburnum anagyroides	3.0
Liriodendron tulipifera	2.3
Platanus x *hispanica*	2.0
Pyrus communis	3.0
Quercus robur	2.1
Robinia pseudoacacia	2.6
s.e.d.	0.24
Residual d.f.	10
l.s.d. ($P \leq 0.05$)	0.53
P	0.006

s.e.d., standard error of difference of means; l.s.d., least significant difference. Form scored on a 1–3 scale, where 1 was a potentially excellent timber tree of high commercial value, 2 was a potential timber tree with some flaws and 3 was a tree that was not 1 or 2 and was a candidate for early thinning.

also be mindful of the fact that species may respond differently to less intensive operational as opposed to experimental standards of post-planting maintenance. The results from the longer term experiments at Boxworth, Fritton and Shutebridge showed that relative growth rates of different species can vary through time, highlighting the danger in making premature judgements about species suitability based solely on very early tree growth. Hence, for those sites which were assessed for the first 5 years only, future relative growth rates, and hence perceived suitability of different species, may vary as time progresses. Key limiting or permitting climatic variables for individual species may also have changed slightly after the trials were initiated due to global warming. In addition, the specific provenance of an individual species may have a significant impact on establishment success.

The site at Boxworth was typical of some of the better quality sites that have become available for new woodland creation over the past decade. Despite the relatively heavy clay soil and potential for profuse, highly competitive weed growth, given the adoption of appropriate silvicultural practice it has been predicted that a wide range of species would be suitable choices for such sites (Pyatt *et al.*, 2001). This includes all the species tested in our experiment apart from *T. plicata*, which Pyatt *et al.* (2001) suggest might be unsuitable due to predicted soil moisture deficit. Our experiment showed that all those species tested, including *T. plicata*, established and grew well, even with an annual average soil moisture deficit for the area of 206 mm (Table 12). However, as trees mature their resource demands grow, and available moisture at the site may yet prove limiting to long-term growth of *T. plicata*. If timber production were an aim, early indications of yield class suggest that *T. plicata* (yield class 24), *P. nigra* (yield class 16) and *P.* x *canadensis* (yield class 12) may be the most productive species on this type of site. Of these, *P. nigra* would be likely to produce the best quality, most saleable timber, provided there is no serious pest or disease problem. For the particular combination of soil type, soil moisture deficit and annual growing degree days historically occurring at the Boxworth site, indicative yield classes from this experiment are generally the same as predicted using the models in Matthews *et al.* (1996) for *P. nigra* and *F. excelsior*, and one class higher (2 $m^3\ ha^{-1}\ year^{-1}$) for *F. sylvatica* and *Q. robur*.

Fritton was drier and better drained than Shutebridge, which is reflected in differences in species performance. Approximate yield classes of between 6 and 8 for *Q. robur* and *F. excelsior*, estimated using actual tree growth (Edwards and Christie, 1981) and site characteristics (Matthews *et al.*, 1996), indicate growth for these reference species is probably within the range that might be expected for such sites. All the species tested, apart from *L. tulipifera* at Fritton and *J. nigra* at Shutebridge, gave acceptable survival and growth, indicating a wide choice of possible future alternatives to the use of native species (Table 12). *Betula papyrifera* grew well at Fritton, and trees were of good form. Other species that established well at Fritton and Shutebridge, but often with poor form, included *J. nigra* and *P. communis*. However, the best performing species were *P.* x *hispanica and R. pseudoacacia*.

Platanus x *hispanica* is thought to have originated in southern France or Spain. Commonly planted in the UK as a street tree, its ultimate size is unknown, but it is often long lived and vigorous – many healthy specimens have reached

Table 12: Suitability of the species tested based on establishment success

	Boxworth (moist, rich, alkaline clay, sheltered)	Fritton (slightly dry, rich, sheltered)	Shutebridge (moist, rich, clay, sheltered)	Aldewood (acid, dry)	St Neots (moist, rich, alkaline clay)	Rockbere (compacted/ anaerobic/ clay)	Bagworth Heath (compacted anaerobic spoil)	Barton (moist, rich, sheltered)	Church Gresley (low-grade restoration)
Acer campestre	–	–	–	–	–	–	–	****	**
Acer platanoides	****	–	–	–	–	–	–	–	–
Acer saccharinum	–	–	–	****	****	****	*	****	*
Ailanthus altissima	–	–	–	*	**	*	*	–	–
Alnus cordata	–	–	–	*	***	*****	*	–	–
Alnus glutinosa	–	–	–	–	–	–	*	**	*
Alnus incana	–	–	–	****	*****	*****	*	*	*
Betula papyrifera	–	*****	–	–	–	–	–	–	–
Betula pendula	–	–	–	–	–	–	**	***	*
Catalpa speciosa	–	–	–	*	*	*	*	–	–
Cornus sanguinea	–	–	–	–	–	–	*	****	*
Corylus avellana	–	–	–	–	–	–	*	****	*
Corylus colurna	–	****	–	*	**	**	*	–	–
Crataegus monogyna	–	–	–	–	–	–	*	****	**
Euonymus europaeus	–	–	–	–	–	–	**	****	**
Fagus sylvatica	**	–	–	–	–	–	–	–	–
Fraxinus excelsior	*****	****	*****	–	–	–	**	**	**
Fraxinus pennsylvanica	–	–	–	**	****	****	**	–	–
Ginkgo biloba	–	–	–	*	*	*	*	–	–
Juglans nigra	–	****	**	–	–	–	–	–	–
Juniperus virginiana	–	****	****	–	–	–	–	–	–
Laburnum alpinum	–	–	–	*	**	*	*	–	–
Laburnum anagyroides	–	****	–	–	–	–	–	–	–
Liriodendron tulipifera	–	*	–	–	–	–	–	–	–
Malus sylvestris	–	–	–	–	–	–	*	****	**
Pinus nigra ssp. *laricio*	*****	–	–	*****	*****	*****	*	–	–
Platanus x *hispanica*	–	*****	*****	*	**	**	*	–	–
Populus alba	–	–	–	*	*****	*****	*	–	–
Populus tremula	–	–	–	–	–	–	*	*****	*
Populus × canadensis	*****	–	–	–	–	–	–	–	–
Prunus avium	****	–	–	–	–	–	*	*****	*
Pyrus communis	–	****	*****	–	–	–	–	–	–
Quercus robur	****	****	****	*****	**	**	*	****	*
Quercus rubra	–	–	–	*****	**	**	*	–	–
Quercus x *turneri*	–	–	–	*	*	**	*	–	–
Rhamnus cathartica	–	–	–	–	–	–	*	****	**
Robinia pseudoacacia	–	*****	–	***	*	*	*	–	–
Salix caprea	–	–	–	–	–	–	*	**	*
Thuja plicata	*****	–	–	–	–	–	–	–	–
Tilia cordata	****	–	–	–	–	–	*	****	*
X *Cupressocyparis leylandii*	–	–	–	*****	*****	*****	***	–	–

This table presents a summary of the data only. For direct comparison of species and sites refer to Tables 5–13, with associated statistical analysis which takes into account the variability in the data. *****, very suitable for the site type in question, >80% survival at the end of the experiment, greater than average growth for the site; ****, suitable for the site, >80% survival, lower than average growth for the site; ***, potentially suitable for the site, 50–79% survival, greater than average growth for the site; **, potentially unsuitable for the site, 50–79% survival, lower than average growth for the site, or survival >80%, but average annual height increment <10 cm; *, unsuitable for the site, <50% survival; –, untested.

30 m tall after 200–300 years (Mitchell, 1996; Johnson, 2003). The species is said to grow well on a range of sites such as poor, man-made or compacted clay soils, so long as summers are warm enough, but is at its best in light, fertile soils (Macdonald *et al.*, 1957; Mitchell, 1996). Within woodlands where lateral growth is restricted, it can have good form, and can also yield decorative timber (White, 1996). This is borne out in our experiments where young *P.* x *hispanica* had better growth and has good form as the native reference species at both Fritton and Shutebridge. However, although performance on the more challenging community woodland sites was better than some native species, it did not fare as well as other exotic species tested.

Robinia pseudoacacia is native to the eastern and mid-western US (Savill, 1991). It is a nitrogen-fixing pioneer species, often found on abandoned fields and dry slopes (Leopold *et al.*, 1998), and is reported as growing well on acid, dry and infertile sandy soils. Hence, it is planted widely in the US on strip-mining sites, and in central Europe (Savill, 1991). In limited British plantings, it is often short lived, although older specimens have reached over 20 m in height (Johnson, 2003). Timber is reported to be very durable (Savill, 1991) and to have potential for decorative work (White, 1994), but trees often suffer from poor form and disease. Extensive breeding programmes have been set up in Europe to improve timber quality (Keresztesi, 1991). In our experiments with unimproved material, *R. pseudoacacia* established well, although with poor form, on the deep sandy soil at Fritton, but survival was poor on the more challenging community woodland sites.

Therefore, based on the results from these two sites, if alternatives to native species are required for good quality, sheltered, fertile lowland new planting sites in the south of Britain, *P.* x *hispanica* would seem to be worth considering. On well-drained sandy soils, *R. pseudoacacia* might be a future option. In addition, *P.* x *hispanica* and *R. pseudoacacia* originate from hotter, drier conditions than are currently present in Britain. Such species could therefore potentially be established in anticipation of future climate change, as a possible strategy for maintaining a broadleaved woodland cover in southern Britain should the most extreme predictions for future global warming over the next 70 years be realized (Broadmeadow *et al.*, 2005). However, further, long-term and larger scale trials on a wider variety of sites – the third and final stage in the assessment cycle of any potential new species as suggested by Savill *et al.* (1997) – are required to confirm the potential of these species. Other long-established introduced species such as *Acer pseudoplatanus* L. (sycamore), *Castanea sativa* Mill. (sweet chestnut) and *Juglans regia* L. (common walnut) were untested in this work, but depending on the scenario might prove to be equally as suitable as more novel exotic species. In addition, due to concerns over invasiveness, under the Wildlife and Countryside Act 1981 and subsequent amendments, it is currently an offence to introduce further specimens of *R. pseudoacacia* into the wild in Scotland.

Although all the Community Forest species trial sites presented challenges to tree establishment, conditions varied from rich but heavy clay (St Neots), to dry sand (Aldewood), a partially reclaimed silt pond (Rockbere) and poorly reclaimed, compacted colliery spoil (Bagworth Heath). There was therefore understandable variation in the performance of individual tree species depending on the severity of the site. X *C. leylandii* is a cross between *Cupressus macrocarpa* and *Chamaecyparis nootkatensis* which originally arose in Wales in the 1880s. It is thought to be tolerant of pollution and capable of growing vigorously on a wide range of soil types (Savill, 1991). The oldest trees in Britain now reach over 30 m in height (Johnson, 2003). At Bagworth Heath, the most challenging site in our experiments and which suffered from severely restricted rooting depth, X *C. leylandii* was the only species to establish satisfactorily. *Fraxinus pennsylvanica* also survived reasonably well, although growth was poor. In its native North America, this species grows on a wide variety of sites, including those that are very wet. In the warmer areas of Britain, the largest and oldest specimens can be over 20 m in height (Johnson, 2003).

On our less challenging community woodland experiment sites, a wider variety of species appeared to have potential as possible alternatives to native species (Table 12). With the native species trials, few species achieved greater than 50 per cent survival, and none more than 90 per cent survival at Bagworth Heath. With the older and slightly better restored site at Church Gresley, only a limited number of native species survived and grew acceptably. On less challenging sites as exemplified by Barton, a much wider range of native species can establish successfully (Table 12). However, comparisons between native and non-native species at Bagworth Heath must be made with caution, as the extreme variability of the site led to differences in performance of the three species common to both the community and native species experiments located there. Similar findings were reported by Rawlinson *et al.* (2004) who found considerable variability in early (3-year) species performance between and within poorly restored sites, and that a wider range of species could survive on the less challenging sites tested.

Our community woodland experiments suggested that on some poorly restored sites, certain exotic species can establish as well as, or in some cases better than, native broadleaves. However, the ultimate suitability of any of these species for use in new community woodland-planting schemes will depend not only how well they are likely to establish but also on the initial objectives of the design, such as the requirements for timber and non-timber products, rapid woodland cover, re-creation of native habitat or other community requirements. For example, in addition to providing a woodland cover on demanding sites, several of the exotic species tested may also have great potential as mature amenity trees, due to their autumn colour, striking form or evergreen foliage. Alternatively, if habitat restoration is the primary aim, very slow growth of native species may be viewed by some practitioners as more acceptable than planting faster growing, exotic species. In reality though, the survival and growth rates in our experiments suggest that these types of poorly restored sites will require extensive additional remediation if designers aspirations for healthy, stable native woodlands are to be realized over the long term. If amenity woodland cover rather than habitat restoration is an overriding objective on challenging, poorly restored sites with no resources for further remediation, it would seem imprudent to routinely exclude a species simply because it is exotic in origin.

Conclusions

The results from these experiments have shown that the relative growth rates of different species can vary through time, highlighting the danger in making premature judgements about species suitability based solely on very early tree growth. Further, long-term and larger scale trials on a wider variety of sites are therefore required to confirm the potential of the species tested here for British conditions. In many cases, particularly on the less challenging experimental sites, native species established as well if not better than the non-natives tested. However, these trials have also shown the potential for establishing a wide range of exotic species, some of which may ultimately prove to be better suited than certain native species for maintaining woodland cover in lowland England, if predicted future extreme climate change scenarios do come to pass.

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None declared.

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