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Original Article

Seventeen coniferous tree species show early promise for future commercial timber production in the UK

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Abstract

In the UK, commercial timber production is dominated by conifer forests consisting primarily of just nine introduced species, with Sitka spruce (*Picea sitchensis* (Bong.) Carr.) making up by far the largest proportion. However, overreliance on such a small range of species poses serious risks, due to the likelihood of future climate change and the increasing incidence of damaging pests and diseases. Diversifying the range of species planted would help to reduce the extent of impacts in the event of a catastrophic failure of one of the UK's principal timber species. Six large scale trials were therefore established across the UK to test the suitability of 17 species as potential alternatives for commercial timber production. Five years after planting many species had successfully established, often performing at least as well as the standard principal species that would otherwise have been used. Some species in particular exceeded expectations. Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) established well on most sites, and may be a more versatile species than is often assumed in the UK. In the long-term it could prove to be a productive alternative to Sitka spruce on some sites, and has potential for wider use in the south and east of the country, where the climate is forecast to become significantly hotter and drier. Maritime pine (*Pinus pinaster* Ait.) also established very well, and may have good potential in our future climate as a fast growing, robust species on suitable freely draining sites. Some other species were consistently very slow growing, and although it is too early to judge them a failure, if they are to be used more widely it is likely that current establishment methods will need to be adapted. Further monitoring is recommended to determine whether the early promise shown by the species tested is fulfilled in the long-term.

Keywords: species trial; common garden; emerging species; principal species; alternatives; sitka spruce

Introduction

The UK has a temperate oceanic climate which is well suited to tree growth. Although only around 35 tree species are regarded as native, there has been a long history of successful introductions from abroad. Since the sixteenth century more than 500 species of tree have been successfully established in gardens and arboreta (Reynolds et al. 2021). In the early twentieth century numerous large scale forest trials were established by Forest Research (the research agency of the Forestry Commission), which led to a relatively small number of mainly coniferous species that showed the most initial promise for timber production being adopted for widespread planting on a commercial basis (Macdonald et al. 1957, Kerr and Jinks 2015). This has been instrumental in driving an expansion of tree cover in the UK, particularly on sites that are relatively marginal for agricultural production, and in the development of thriving forest and timber processing industries.

Currently, woodland covers around 3.28 million ha or 13.5% of the land area of the UK, with around half (48%) of this being made up of coniferous species, and half of broadleaves. Of the coniferous forests, which produce more than 90% of the timber harvested, 96% consists of just nine species:- Sitka spruce (*Picea sitchensis* (Bong.) Carr.); Scots pine (*Pinus sylvestris* L.); Corsican pine (*Pinus nigra ssp. laricio* Maire); Norway spruce (*Picea abies* (L.) H. Karst.) hybrid larch (*Larix x marschlinsii* Coaz); European larch (*Larix decidua* Mill.); Japanese larch (*Larix kaempferi* (Lamb.) Carr.); Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco); and Lodgepole pine (*Pinus contorta* Douglas ex Loudon) (Forest Research 2024). All of these are introduced species, except for Scots pine which is native to Scotland. Collectively these nine conifers have been described as 'principal species', in that they are currently widely used for timber production and will continue to be the dominant species unless adversely affected by a new pest or disease, or climate change (Kerr and Jinks 2015, Reynolds et al. 2021). Of these principal species, Sitka spruce accounts for around 21% of the entire forest cover of the UK and ~50% of all timber produced. Sitka spruce has become so extensively used for a number of reasons:- it produces high yields of timber on a wide range of site types including those with wet, nutrient poor soils and in areas suffering from high wind exposure; it is relatively easy to establish with high initial growth rates; and its low palatability to deer means that, providing there are other food sources nearby, fencing is rarely necessary (Malcolm 1987, Stokes et al. 2023).

However, over-reliance on such a small range of species for commercial timber production poses considerable risks. The UK's climate is changing, with hotter, drier summers and wetter milder winters being predicted, along with a likely increase in extreme weather events (Lowe et al. 2019). Species well adapted to the UK's current climate may be far less suited to that predicted for the 2080s. In addition, since the mid-1990s, probably due to a combination of climate change and increased global trade, there has been a dramatic increase in the incidence of damaging pests and diseases affecting the UK's forests, and this has already had

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a significant impact on the principal commercial timber species. For example, Dothistroma Needle Blight (caused by the pathogens *Dothistroma septosporum* (Dorogin) M. Morelet and *Dothistroma pini* Hulbary (Barnes, Crous, Wingfield and Wingfield)), has led to a widespread decline in growth and in some cases death of plantation grown Corsican pine (Brown and Webber 2008), and Ramorum Disease (caused by the pathogen *Phytophthora ramorum* Werres.) has required the large scale removal of larch species in the west of the country in an attempt to prevent the disease spreading further (Brasier and Webber 2010; Forest Research 2024). In both cases this has led to these tree species no longer being suitable for planting across significant parts of the country where they were formally important or dominant constituents of many conifer plantations. Most recently, in order to control an outbreak of the eight-toothed spruce bark beetle (*Ips typographus* L.), a moratorium on planting any spruce species has been imposed in a demarcated area in the southeast of England, due to the threat of extensive deaths of mature trees if this insect pest were to be left to spread unchecked (Forestry Commission 2024). There is therefore a risk that currently healthy and well-adapted principal species such as Sitka spruce might potentially suffer a similar fate as Corsican pine and larches in the future, which could have a very negative effect on the UK forest industry. Worse still, a catastrophic forest ecosystem collapse could take place if multiple threats to more than one principal species occurred simultaneously (Tew et al. 2023).

Diversifying the range of species planted would clearly reduce the extent of impacts if there were to be a failure of one of the UK's principal timber producing species. There is also some evidence that a diversity of species helps to improve overall forest resistance to natural disturbances (Jactel et al. 2017). In addition, increasing the variety of provenances and ages within a stand, and maintaining a continuous canopy cover of trees, have also been proposed as means of increasing resilience (Brang et al. 2014). Conversely, intimately mixed species stands are not necessarily always more resistant to drought (Ovenden et al. 2022), and the widespread use of species and provenances that have not been rigorously screened for both biodiversity threats and silvicultural suitability for the UK's current and future climate could potentially worsen long-term forest sustainability (Ennos et al. 2019). Nevertheless, recognising the potential benefits of diversification, the use of a wider range of species has become an important theme of forest policy in the UK in recent years (e.g. DAERA 2006; Welsh Government 2018; Scottish Government 2019; DEFRA 2021; Forest Research 2023).

However, whilst most stakeholders appear open to the general concept of greater species diversity in commercial conifer forestry, how willing or able they are to actually adopt it in practice can vary. Many managers in the private sector are constrained by the need to maximize returns on their clients' investments, and by a lack of confidence in the performance of alternatives to principal species such as Sitka spruce (Williams 2018, Lawrence 2020). In addition, alternative species are perceived as needing more time and effort to establish successfully, and they may also require the use of silvicultural approaches such as underplanting, that are more complex and costly to undertake than conventional clear-fell and restock systems (Wilson 2011, Stokes et al. 2023). Public sector managers are usually less constrained, but are often forced to take an experimental approach because of a lack of information on how and where best to grow alternative species (Lawrence 2020).

In addition to principal species, Kerr and Jinks (2015) identified a number of what they termed 'emerging species' from those already growing on a small scale in the British Isles, which may have the most potential for diversifying commercial forests. They further subdivided this list into 'secondary' and 'plot stage' species. Secondary tree species are those which have been planted on a much smaller scale in Britain than principal species, are reasonably well understood in terms of their potential growth rates, timber production and hardiness under current conditions, but may have been overlooked in the past as their absolute yield, or ease of establishment, does not match that of the principal species, or where information on their potential for adapting to the UK's future climate is less well known. Plot stage species are those which have not been planted on any significant scale in the UK, but have demonstrated silvicultural characteristics in small scale trial plots that warrant further testing. From 2010 onwards there has been a renewed focus by Forestry England (the Agency of the Forestry Commission that manages the nation's forests in England) and Forestry and Land Scotland (formerly part of Forestry Commission Scotland) on planting a wider range of these emerging conifer species on their estates, with the objective of reducing their reliance on existing principal timber producing species, and increasing resilience to climate change. This planting took place primarily (although not exclusively) on clear-fell sites, was typically carried out on a relatively small scale, and utilized the same establishment methods developed for principal species. Although a laudable initiative, these novel plantings were not designed as formal experiments and so are not organized in a way that evidence could be easily gathered or shared more widely on the success or failure of different species. Therefore, in 2015 a partnership was formed with Forest Research to establish a series of what were termed 'operational species trials', utilising a simple but robust experimental design. This allowed planting to continue as before on a commercial basis, but also provided an opportunity for formal long-term monitoring of growth and survival, with the aim of identifying conifers with the long-term potential for more widespread use across the UK, as alternatives to current principal commercial timber producing species. This paper describes the first results from these operational species trials. In addition to the long-term aim, our objective for this early stage of the research was to test the hypothesis that for restock sites currently reliant on a limited number of principal commercial species, a wider range of emerging conifers have the potential to establish and thrive, without the need, apart from fencing, to substantially change the normal silvicultural methods used. For this purpose Douglas fir was treated as an emerging species, following the hypothesis that it has the potential to be used successfully on a wider range of site types than it is currently.

Methods

Four experiments—Black Isle, Cowal, Newcastleton, and Sherwood—were established on clear-fell sites in the spring of 2015. A further two experiments—Wykeham and Thetford—were established in 2016 and 2018 respectively. These covered a broad range of geographic locations and soil types (see Fig. 1 and Table 1), although it was not possible to systematically cover all representative environmental conditions present in UK forestry.

All establishment and maintenance operations were undertaken by local operational teams, using the same methods as would have been followed by them if the sites were being restocked with standard principal commercial species, with the exception that the experiments were rabbit and deer fenced, and planting followed a common design and layout provided by Forest Research. Table 1 gives any site-specific establishment

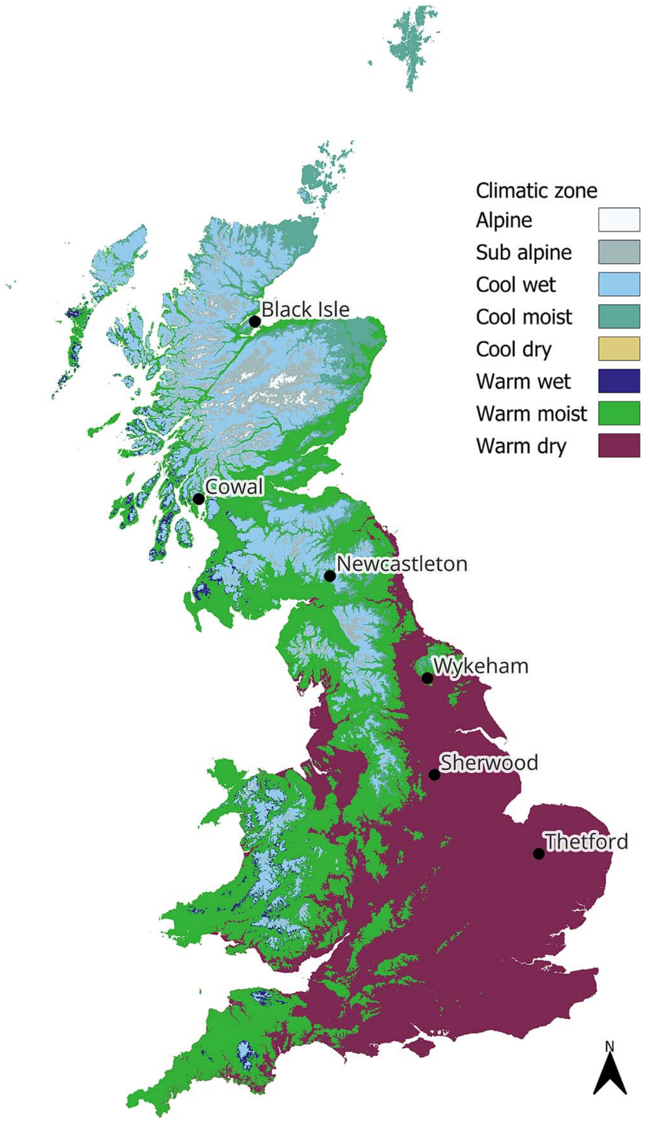

Figure 1. Location of the experiment sites in great Britain in relation to climatic zones. Notes. The climatic zones referred to in the figure are derived from mean accumulated temperature and moisture deficit values for 1961–1990, as shown below, following Pyatt et al. (2001). Blank areas indicate that combination is not present in Great Britain.

practices undertaken but, in general, each site was cultivated (by scarification at Black Isle and Wykeham; by mulching and scarification at Sherwood; by mounding at Cowal and Newcastleton; and by ploughing at Thetford), weeded if necessary, fenced, then trees planted at 1.9 m × 1.9 m spacing to achieve an equivalent stocking density of 2700 stems ha^{-1}. Planting took place in pure species plots which were 0.1 ha (32 m × 32 m) in size. Each plot contained 270 trees, of which the central 25 trees were assessed. There were three replicates of each species plot, arranged in a randomized block design. Each 1.9 ha block consisted of 19 species plots. Where possible blocks were laid out to reflect uniform areas of soil, gradient and exposure. The total size of each experiment was 5.7 ha, consisting of 15 390 trees.

Nineteen mainly coniferous species were planted on each site, as shown in Table 2. Trees were sourced from commercial nurseries (primarily the Forestry Commission nursery at Delamere, Cheshire) and utilized the standard provenances of planting stock readily available for purchase at the time. This meant that for the same species, in some instances, different provenances were used on different sites (see Supplementary Data Table S1 for details). In addition, due to lack of availability, on the three Scottish sites—Black Isle, Cowal and Newcastleton—six species (seven at Cowal) were planted a year later than the others, and Leyland cypress (*Cupressus x leylandii* A. B. Jacks. and Dallim.) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) were not used at all at Cowal.

At each location Scots pine was planted as a standard 'national control', being a principal species that would be likely to establish and grow satisfactorily on all trial sites. In addition, at each site a standard 'local control' was planted, which represented the principal commercial species that would normally have been planted on the site if diversification had not been an aim.

The remaining 17 species used covered all of the secondary coniferous species not restricted by pests and diseases identified by Kerr and Jinks (2015), the balance being promising plot stage species that were in production and readily available from commercial nurseries. Although classified as a principal species, Douglas fir was included following the hypothesis that it may be relatively underused, and might be a productive alternative to Sitka spruce on a much wider range of site types than is currently often assumed (Stokes et al. 2023, Ovenden et al. 2024).

Except for the local control, the three English sites (Sherwood, Thetford, Wykeham) all used the same range of species. However, at the request of local managers at the three Scottish sites (Black Isle, Cowal, Newcastleton) the broadleaved species aspen (*Populus tremula* L.) was planted instead of Maritime pine (*Pinus pinaster* Ait.).

Height and root collar diameter were measured after planting and at the end of each of the first five growing seasons (four growing seasons for seven species at the Scottish sites) to allow growth increments to be calculated. Survival was measured at the end of each growing season. Dead trees were beaten up (replaced) with the same species on at least one occasion depending on site (see Table 1) to maintain conditions of even competition, but all of these trees were excluded from the subsequent analysis.

In addition to the assessments described above, although not part of the work reported here, the experiments were designed so they could also be used in future as long-term mensuration sample plots to help develop growth and yield models, and also for use as demonstration sites for forest managers looking to increase their knowledge of how to diversify their own estates.

Statistical analysis

Analyses were carried out using R Version 4.4.2 (R Core Team 2022), and data visualisations were created using *ggplot2* (Wickham 2016). Throughout this paper, any results referred to as 'significant' are so at the $P \leq .05$ level.

Height increment was calculated by subtracting the height at Year 5 (or Year 4 for the species planted a year later at the Scottish sites) from the baseline height immediately after planting. A mixed linear model in the *lme4* package (Bates et al. 2015) was used with the square root of increment growth as the outcome variable, site and species as fixed effect covariates as well as their interaction, and block as a random effect. Height increment at Year 4 for the Scottish sites were analysed for each site separately. For these, mixed linear models were used with the square root of increment growth as the outcome variable, species and block as fixed effect covariates, and plot as a random effect. The same models were applied to root collar diameter at each site.

Survival at Year 5 (or Year 4 for the species planted a year later at the Scottish sites) was analysed using a generalized

Table 1. Experiment site details.

Experiment name	Black Isle	Cowal	Newcastleton	Sherwood	Thetford	Wykeham
Location	Grey Carin Wood, Black Isle, Highland	Corlarach Forest, Argyll and Bute	Newcastleton Forest, Scottish Borders	Clumber Park, Nottinghamshire	Thetford Forest, Norfolk	Wass College Moor, North Yorkshire
Latitude, longitude	57°37′57″N, 004°08′49″W	55°54′31″N, 005°00′45″W	55°12′10″N, 002°45′04″W	53°17′29″N, 001°02′18″W	52°30′27″N, 000°35′31″E	54°13′11″N, 001°08′00″W
UK National Grid Reference	NH 719623	NS 118725	NY 523901	SK 642776	TL 760931	SE 566808
Elevation (m above sea level)[1]	180	140	180	51	22	249
Aspect[1]	Plateau	West	Northwest	East	Plateau	Southwest
Average annual rainfall (mm)[1]	833	1832	1387	628	614	844
Annual average moisture deficit (mm)[1]	86 *(Wet)*	89 *(Wet)*	119 *(Moist)*	186 *(Dry)*	220 *(Dry)*	127 *(Moist)*
Degree days > 5 °C (AT5)[1]	1067 *(Cool)*	1248 *(Warm)*	1290 *(Warm)*	1671 *(Warm)*	1794 *(Warm)*	1246 *(Warm)*
Exposure (DAMS score)[1]	16	15	15	13	12	14
Soil type and approximate proportions	80% Podzolic ironpan (indurated) (4zx)/20% Podzolic surface water gley (indurated) (7zx)	25% Upland brown earth (1u)/25% Typical podzol (3)/ 25% *Calluna*, *Eriophorum* blanket bog (11b)/25% Typical peaty surface water gley (6p)	50% Typical ironpan (4)/50% Typical peaty surface water gley (6)	100% Typical brown earth (1)	80% Calcareous brown earth (12b)/20% Argillic brown earth (12 t)	100% Typical ironpan (4)
Soil moisture regime[1,2]	Fresh (Low)	Fresh/slightly dry/wet (Low)	Fresh/Wet (Low/High)	Fresh (Low)	Slightly dry (Low)	Fresh (Low)
Soil nutrient regime[1,2]	Very poor (Low)	Poor/very poor (Low)	Very poor/Poor (Low)	Medium (High)	Carbonate (High)	Very poor (Low)
Previous crop	Scots pine/western hemlock, felled 2012	Sitka spruce/Norway spruce/Japanese larch, felled 2013	Sitka spruce/Norway spruce, felled 2014	Corsican pine/Scots pine, felled 2012	Grand fir, felled 2013	Red oak (*Quercus rubra* L.), felled 2014
Establishment operations	Before planting:-scarified. After planting:- beaten up 2015 (end year 1) and 2017 (end year 2); hand weeded to remove natural regeneration 2017 and 2018.	Before planting:-mounded, After planting:- sprayed against *Hylobius*; beaten up 2015 (end year 2), 2017 (end year 3); chemically weeded 2016 and 2018.	Before planting:-mounded, After planting:- sprayed against *Hylobius*; beaten up 2015 (end year 1), hand weeded to remove natural regeneration 2016.	Before planting:-mulched; scarified; After planting:-chemically weeded 2016 and 2017; mechanically weeded 2016, 2018 and 2019. Beaten up 2018 (year 3) from on-site reserve.	Before planting:-chemically weeded; mechanically weeded; ploughed. After planting:- beaten up 2018 (end year 1) and 2019 (end year 2) from on-site reserve.	Before planting:- scarified. After planting:- chemically weeded 2016, 2018 and 2019; mechanically weeded 2019; Beaten up 2016 (end year 1), 2017 (year 2), 2018 (year 3), 2019 (year 4) from on-site reserve.

Notes: [1]Information obtained from the Forest Research Ecological Site Classification system (Pyatt et al. 2001, ESC 2024). DAMS is the windiness score based on the Detailed Aspect Method of Scoring (Quine and White 1993) where:- 3–12 = sheltered, 12–16 = moderately exposed; 16–19 = highly exposed; 19–22 = severely exposed; 22+ = too exposed for commercial forestry. Equivalent climatic zones for accumulated temperature (Cool/Warm) and moisture deficit (Wet/Moist/Dry) as defined by ESC, are given in italics and brackets—see also Fig. 1. [2]The equivalent ‘aggregated’ categories for soil nutrient regimes are given in brackets, following the methods used by Stokes et al. (2023).

Table 2. Species used and planting dates for the experiment sites.

Species			Planting date					
Common name	Scientific name	Species category[1]	Black Isle	Cowal	Newcastleton	Sherwood	Thetford	Wykeham
Hybrid larch[2]	*Larix* x *marschlinsii* Coaz	Principal	March 2015	-	-	-	-	-
Sitka spruce[2]	*Picea sitchensis* (Bong.) Carrière	Principal	-	April 2015	March 2015	-	-	-
Norway spruce[2]	*Picea abies* (L.) H. Karst.	Principal	-	-	-	March 2015	February 2018[4]	March 2016
Scots pine[3]	*Pinus sylvestris* L.	Principal	March 2015	May 2016	March 2015	March 2015	February 2018	March 2016
Noble fir	*Abies procera* Rehder	Secondary	March 2015	April 2015	March 2015	March 2015	February 2018	March 2016
Grand fir	*Abies grandis* Lindl.	Secondary	March 2015	April 2015	March 2015	March 2015	February 2018	March 2016
Pacific silver fir	*Abies amabilis* Dougl. Ex Forb.	Plot stage	December 2015	May 2016	March 2016	March 2015	February 2018	March 2016
European silver fir	*Abies alba* Mill.	Plot stage	March 2015	April 2015	March 2015	March 2015	February 2018	March 2016
Douglas fir	*Pseudotsuga menziesii* (Mirb.) Franco	Principal	March 2015	April 2015	March 2015	March 2015	February 2018	March 2016
Macedonian pine	*Pinus peuce* Griseb.	Plot stage	December 2015	May 2016	March 2016	March 2015	February 2018	March 2016
Weymouth pine	*Pinus strobus* L.	Plot stage	March 2015	April 2015	March 2015	March 2015	February 2018	March 2016
Maritime pine	*Pinus pinaster* Ait.	Plot stage	-	-	-	March 2015	February 2018	March 2016
Serbian spruce	*Picea omorika* (Pančić) Purkynč	Secondary	March 2015	April 2015	March 2015	March 2015	February 2018	March 2016
Oriental spruce	*Picea orientalis* (L.) Link	Plot stage	December 2015	May 2016	March 2016	March 2015	February 2018	March 2016
Western red cedar	*Thuja plicata* D. Don	Secondary	March 2015	April 2015	March 2015	March 2015	February 2018	March 2016
Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.	Secondary	-	April 2015	March 2015	March 2015	February 2018	March 2016
Coast redwood	*Sequoia sempervirens* (D. Don) End.	Plot stage	March 2015	April 2015	March 2015	March 2015	February 2018	March 2016
Wellingtonia	*Sequoiadendron giganteum* (Lindl.) J. Buchh.	Plot stage	December 2015	May 2016	March 2016	March 2015	February 2018	March 2016
Japanese red cedar	*Cryptomeria japonica* (L.f.) Don	Plot stage	March 2015	April 2015	March 2015	March 2015	February 2018	March 2016
Leyland cypress	*Cupressus* x *leylandii* A. B. Jacks. & Dallim.	Secondary	December 2015	-	March 2016	March 2015	February 2018	March 2016
Atlas cedar	*Cedrus atlantica* (Endl.) Carr.	Plot stage	December 2015	May 2016	March 2016	March 2015	February 2018	March 2016
Aspen[5]	*Populus tremula* L.	Secondary	March 2015	April 2015	March 2015	-	-	-

Notes: [1]Species categories as defined by Kerr and Jinks (2015). Principal species are currently widely used for timber production and will continue to be the dominant species unless adversely affected by a new pest or disease or climate change. Secondary tree species are those which have been planted on a much smaller scale than principal species, but are reasonably well understood in terms of their potential growth rates, timber production and hardiness under current conditions, but may have been overlooked in the past as their absolute yield, or ease of establishment, does not match that of the principal species, or where information on their potential for adapting to the UK's future climate is less well known. Plot stage species are those which have not been planted on any significant scale, but have demonstrated silvicultural characteristics in small scale trial plots that warrant further testing. Western hemlock, western red cedar, noble fir and grand fir have recently been identified as candidates for potential future reclassification to 'principal' status. [2]The standard commercial species for the site, referred to as the 'local control'. The default, principal productive species that would normally be chosen for the site if no efforts to diversify the range of species used were taking place. [3]The 'national control' species, common to every site. Scots pine is considered to be a native species to Scotland, but not the rest of the UK. [4]Historically, the normal standard commercial species for the Thetford site would be Corsican pine (*Pinus nigra ssp. laricio* Maire), but at the time the experiments were established there was a moratorium on planting it due to the impact of Dothistroma Needle Blight. The standard substitute species for Corsican pine is Scots pine, but as that was already included as the standard 'national control', Norway spruce was selected as the 'local control' species instead. [5]Aspen is considered to be a native species to the UK.

linear model with survival as the outcome variable. Species, site and block were included as covariates as well as the interaction between species and site and binomial errors were used. An exact binomial test with 75 trials (corresponding to the total number of trees per species) was used to calculate error bars for species with 0% or 100% survival.

The *emmeans* package (Lenth 2022) was used to extract adjusted marginal means, and to make *post-hoc* between species comparisons. Adjusted marginal means are given rather than actual means to show values adjusted across blocks, which allows for a more direct comparison between species or site without the effect of blocks. A 95% confidence interval is included around each estimate. All species were compared to the local and national control species, and Dunnett's tests used to correct for multiple comparisons (Dunnett 1955).

For Japanese red cedar (*Cryptomeria japonica* (L.f.) Don) and Pacific silver fir (*Abies amabilis* Dougl. Ex Forb.) at Thetford no trees survived, and so to avoid unreliable P values when comparing with the control, a Fisher Exact Test was used (Fisher 1992) from which it was concluded that these species had a lower survival than Scots pine. This same approach was used to compare Oriental spruce (*Picea orientalis* (L.) Link), Atlas cedar (*Cedrus atlantica* (Endl.) Carr.), western hemlock and western red cedar (*Thuja plicata* D. Don) with the control at Wykeham where all trees of these species survived.

Early species performance was also compared with predicted long-term site suitability (Table 3). Species performance was based on survival and height increment after five growing seasons. Species where trees had achieved a five year height increment of at least 100 cm were classed as 'established', or 'well established' when this was combined with five year survival rates of at least 75%. Predicted long-term suitability was determined using the Forest Research Ecological Site Classification system (ESC) (Pyatt et al. 2001, ESC 2024). This is a web-based decision support system that uses a multi-dimensional approach to classify sites based on climate, soil moisture and soil nutrient regime, and then assigns a suitability rating based on the predicted performance of the tree species in that specific ecological niche. Suitability in the ESC system is based on general yield class, with species classed as 'very suitable' predicted to achieve 75% or more of the maximum general yield class for the species in British conditions. General yield class is defined as the maximum mean annual timber volume increment of the stand (Edwards and Christie 1981). So for example general yield class 14 means the stand is predicted to have a maximum mean annual increment of 14 m^3 timber ha^{-1} $year^{-1}$.

Results

Overview

After 5 years, there were significant differences in survival and growth both between and within sites. In general, the results for diameter increment followed a similar pattern to height growth on each site, so for reasons of brevity they are not presented here, but are available in the supplemental data (Figs. S1–S6). Similarly, for brevity, Year 4 increment data for those species planted a year later at the Black Isle, Cowal and Newcastleton sites—Pacific silver fir, Macedonian pine (*Pinus peuce* Griseb.), Oriental spruce , Wellingtonia (*Sequoiadendron giganteum* (Lindl.) J. Buchh.), Leyland cypress, Atlas cedar and Scots pine (Cowal only)—are not presented here, but are available in the supplemental data (Figs. S7–S9). The results of the cross site analysis of survival and height increment are also available in the supplemental data (Figs. S10 and S11).

Black isle

All species apart from western red cedar , coast redwood (*Sequoia sempervirens* (D. Don) End.), Weymouth pine (*Pinus strobus* L.) and Leyland cypress had significantly better survival than the national control Scots pine, and survival that was not worse than the local control hybrid larch (Fig. 2).

After 5 years no species significantly outperformed the local or national controls in height increment, but aspen, coast redwood, western red cedar, European silver fir (*Abies alba* Mill.), grand fir (*Abies grandis* Lindl.), Japanese red cedar, noble fir (*Abies procera* Rehder) and Serbian spruce (*Picea omorika* (Pančić) Purkynč) grew significantly slower than Scots pine, and these same species along with Douglas fir and Weymouth pine, all grew slower than hybrid larch (Fig. 3).

After 4 years Pacific silver fir, Wellingtonia, coast redwood, Japanese red cedar, Atlas cedar, western red cedar, European silver fir and Leyland cypress grew significantly slower than both hybrid larch and Scots pine, and noble fir, aspen, Macedonian pine, Serbian spruce, grand fir and Douglas fir grew slower than hybrid larch (Fig. S7).

Five years after planting only hybrid larch had successfully established at Black Isle, but Scots pine, Douglas fir, Macedonian pine, Weymouth pine and western hemlock also appeared to be growing strongly. Although ESC predicted several of the species being tested as not suitable for the site given our current climate, at this early stage only coast redwood could be classed as clearly unlikely to establish a satisfactory crop (Table 3).

Cowal

No species had significantly worse survival than the national or local controls, although in the latter case this is due in part to the unexpectedly poor early performance of Sitka spruce (Fig. 2). After 5 years aspen, coast redwood, Douglas fir and Japanese red cedar all grew significantly faster than Sitka spruce, but no species grew significantly slower (Fig. 3). After 4 years Douglas fir and aspen grew significantly faster than both Scots pine and Sitka spruce, but no species grew significantly worse than the controls (Fig. S8).

Five years after planting only Douglas fir, Japanese red cedar and aspen had successfully established at Cowal, but coast redwood also appeared to be growing strongly. ESC did not predict any of the species tested to be unsuitable for the site in our current climate, but early indications are that Macedonian pine, Weymouth pine and Serbian spruce may fail to establish successfully. In addition, initial establishment of Sitka spruce and Scots pine appeared to be unexpectedly poor (Table 3), although growth of nearby crops indicates the species should be well matched to this site.

Newcastleton

No species had significantly worse survival than the national control Scots pine or the local control Sitka spruce. All species apart from Serbian spruce and Wellingtonia had better survival than Scots pine, whilst aspen, Atlas cedar, Doulgas fir, European silver fir, grand fir and Leyland cypress had significantly better survival than both Sitka spruce and Scots pine (Fig. 2). Douglas fir grew significantly faster than Scots pine and Sitka spruce after 5 years, whilst coast redwood, European silver fir Japanese red cedar and western red cedar grew significantly slower than both species. Aspen and Serbian spruce had a significantly lower height growth increment than Scots pine (Fig. 3). After 4 years, Douglas fir and

Table 3. Predicted site suitability and summary of actual performance after 5 years for 22 tree species planted at Black Isle, Cowal, Newcastleton, Sherwood, Thetford and Wykeham.

	Black Isle			Cowal			Newcastleton			Sherwood			Thetford			Wykeham		
Site type	AT: Cool. SMR: Low. SNR: Low.			AT: Warm. SMR: Low. SNR: Low.			AT: Warm. SMR: Low/High. SNR: Low.			AT: Warm. SMR: Low. SNR: High.			AT: Warm. SMR: Low. SNR: High.			AT: Warm. SMR: Low. SNR: Low.		
Species	ESC now	ESC 2080	Performance	ESC now	ESC 2080	Performance	ESC now	ESC 2080	Performance	ESC now	ESC 2080	Performance	ESC now	ESC 2080	Performance	ESC now	ESC 2080	Performance
Hybrid larch	7	8	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sitka spruce	-	-	-	21	22	✓	28	21	✓	-	-	-	-	-	-	-	-	-
Norway spruce	-	-	-	-	-	-	-	-	-	21	6	✓	10	0		12	10	✓
Scots pine	7	7		12	12	✓	9	9	✓	13	10	✓✓	3	3	✓	9	9	✓✓
Noble fir	6	6		17	10	✓	16	4	✓	5	0	✓	0	0		12	0	✓
Grand fir	0	0		16	20	✓	15	18	✓	20	0	✓✓	0	0		8	10	✓
Pacific silver fir	12	13		25	25	✓	23	21	✓	20	0		0	0		19	14	✓
European silver fir	5	7		12	15	✓	13	16		16	1		10	0		9	11	
Douglas fir	3	5	✓	17	18	✓✓	0	0	✓✓	20	12		0	0		11	12	✓✓
Macedonian pine	7	7		12	12		14	14	✓	14	12	✓	3	3		9	9	✓
Weymouth pine	3	4		8	9	✓	0	0	✓	12	5		0	0		6	6	✓
Maritime pine	-	-	-	-	-	-	-	-	-	10	11	✓✓	3	3		5	9	✓✓
Serbian spruce	6	6		13	13		18	16	✓	18	12	✓	15	5		10	9	✓
Oriental spruce	0	0		10	13	✓	10	13	✓	18	18		0	0		4	6	
Western red cedar	0	0		15	16	✓	18	18		18	10	LOW	16	0		6	7	✓✓
Western hemlock	12	13	✓	-	-	-	15	14	✓	17	0		0	0		18	15	✓✓
Coast redwood	3	6		12	17	✓✓	18	24		24	13		8	0		8	11	✓
Wellingtonia	0	0		11	12	✓	0	0	✓	25	12	✓✓	0	0		0	0	✓
Japanese red cedar	0	0		15	16	✓✓	16	17		13	0		0	0		6	6	✓✓
Leyland cypress	2	3		-	-	-	14	14	✓✓	20	0	✓✓	14	0		10	10	✓✓
Atlas cedar	N/A	N/A		N/A	N/A	✓	N/A	N/A	✓	N/A	N/A	✓✓	N/A	N/A		N/A	N/A	✓
Aspen	0	0		7	7	✓✓	11	10	✓	-	-	-	-	-	-	-	-	-

Notes

Criteria used to classify species performance, based on survival and height increment after 5 growing seasons, except for Pacific silver fir, Macedonian pine, Oriental spruce, Wellingtonia, Leyland Cypress and Atlas cedar at Black Isle, Cowal and Newcastleton, where the classification is based on 4 years growth.

Height growth	Survival		
	≤ 50%	> 50 % to ≤ 75%	≥ 75%
0 to < 100 cm			
≥ 100 cm to ≤ 200 cm	LOW		
≥ 200 cm	LOW		

	Species failed, or at this stage looks unlikely to establish satisfactorily in a reasonable timescale, or may require multiple beat ups to form a productive crop.
	Species not yet established.
LOW	Species established, but original plantings are at a low density and on similar sites may require multiple beat ups to form a productive crop.
	Species established.
	Species well established.
✓	Height increment and survival not significantly worse than the local control species for the site (taken to be Scots pine at Thetford).
✓✓	Height increment significantly higher, and survival not significantly worse, than the local control species for the site (taken to be Scots pine at Thetford).

Predicted species suitability according to the Ecological Site Classification decision support system (ESC, 2024).

	Very suitable for the site, with the potential to achieve 75% or more of the maximum general yield class (Edwards and Christie, 1981) for the given species in British conditions. Number represents predicted yield class.
	Suitable for the site, with the potential to achieve 50% or more of the maximum general yield class for the given species in British conditions. Number represents predicted yield class.
	Marginal for the site, with the potential to achieve 30% or more of the maximum general yield class for the given species in British conditions. Number represents predicted yield class.
	Unsuitable conditions for timber production, where the predicted yield is less than 30% of the maximum general yield class for the given species in British conditions. Number represents predicted yield class.
-	Species not planted.
N/A	No information on species in ESC.

CZ = Climatic Zone; SMR = Soil Moisture Regime; SNR = Soil Nutrient Regime; See Figure 1 and Table 1 for further details.

ESC Now = Species suitability based on the current baseline climate, 1961-1990.

ESC 2080 = Species suitability based on the predicted climate in 2080 according to UKCP09 A1b medium high emissions scenarios (Met Office Hadley Centre, 2008). These represent a realistic worst case scenario for the UK climate if global greenhouse gas emissions continue to rise unabated, resulting in a doubling of pre-industrial carbon dioxide levels by 2045

Leyland cypress grew significantly faster than Sitka spruce, whilst western red cedar, European silver fir and Oriental spruce all grew significantly slower than Scots pine (Fig. S9).

After 5 years only Douglas fir had successfully established, but Sitka spruce, western hemlock, Leyland cypress, noble fir, Weymouth pine and grand fir appeared to be growing strongly. ESC predicted Douglas fir, Weymouth pine and Wellingtonia as being unsuitable for the site in our current and future climates, but only Macedonian pine and Wellingtonia could be classed as unlikely to form a satisfactory crop at this stage (Table 3).

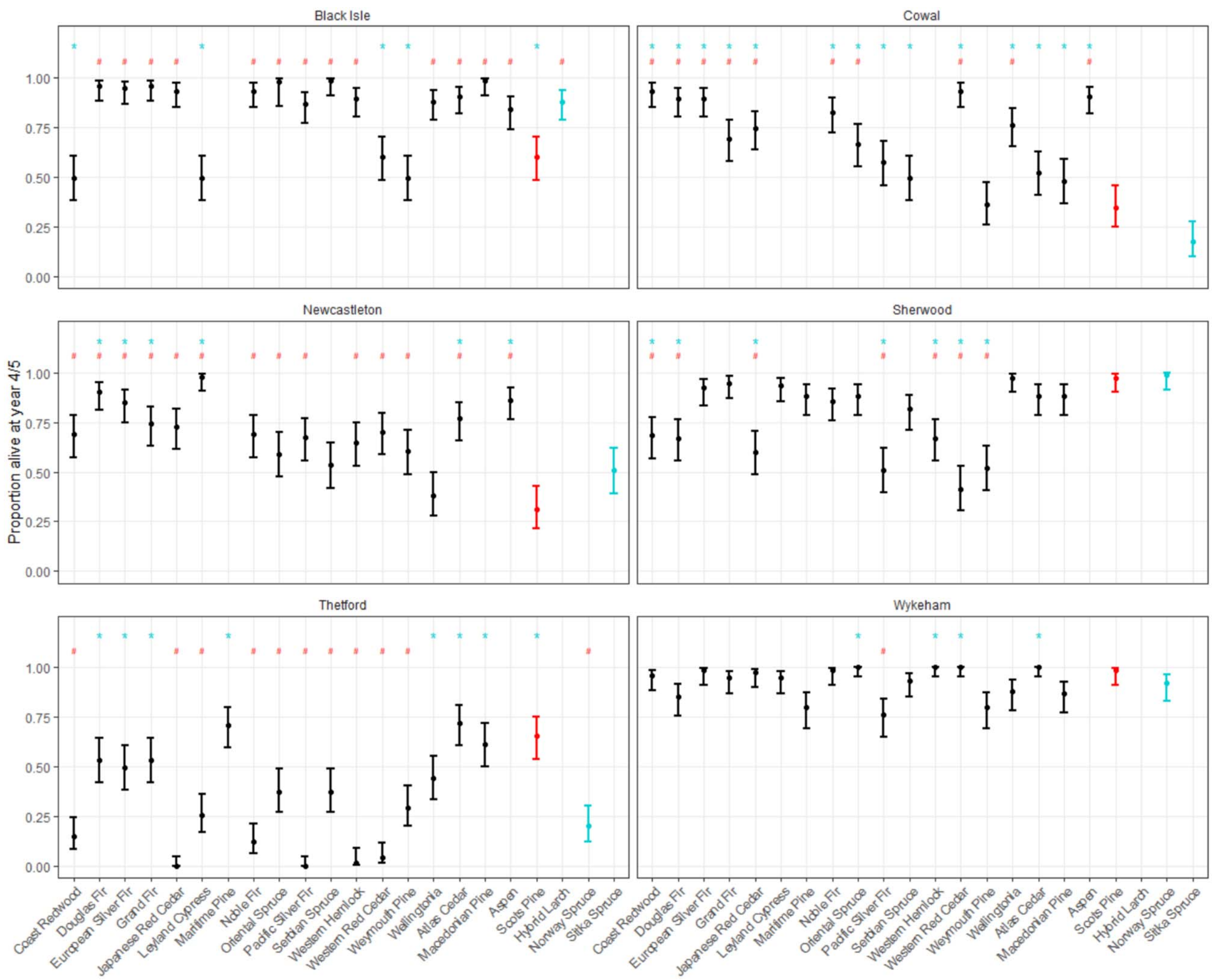

Figure 2. Tree survival after 5 years at black isle, Cowal, Newcastleton, Sherwood, Thetford and Wykeham. Notes. The solid black dots show back transformed, adjusted marginal means from the mixed linear models, with the error bars representing the 95% confidence intervals of these estimates. Species denoted by a '#' have a significantly different survival ($P \leq .05$) compared to the national control, Scots pine. Species denoted by a '∗' have a significantly different survival ($P \leq .05$) compared to the local control, which was: Black Isle—hybrid larch; Cowal and Newcastleton—Sitka spruce; Sherwood, Thetford and Wykeham—Norway spruce. Note that for the following site/species combinations, trees were planted a year later than other species, so Year 4 survival was used for the analysis: Black isle and Newcastleton—Macedonian pine, Atlas cedar, Oriental spruce, Pacific silver fir, Leyland cypress and Wellingtonia; Cowal—Macedonian pine, Atlas cedar, Oriental spruce and Pacific silver fir.

Sherwood

After 5 years, coast redwood, western hemlock, Douglas fir, Japanese red cedar, Weymouth pine, Pacific silver fir and western red cedar all had significantly worse survival than both Scots pine, and the local control species Norway spruce. No species had significantly better survival than the two controls (Fig. 2). Leyland cypress and Maritime pine grew significantly faster than Norway spruce and Scots pine, whilst European silver fir, Oriental spruce and Pacific silver fir grew significantly slower than both species (Fig. 3).

Overall establishment was good at this site. After 5 years Norway spruce, grand fir, Douglas fir, Macedonian pine, Wellingtonia, Weymouth pine, western hemlock, coast redwood, Japanese red cedar and Atlas cedar could be considered to be established; and Scots pine, Maritime pine and Leyland cypress had already formed a very well established crop (Table 3). No species could be categorized as unlikely to form a productive crop at this stage, despite ESC predicting noble fir to be unsuitable in our current climate, and several species to be potentially unsuitable for our future climate. However, even in the realistic worst case climate change scenario for 2080 used by ESC, many species that are already established, including Scots pine and Maritime pine, are predicted as remaining suitable for timber production on this site (Table 3).

Thetford

As explained in Table 2, as Corsican pine could not be planted the most appropriate local control species for this site for comparison purposes is Scots pine, not Norway spruce. In comparison to Scots pine, 5 years after planting coast redwood, Japanese red cedar, Leyland cypress, Oriental spruce, Pacific silver fir, noble fir, Serbian spruce, western red cedar, western hemlock and Weymouth pine, and had significantly poorer survival. No species had significantly better survival than Scots pine (Fig. 2). All species grew significantly slower than Scots pine (Fig. 3).

On this very challenging dry, alkaline site, establishment after 5 years was generally poor (Table 3). Only Scots pine and Maritime pine could be categorized as being successfully established, and

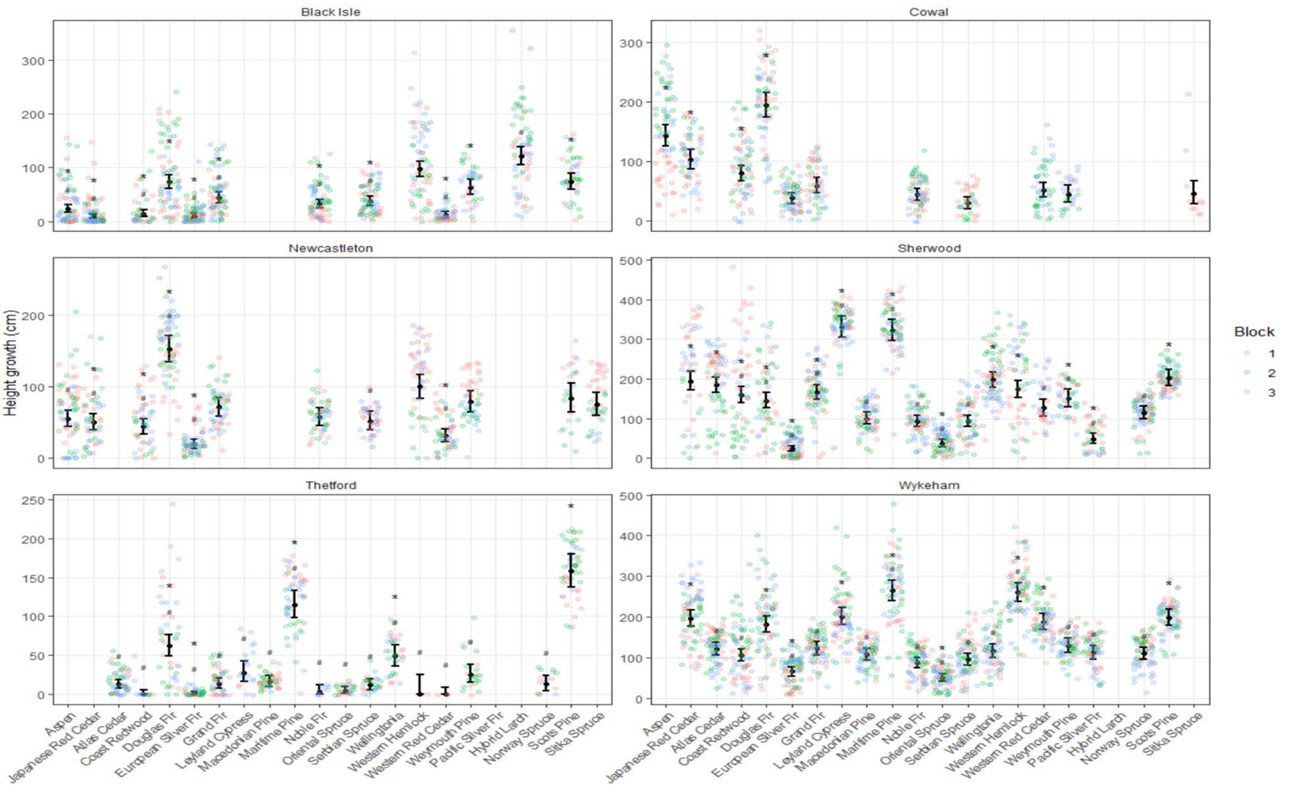

Figure 3. Tree height growth increment after 5 years at Black Isle, Cowal, Newcastleton, Sherwood, Thetford and Wykeham. Notes. The solid black dots show back transformed, adjusted marginal means from the mixed linear models, with the error bars representing the 95% confidence intervals of these estimates. The lighter shaded dots associated with each estimated mean represent the height increment of individual trees from the raw data, coloured according to block. Species denoted by a '#' have a significantly different height growth increment ($P \leq .05$) compared to the national control, Scots pine. Species denoted by a '*' have a significantly different height growth increment ($P \leq .05$) compared to the local control, which was:- Black Isle—hybrid larch; Cowal and Newcastleton—Sitka spruce; Sherwood, Thetford and Wykeham—Norway spruce.

apart from grand fir, Macedonian pine, Douglas fir and Atlas cedar, all other species had either failed or appear very unlikely to form a satisfactory timber crop. ESC predicted that none of the species tested would be suitable for timber production in our future climate under a realistic worst case scenario, but the current growth of Maritime pine and Douglas fir is better than predicted for our current climate. On less alkaline sites within a similar geographic area, ESC predicts most of the pine species tested to be suitable for our current or future climate.

Wykeham

Five years after planting only Pacific silver fir had significantly worse survival than Scots pine, and no species had poorer survival than the local control Norway spruce. No species had significantly better survival than Scots pine, but Oriental spruce, western hemlock, western red cedar and Atlas cedar had significantly better survival than Norway spruce (Fig. 2). Maritime pine, western hemlock, Scots pine, Leyland cypress, Japanese red cedar, western red cedar and Douglas fir all grew significantly faster than Norway spruce. The remaining species all grew significantly slower than Scots pine. Only European silver fir and Oriental spruce grew significantly slower than Norway spruce (Fig. 3).

Overall establishment was good at this site and after 5 years, apart from European silver fir and Oriental spruce, all of the species could be classified as established. Of these, Scots pine, Douglas fir, Maritime pine, western red cedar, western hemlock, Japanese red cedar and Leyland cypress could be considered as very well established. ESC predicted grand fir, Oriental spruce, western red cedar, coast redwood, Wellingtonia and Japanese red cedar as unsuitable in our current climate but, out of these, only Oriental spruce is yet to establish. ESC predicts that Scots pine, Pacific silver fir, Macedonian pine, Maritime pine and western hemlock, are likely to remain suitable for timber production on this site, even under the realistic worst-case climate projections, and all of these species are currently established (Table 3).

Cross site analysis

In addition to the variations in growth and survival within each site, as might be expected given the contrasting initial site conditions, there were also significant differences in the relative performance of the species between locations. Overall, 5 years after planting, across most species survival and growth was generally best at Sherwood and Wykeham, and poorest at Thetford (Figs. S10 and S11, and Table 3). For coast redwood, European silver fir, Japanese red cedar, Leyland cypress, noble fir, Pacific silver fir, western hemlock and western red cedar, growth and survival were significantly poorer at Thetford than all the other sites.

Relative establishment success followed a similar pattern, being best at Sherwood and Wykeham, and poorest at Thetford, and this also matches the pattern of species suitability predicted by ESC (Table 3) . However in general, as noted earlier, on all sites a wider range of species established than were forecast as being suitable in the long term by ESC.

Discussion

The aim of this research is to identify conifers that might have potential, in the longer term, for more widespread use across the UK, as alternatives to current commercial timber producing species. Our more immediate hypothesis was that for restock sites currently reliant on a limited number of principal commercial species, a wider range of emerging conifers may have the potential to establish and thrive, without the need, apart from fencing, to substantially change the normal silvicultural methods used. Although there was variability between sites, after 5 years a broad range of species had either already successfully established, or looked likely to do so. This included many species-site combinations that ESC predicted as being unsuitable. Even on the most challenging sites there was always at least one species that performed as well as the local control, the principal commercial conifer that would otherwise normally be planted and, at three locations, there were multiple species that outperformed them. Some of the species tested have already exceeded initial expectations.

Douglas fir is already classed as a principal species but, in the UK, planting often tends to be focused on better quality sheltered sites, with fertile, moist, freely draining soils. It currently only makes up around 4% of Britain's total area of coniferous forest (Forest Research 2024), and our hypothesis was that it is a species that could be successfully used much more widely. On the freely draining lowland brown earth soils of Sherwood, Douglas fir performed as expected, establishing and growing well. However, it also established effectively on a less fertile, ironpan soil at Wykeham, and on exposed upland sites with elements of peaty, surface water gleys (as well as upland brown earths and ironpan soils) at Cowal and Newcastleton. It even showed potential on a very dry, calcareous brown earth at Thetford, when the only other species to establish successfully were pines. Experience from elsewhere in Europe suggests that Douglas fir can maintain high growth rates even under extreme drought conditions (Vitali et al. 2017). It therefore appears to be a potentially much more versatile species than is often assumed to be the case in the UK, a finding echoed in a recent series of trials reported on by Ovenden et al. (2024), who also found very few differences in early survival and growth between Oregon Coast, Oregon Siskiyou and Washington Cascade provenances. Current recommendations for the UK are to select provenances originating from the Washington Coast in the wetter north and west of Britain, and South Washington Cascades origins for the drier south and east of the country (Fletcher and Samuel 2010). In our experiments, Black Isle and Newcastleton used South Washington Cascades origin material, while the warmer and drier sites of Sherwood, Thetford and Wykeham used material from a French seed orchard where 42% of the parent trees originated from the North Washington Cascades, and 16% from the Washington Coast. However, Douglas fir has a wide native range, extending south into California and Oregon, and there may be some potential to further refine provenance choice through new dedicated field experiments, testing alternative origins that might be better adapted to our future climate in the south and the east of the UK, where conditions are expected to become significantly hotter and drier than today.

Maritime pine is another species that exceeded our expectations. It is currently classified as a plot stage species and has not been planted on any significant scale in the UK. Although the available evidence is not definitive, it is usually thought to be relatively resistant to Dothistroma Needle Blight compared to species such as Corsican pine (Drenkhan et al. 2016). In our work Maritime pine established very well at Sherwood and Wykeham, growing to over three metres tall in 5 years, and it was also the only species, apart from Scots pine, to successfully establish on the dry calcareous brown earth soil at Thetford, although its relative susceptibility to lime-induced chlorosis on such sites in the longer term is unknown. ESC predicts it is a species that is likely to be well adapted to our future climate, even in the south and east of the UK. There have been some anecdotal reports of poor initial form from commercial plantings, and this will be formally assessed on our study sites at the planned 10-year assessment. Unfortunately, Maritime pine was not included in the Scottish trial sites, and under the Wildlife and Environment (WANE) Act (Forestry Commission Scotland 2015), which is intended to protect Scotland's environment from the damage that can sometimes be caused by non-native species, it is currently listed as a conifer that cannot be planted outside experimental areas. However, Maritime pine would seem to have great potential as a fast growing, robust, future secondary or principal species on suitable sheltered, freely draining sites throughout the UK, and further testing of it, including into the likely timber quality from different provenances and from improved material emanating from breeding programs in France, is recommended.

Some species fared poorly, performing worse than expectations. Macedonian pine did not successfully establish on any site in Scotland, although it is known to be slow growing initially, and subsequent growth, in particular at Black Isle (data not reported here), has been strong. European silver fir performed poorly on all sites and had largely failed at Thetford. However, this is an example of a species, along with Pacific silver fir, grand fir, western red cedar and coast redwood, which may not be suited to establishment on large clear-fell sites, but might be much more successful if underplanted in shaded conditions beneath a retained overstory of trees (Kerr and Haufe 2016). Oriental spruce and Serbian spruce also did not establish well on any site.

Stokes et al. (2023) analysed a large number of long-term experiments to identify alternative productive conifer species to Sitka spruce across a range of climate/soil categories, and Tables 1 and 3 give the equivalent climate/soil categories for our sites using the same system. The authors identified a particular lack of evidence of alternatives to Sitka spruce in the Accumulated Temperate (AT) Warm, Soil Nutrient Regime (SNR) Low, and Soil Moisture Regime (SMR) Low categories. In this category of site, only grand fir and western red cedar were identified as having estimated yield classes that were not significantly different from Sitka spruce. In our work, the Cowal and Newcastleton sites would fall into these same broad climate/soil categories, and they also included Sitka spruce as a local control species. Early evidence from Cowal and Newcastleton suggests that in addition to those species identified by Stokes et al. (2023), Douglas fir and Leyland cypress might also have long-term potential as productive alternatives to Sitka spruce on Accumulated Temperate Warm, Soil Moisture Regime Low, Soil Nutrient Regime Low site types. However, Leyland cypress is a species that currently relies on a very limited number of clones for producing planting material, and unless a breeding programme is set up to substantially widen its genetic base it will remain inherently more vulnerable to catastrophic collapse, should it start to be impacted by a future pest or disease threat. Therefore, at the moment it is probably only suitable for use on a relatively small scale.

However, in considering the future potential for the species under test in these experiments an important caveat to note is that we are only reporting on early growth, over the first 5 years after planting. It is well known that species that initially appear to show promise, or alternatively a lack of it, can perform very differently when assessed later in their life (Willoughby et al. 2007, Reynolds et al. 2021). The long-term potential of any species could be obscured by other factors such as early management, pest and disease attack, weed competition, weather, and plant quality (Reynolds et al. 2021). It is also highly likely that we do not fully understand the optimal early silvicultural practices required for successful establishment in British conditions for many of the species tested, and this should be a focus for future research.

If they are to have any potential for use as large scale alternatives to our current principal commercial species, in addition to early establishment success, it is critical that in the longer term the conifers under test have the capability to produce sufficiently high yields of timber, of an acceptable quality, and on a range of site types typical of UK forestry. All of the species under test were selected because they are thought to have the potential to fulfil these criteria, although current evidence of performance in UK conditions is often very limited. On all of our experimental sites, the Ecological Stie Classification system identified at least one species that is predicted, based on our current understanding, to have the potential to give comparable long-term yields to the normal principal commercial species used on the site. Of the species in our experiments, Douglas fir, Western hemlock, Pacific silver fir and Serbian spruce have been estimated as producing timber that meets strength class C16, equivalent to UK grown Sika spruce, and demonstrate the minimum stiffness, strength and density qualities to be acceptable as structural timber, which represents one of the higher value bulk markets for wood products. Grand fir, Japanese red cedar, noble fir and western red cedar have been estimated as meeting the lower strength class of C14, suitable for lower value, non-structural building timber, but this is likely to be highly dependent on provenance of the planting material used (Price et al. 2024). Even where timber does not meet C14 or C16 grades, it has the potential for use in lower value, yet still commercially important markets such as packaging, fencing, pulp, chipwood and biomass energy. For the other species tested in our experiments, although there is currently insufficient information to estimate a strength class for UK grown timber, evidence from abroad suggests that there is often a ready market for the wood produced (Wilson 2011, Savill 2015, Savill and Wilson 2015, Savill et al. 2017).

Longer term monitoring of silvicultural suitability, including yields, disease resistance and timber quality is therefore required before any firm conclusions about large scale future species diversification are taken, and it is too early to dismiss the potential of any species on the basis of the initial results reported here. Nevertheless, all of our trial sites were established by operational teams using the same methods that would have been followed by them if the sites were being restocked with standard, principal commercial species, with the exception that the experiments were rabbit and deer fenced. Therefore, we can conclude that species that are not as well established after 5 years as the principal, local or national control species, are likely to require more intensive and expensive silvicultural interventions than those commonly practised, if they are to realize their long-term potential. Hence even if species such as Macedonian pine, European silver fir or Serbian spruce prove, in the long-term, to be well suited to sites similar to those under test, they are unlikely to be widely adopted as alternatives to species such as Sitka spruce unless managers are prepared to lavish more care, attention and resources, over a longer period of time, to achieve their successful establishment.

A further caveat to our results is that the summary of ecological suitability following ESC given in Table 3 utilizes the average soil type for the site based on historic, large scale soil surveys. For more accurate predictions, the soil type in every plot would need to be determined in order to better categorize the precise conditions experienced by each species. This is scheduled to take place at the planned 10-year assessment.

All of our trial sites utilized relatively large (0.1 ha), pure species plots. It could be that some of the species tested grow better in intimate mixtures, so they can benefit from possible nurse effects, as long as their relative growth rates are sufficiently well matched for this to be appropriate (Kerr et al. 2020). Intimate mixtures at the stand level, if they can be achieved, can also be a good means of increasing diversity and overall woodland resilience. However, although the UK Forestry Standard requires that no more than 65% of a forest management unit is made up of a single species, with 5% consisting of native broadleaved trees or shrubs and 10% of other tree species (Forest Research 2023), the scale on which this diversity is best achieved could vary. Rather than always attempting to create complicated, potentially difficult to manage intimate mixtures of tree species with inadequately matched growth rates at the stand level, it may instead sometimes be more practical to plant small (e.g. 0.05 ha) pure species groups. Alternatively, if neither intimate mixtures or group planting are practical, depending on the size and nature of the forest management unit it may be possible to achieve the required diversity at a landscape scale through establishing a network of larger (e.g. > 0.2 ha), easier to manage, single species blocks.

In contrast to the network of common garden experiments set up in Switzerland (Streit et al. 2024), or the arboreta established in four countries across the Atlantic region of Europe under the REINFFORCE project (Correia et al. 2018), siting of our experiments was more opportunistic, taking advantage of planned operational scale restocking. As a result our work has the disadvantage that it does not allow direct comparison of different provenances within the same species, nor has it been it possible to systematically cover the full range of representative environmental conditions, exposure and soil types present in UK forestry. However, the sites selected do cover the broad climatic zones Warm/Dry, Warm/-Moist, Cool/Wet and Warm/Wet, as defined by ESC (see Fig. 1), that together represent 98% of the land area of Great Britain (Pyatt et al. 2001), and also include more challenging sites (e.g. hotter drier, more exposed, poorer soils—see Table 1), that are perhaps better representative of the conditions faced by many commercial growers than those present in long established forest gardens such as Kilmun (Mason et al. 2018). Because our trials utilize relatively large experimental plots, they are also well suited for potential future use as mensuration sample areas to help improve yield models (Craig and Baden 2020), assessment of timber properties (Price et al. 2024), testing for resilience to local pathogens (Morton et al. 2025), and as demonstration areas to help illustrate the potential of a wide range of species, planted on an operational scale, to potentially skeptical forest managers. In addition, as they were established by operational teams, and likely with less intensive initial care and maintenance than might be the case for other species trials, they may give a better indication of real world potential. Overall then, in the long-term this series of experiments will compliment data generated from trials of other species both in the UK (Mason et al. 2018, Reynolds et al. 2021, Ovenden et al. 2024), and from networks in other parts of Europe that may provide important analogues for our future climate (Correia et al. 2018, Streit et al. 2024).

Conclusions

Although a wide range of species look likely to have the ability to successfully establish across the six sites tested, at this stage it is too early to draw firm conclusions as to their long-term wider suitability as alternatives for our current principal commercial conifer species. It is also important to note that our results are derived from single species stands planted on clear-fell sites.

Nevertheless, some species have already exceeded initial expectations. Douglas fir established well on most sites, and appears to be a much more versatile species than is often assumed to be the case in the UK. Along with on a small scale Leyland cypress, in the long-term Douglas fir may prove to be a productive alternative to Sitka spruce on some sites. Douglas fir also showed potential for wider use in the south and east of the country, where the climate is forecast to become significantly hotter and drier than today, and further testing to refine provenance selection for these types of sites is recommended.

Maritime pine also established very well, and although in our work it was not used in Scotland, it would seem to have great potential as a fast growing, robust, future secondary or principal species on suitable freely draining sites throughout the UK, and more widespread testing of it is recommended.

Similarly, based on our results it is also too early to judge any species a total failure. However, it is already clear that some species, such as for example Oriental spruce, Serbian spruce, and European silver fir, are often very slow to establish. Even if they do prove to have long-term promise, if they are ever to be used more widely it is likely that current standard establishment methods will need to be adapted, e.g. through introducing longer periods of aftercare, or for shade tolerant species through the greater the use of underplanting.

Further monitoring of these trial sites is required to determine whether the early promise showed by many species is fulfilled in the long-term. Additional studies should also be undertaken to determine whether some of the poorer performing species in our work might fare better if used in mixture with nurse crops, or if underplanted beneath an existing canopy of trees.

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Author contributions

Ian H Willoughby (Conceptualization, Investigation, Methodology, Project administration, Supervision, Writing—original draft, Writing—review & editing), Rajni Dhanda (Formal analysis, Visualization), Toni Clarke (Formal analysis, Visualization), Chris Reynolds (Conceptualization)

Supplementary Data

Supplementary data are available at *Forestry* online.

Conflict of interest: None declared.

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Data availability

All relevant data are given in the text and its online supplementary material. The data underlying this article will be shared on reasonable request to the corresponding author.

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