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Top Five Alternative Conifer Tree Species in Great Britain

Mae'r ddogfen yma hefyd ar gael yn Gymraeg.
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Top Five Alternative Conifer Tree Species in Great Britain

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Please note this a corrected version of the report published on the 23rd June 2021 which now lists the top five ranked species in Table 3.6 in the correct order (*Thuja plicata* and *Sequoiadendron giganteum* were in the wrong order in the previous version).

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Glossary

The following acronyms and keywords are used throughout this report. The definitions below apply unless stated otherwise.

Acronym/Key word	Definition
C12-C35	Timber strength classes
CCF	Continuous cover forestry
CONFOR	Confederation of Forest Industries (UK) Ltd
Defra	Department for Environment Food and Rural Affairs
ESC	Ecological site classification
EUFORGEN	European Forest Genetic Resources Programme
FC	Forestry Commission (England and Scotland)
FR	Forest Research
GB	Great Britain (England, Scotland and Wales)
Massive wood	Massive wood products includes cross-laminated timber, laminated veneer lumber and glulam and are increasingly being used in tall buildings made of wood or in wooden structures with long spans.
MCA	Multi criteria analysis
Met Office	Meteorological Office (UK)
MOE	Modus of elasticity (kN/mm^2)
NRW	Natural Resources Wales
RFS	Royal Forestry Society
ROC	Rank order centroid
SilviFuture	A UK-based network promoting novel forest species
SMART	Simple multi-attribute rating technique
SMARTER	Simple multi-attribute rating technique exploiting ranks
TRADA	The Timber Research and Development Program
UK	United Kingdom (England, Scotland, Wales and N. Ireland)
UKCCC	United Kingdom's Climate Change Committee
UN	United Nations
Brexit	UK's exit from the EU
Native	In Britain since the English Channel was flooded in the early part of the present interglacial period about 6,000 years ago
Origin	The place from which the species originated, i.e., the native range of a tree
Provenance	The geographic locality from which seed, scions etc. were collected, not necessarily the same as the origin of the population.

1. Introduction/Background

1.1 Devolved government policy in England, Scotland and Wales supports the significant future expansion and sustainable management of plantation woodlands (Defra, 2020; Scottish Government, 2019; Welsh Government, 2018). The UK Climate Change Committee have set out strong recommendations for 30,000 hectares of new woodland per annum by 2050 (UKCCC, 2020), of which a significant portion will likely be commercial plantation woodlands. Expansion and sustainable management of this new woodland will act as a mechanism for meeting UN Sustainable Development Goal 15, combatting climate change, improving home-grown timber supply for the construction sector, and providing a wide range of valuable public goods. Plantations, alongside other forms of woodland creation, have an important role in carbon sequestration and biodiversity conservation, providing public amenity and recreational benefits and biodiversity conservation. Great Britain (GB) has a long history of using a wide range of species (often coniferous) in its plantation woodlands. However, in recent times a small number of species, particularly Sitka spruce, have become the dominant tree in many areas. These species are likely to remain key components of future plantation woodlands where the primary aim is commercial timber production. Nonetheless, there are very good reasons to increase the use of other productive tree species as a greater component of future plantations including those established to meet societal need for low-carbon products and materials, whilst delivering greater ecological and economic resilience in the context of climate change and associated increased pest and pathogen risks.

The coniferous forest resource of Great Britain

1.2 The coniferous forest resource in GB is increasingly expected to deliver a broad range of ecosystem services to society; this alongside the provision of timber and other forest products, through management for multiple objectives, often within a small geographical area (Ennos *et al*., 2019; Forestry Commission, 2017). Due to the lack of native conifer species, GB's commercial forestry sector has historically utilised non-native conifer species (Macdonald *et al.,* 1957). Of the three native conifer species in GB, Scots pine (*Pinus sylvestris*) is the only one considered an important commercial species, the others being juniper (*Juniperus communis*) and yew (*Taxus baccata*). Although Scots pine has the largest native range of any member of the *Pinus* genus (Durrant *et al*., 2016), it is not suitable for many of GB's wetter sites usually considered for commercial forestry (Ennos *et al.,* 2019) and is increasingly under threat from pests and diseases (Durrant *et al*., 2016).

Box 1.1: What are conifers?

Today there are an estimated 615 naturally occurring conifer species worldwide, of which only 41 are native in Europe (Farjon, 2018; Neale and Wheeler, 2019). Conifers are an ancient taxon of trees, which evolved in the Carboniferous period, and the rich fossil records indicate that the group was previously far more diverse than it is currently (Gernandt *et al.,* 2011). Conifers are formally part of the phylum, Pinophyta and are all cone-bearing seed plants in the group Gymnosperms. In contrast to the flowering plants (angiosperms), the seeds of gymnosperms are not enclosed in fruits or ovaries (Hansen *et al.,* 1997). Conifers are found on all the continents (excluding Antarctica) from tropical conditions to the Arctic. The most extensive coniferous forests are in the Northern boreal forests (Debreczy *et al*., 2011). Conifers are comprised of six families: Pinaceae, Podocarpaceae, Araucariaceae, Sciadopitaceae, Taxaceae and Cupressaceae. Although not strictly coniferous, for the purposes of this study we have included the related phylum Ginkgophyta, as it is genetically closer to the conifers than broadleaves (Soltis *et al*., 2018). Most conifers are trees that express apical dominance, and their wood is made up of thick-walled vertical tracheids exhibiting bordered pits, which results in fast-growing trees with good timber properties (Shmulsky and Jones, 2019).

1.3 The first wave of human introductions of exotic conifer species to GB came from Europe and then later North America (Samuel, 2007). In the last 100 years, commercial forestry in GB has been monopolised by the more recent introductions from north-western North America, principally the widespread use of Sitka spruce (*Picea sitchensis)*. Ninety-seven per cent of GB's commercial coniferous forest are comprised of as few as eight species and one hybrid, with Sitka spruce accounting for approximately fifty-one percent of GB's coniferous plantations (Forest Research, 2020). Forty-six percent of the British conifer resource is composed of a further seven species and one hybrid, namely lodgepole pine (*Pinus contorta*), European, Japanese and hybrid larch (*Larix decidua, Larix kaempferi* and *Larix x eurolepsis* respectively), Norway spruce (*Picea abies*)*,* Corsican pine (*Pinus nigra* subsp. *laricio*) and Douglas fir (*Pseudotsuga menziesii*) (Forest Research, 2020; Kerr and Jinks, 2015).

1.4 These frequently planted, non-native species, known as principal tree species, have been tested and grown successfully for decades in GB (Kerr and Jinks, 2015). Now, anthropogenic climate change interacting with the advent of novel pests and diseases introduced through the rise in international trade, sheds doubt on this continuing (Ennos *et al*., 2019). These principal timber producing species have generally been grown in single-aged and single species stands managed using patch clear-fell silvicultural systems (Malcolm, 1997). A long history of tree improvement and breeding programs, which have selected individuals with desirable characteristics, has potentially reduced the genetic diversity of many principal conifer species further reducing their resilience (Lee and Watt, 2012).

1.5 The commercially successful conifer tree species in GB are typically fast-growing, grown outside their native range (limiting exposure to their natural pests and pathogens) and are able to grow on relatively poor soils (Liebhold, 2012; Wingfield *et al*., 2015). The ability to produce high volumes of timber on relatively short rotations is a key factor in conifers often being favoured by forest planners and managers worldwide. As a result, commercial coniferous timber production accounts for approximately 7% of the World's total forest area, but 60-70% of industrial wood production (Carle and Holmgren, 2008; Fargon, 2017). Globally, non-native conifer plantations are predicted to double in area, by the end of the 21st century (Brockerhoff *et al.,* 2013). In GB 92% of roundwood harvesting in 2020 was from coniferous trees amounting to 9.8 million green tonnes, which is significantly higher than the 0.9 million green tonnes of hardwoods harvested in 2020 (Forest Research, 2020). These non-native conifer plantations are essential for provisioning low carbon material for construction and other uses, but are now increasingly at risk from imported non-native pests and pathogens and this trend is expected to continue (Kenis *et al*., 2017).

Challenges from current and future pests and pathogens

1.6 The damage to conifer plantations globally by pests and pathogens interrupts the international timber supply chain and diminishes the economic viability of forest stands (Wingfield *et al.,* 2001). There are three mechanisms through which pests and pathogens can affect the economic viability of commercial crops of trees (Kenis *et al*., 2017). Firstly, an outbreak can reduce the growth rate of the trees, thus reducing the annual increment or 'yield class' (Seidl *et al.,* 2018). An example of this is the green spruce beetle (*Elatobium abietinum*), which has caused serious defoliation to Sitka spruce crops in the UK and Europe, reducing their annual height increment by 20-60% (Lavin, 2016). Secondly, a pest or pathogen can kill the mature trees; an example of this is *Phytophthora ramorum* on Japanese larch in the UK (Brasier and Webber, 2010). Thirdly, the pest or pathogen can interfere with regeneration processes by killing seeds or seedlings or by infecting the nursery or seed source (Kenis *et al*., 2017). The extent of the damage caused by non-native pests and pathogens ranges from minor sub-lethal damage, through significant damage to an ecosystem, to complete destruction of an entire stand or even forest (Kenis *et al*., 2009).

1.7 In recent years, outbreaks of novel pests and pathogens affecting commonly grown commercial tree species have increased in both frequency and ecological impact (Defra, 2013). A key cross-cutting issue is that while some of these pest and pathogen species are well established and well known, with their host range well characterised, existing knowledge is far from complete for many others, including their potential to infect additional tree species. This was recently demonstrated by *P. ramorum,* when it went from a known pathogen of tanoaks (*Notholithocarpus densiflorus*) to affecting

Quercus spp. and a range of other tree species, including rhododendron and other ornamental species first in its native range of California and then in Europe, to then attacking Japanese larch in forest plantations in GB (Grünwald *et al.,* 2012). Therefore, tree species selection for plantations has to be carried out under conditions of uncertainty, with a weak basis to quantify risks.

1.8 The biggest threat currently to the commercial forest resource in GB is the exponential growth in invasions of novel pests and pathogens. This is in part due to increasing reliance on imported horticultural material (plants and rooting media), wood, wood products and food which can harbour exotic pests and pathogens, and to the lack of biosecurity regulations (Liebhold, 2012; Ghelardin *et al*, 2017). An increase in international trade and travel in the last century has led to an increase in imports of tree pests and pathogens (Weste and Marks, 1987; Anagnostakis, 2001; Brasier, 2000; Parker and Gilbert, 2004; Wingfield et al., 2001; Liebhold et al., 2017). Cross-border activity has assisted these organisms to overcome the natural geographical barriers which prevented them leaving their native ranges (Richardson *et al*., 2000). This increased movement of destructive tree pathogens (Santini *et al*., 2013) has facilitated the evolution of new and previously unknown aggressive pathogen hybrids (Ennos *et al*., 2020; Olson and Stenlid, 2002) and fostered negative novel associations between insects, pathogens, and trees (Wingfield *et al.,* 2010).

1.9 European forests escaped many of the issues caused by non-native pests and pathogens in the 20th century, when compared with other continents (Kenis *et al.,* 2017). However, the rate of new pests arriving in Europe is now faster than elsewhere globally and newly established species are now threatening forests across Europe (Roques, 2010; Santini *et al*., 2013). This has had, and will continue to have, economic and provisioning ecosystem service impacts. For example, the pine wood nematode *Bursaphelenchus xylophilus*, which can act as a vector for pine wilt disease in continental Europe, is estimated to have caused damage totalling €22 billion to plantations over a 20 year period (Soliman *et al*., 2012). A major threat to British forestry is posed by known pests and pathogens currently in continental Europe moving north and west, such as the pine processionary moth (*Thaumetopoea processionea*); the Siberian silk moth (*Dendrolimus sibiricus)* and the pine wood nematode (*Bursaphelenchus xylophilus*) (Forest Research, 2021a).

1.10 The diversity of pests and pathogens already present, and the fact that the UK Plant Health Register lists a further 127 pests and pathogens at risk of arriving in the UK (Defra, 2021), has made it essential to increase the diversity of tree species grown in commercial plantations to lessen the potential effects of these risks. Similarly, climate change may alter the suitable climate space for principal, as well as alternative tree species. Trees are vital environmental, social and economic assets (natural capital): they shape the landscape, provide timber, provide habitat and support our health and wellbeing. Protecting these trees and the wider treescapes from pests and pathogens will be crucial in the devolved governments' ambitions to leave the environment in a better state for the future generations. The Tree Health Resilience Strategy sets out strategic goals for not only increasing the extent of woodland cover but also the diversity of this new woodland (Defra, 2018). Both native and introduced tree species have the potential to help diversify and enhance the resilience of future commercial plantation woodlands.

Climate change

1.11 Climate change is now increasingly affecting trees and forests in GB, with future climate predictions suggesting that hotter drier summers in the south and midlands, and milder wetter winters in the west and north, will be increasingly frequent (Sayers *et al*., 2020). Recent reporting highlights that the ten warmest years since 1884 have all occurred since 2002 (Met Office, 2020). Climate change modelling for GB predicts that under one of the most likely scenarios average warming of 2.5-3 °C will occur between 2010 and 2100 (Ray *et al*, 2010; Broadmeadow *et al*., 2009). There is also likely to be an increase in the frequency and intensity of extreme weather events leading to increased flooding, windthrow events, droughts and lightning storms causing forest fires (Reynolds *et al*., 2021). In GB, the ecological site classification (ESC; Pyatt *et al.,* 2001) is an online decision support system, enabling foresters to take into consideration potential impacts of a changing climate on forests when making decisions about tree species selection for a given site (Ennos *et al.,* 2020). The models underpinning ESC (Broadmeadow *et al*., 2009) and process-based tree growth models (Coops and Waring, 2011), both anticipate a reduction in timber production as a result of drought stress in the east of GB, particularly in stands of Sitka spruce (Meason and Mason, 2014).

1.12 Predicting the effect of climate change on pest damage to trees is a complex undertaking. It is multifaceted with many potential interactions, so as a result can have a positive or negative effect on forest health at a given locality (Forestry Commission, 2002; Sturrock *et al.,* 2011; Jactel *et al*., 2019). Current research suggests there to be an increase in damage to forest crops from insects, driven by a number of factors including:

- Higher winter survival rates (David *et al*., 2017)
- Faster growth rates of insect pests (Pureswaran *et al*., 2018)
- Changes to natural enemy populations (Wainhouse and Inward, 2016)
- More generations per year (Strange and Ayres, 2010)
- Increased range or distribution (Battisti and Larsson, 2015; Cannon, 1998)
- More storm damage increasing beetle reproductive substrate availability (Seidl and Rammer, 2017; Marini *et al.,* 2017)
- Reduced tree health due to stress (Linnakoski *et al.,* 2019).

1.13 The effects of climate change on tree pathogens are expected to be similar to the effect on pest species: in certain circumstances it could decrease the damage to a forest from a particular pathogen species, but on average damage is anticipated to increase globally (La Porta *et al*., 2008). The main driver of this increase in pathogen damage is expected to be increasing temperatures leading to:

- Extending pathogen ranges (Brodde *et al.*, 2019; Broadmeadow, 2002)
- Increased survival and distribution of pathogen reproductive material (Elad and Pertot, 2014)

- Increased activity during winter (Seidl *et al.,* 2017)
- Summer droughts favouring root infection microbes (Madmony *et al*., 2018; Holuša *et al.,* 2018; Terhonen *et al*., 2019)
- Increased host stress (Holopainen *et al*., 2018)
- Decreased protective influence of beneficial mycorrhizal fungi (Bidartondo *et al.,* 2018).

1.14 The combined interacting threats of pests, pathogens and anthropogenic climate change present both opportunities and challenges to commercial conifer growing in GB (Reynolds *et al.,* 2021). Forest yield models suggest that most GB conifer trees species will increase in yield class as a result of warmer weather by increasing growth rates, although increases in pest and pathogen damage are expected to negate this (Kirilenko and Sedjo, 2007). For many tree species, particularly in central Europe, summer droughts are likely to negatively affect growth (Seidl *et al.*, 2017). The significant increase in threats to the commercial forestry sector has led to a renewed interest in the diversification of plantation tree species in GB (Ennos *et al.,* 2020). The wider use of novel or alternative exotic tree species is seen as one of the primary potential mitigation strategies for these threats. This approach could ensure the continued provision of ecosystem services by plantation woodlands in GB, by utilising species that have not previously been grown in quantity at the landscape scale (Meason and Mason, 2014). While this strategy has potential benefits it also carries risks (Bindewald *et al.,* 2020; Castro-Díez *et al.*, 2019; Felton *et al.,* 2013; Kjær *et al*., 2013, 2014; Jinks, 2017; Meurisse *et al*., 2019; Pötzelsberger *et al*., 2020) and it is not as novel as it may seem. There is a long history of experimentation with exotic and novel conifers in GB (Box 1.2).

Box 1.2: The history of non-native conifer tree species and species trials in GB

The climate in GB is conducive to growing a wide range of exotic non-native conifer tree species, therefore many were historically introduced to GB (Samuel, 2007). The first, Norway spruce (*Picea abies*), was introduced in the sixteenth century, followed by European and Japanese larch in the eighteenth and nineteenth centuries (Anderson and Taylor, 1967). As many as 500 introduced conifer species, out of a global total of ca. 615, have been grown in private estates, gardens, arboreta, and botanic gardens across GB (Macdonald *et al*., 1957; Reynolds *et al.,* 2021). The peak of interest in exotic non-native conifers was around the 1830's, when plant collectors such as David Douglas, Archibald Menzies and William Murray were sent to the American Pacific north-west on expeditions to collect new ornamental and horticultural plants, which would grow well in GB. David Douglas, probably the most famous amongst them, is credited with translocating seven species of tree and over 200 species of plant into GB and Europe, during the late 1820's and early 1830's, including Douglas fir, which was named after him, (Nisbet, 2009).

During this period, botany was fashionable and as a result a network of pineta and arboreta were developed across GB, including the Bicton Pinetum and Arboretum in Devon, Elvaston Castle in Derbyshire (where William Barron planted numerous species of conifers), the Clinton-Baker Pinetum at the Bayfordbury Estates in Hertfordshire and Westonbirt in Gloucestershire (now owned by the Forestry Commission) (Piebenga and Tommer, 2007). Knight and Perry's seminal work, published in 1850, was the guidebook used by many of the early horticulturalists to choose tree species for their collections (later updated by Veitch, 1881). Tortworth Court was particularly notable for its extensive arboretum developed by the 3rd Earl of Ducie between 1853 and 1921, who also authored one of the earliest books on exotic conifers in the UK, followed by many others as more species were discovered and bought from China and Japan in the late 19^{th} and early 20^{th} centuries (Macdonald *et al*., 1957).

The National Conifer Collection at Bedgebury, Kent was first planted by Field-Marshal Viscount Beresford and his wife Lady Louisa in 1836, with some of the most recently introduced species (Morgan, 1999). The estate was then purchased by the Crown Estate and then subsequently taken over in 1925, by the Forestry Commission (in collaboration with Kew Gardens). This collaboration was organised by the acclaimed conifer expert William Dallimore, due to his concerns that the unsatisfactory atmospheric conditions at Kew were potentially damaging to many conifer genera (Dallimore, 1931). This led to Bedgebury being established as the National Conifer Collection and it is now the largest collection of conifers on a single site in GB, with 10,000 specimens growing over 129 hectares, which includes 91 endangered tree species (Dallimore and Wood, 1951; Mitchell and Westall, 1972; Morgan, 1999).

A review of potential alternative species was conducted in the 1950's, in the Forestry Commission Bulletin no. 30, entitled *Exotic forest trees in Great Britain* (MacDonald, 1957). Forest Research continued this work, with many species undergoing experimental plot trials into the 1960's when they ceased, mainly due to economic considerations (Reynolds *et al.,* 2021). In 1965, the successful partnership between the Forestry Commission and Royal Botanic Gardens Kew came to an end and Kew moved their focus to developing the Wakehurst Place collection, the eventual location of their Millennium Seed Bank, a site which boasts the largest Christmas tree in England at 35 m tall (Cloutman, 2002). Wakehurst Place has been the focus of many conifer research studies over the years, such as provenance trails for *Abies* (Robertshaw, 2020; Morgan, 1999) and aphid susceptibility surveys (Dransfield and Brightwell, 2017).

In the mid 1990's Forest Research revisited species trials that were planted in the 1930's, in what were then known as forest gardens. A forest garden differs from a pinetum or arboretum as it is set up not to establish a collection of individual specimens of species but rather to evaluate single species stands (Mason *et al.,* 1999). This forest garden method of assessing tree species is better than single specimens as it can be used to assess tree growth and the impact of pests and pathogens under plantation stand conditions (Macdonald *et al*., 1957). The forest gardens which survive today include Kilburn, Kirroughtree, Crarae and Lael in Scotland, Bedgebury and Westonbirt in England, and Brechfa and Vivod in Wales (Mason *et al.,* 1999). They have provided an important stimulus to renewed interest in tree species diversification and publication of articles on this subject (Wilson 2007, Bladon and Evans, 2015; Wilson *et al.,* 2016).

In 2009 Forest Research commenced a new programme of species trial experiments (Reynolds *et al*., 2021). The REINFFORCE project funded by the EU was a short-term four-year study to investigate the tolerance of European Atlantic coast forest tree species to climate change (Prieto-Recio *et al*., 2012). The REINFORCE experimental sites in GB ranged from Mull (Scotland) to Landovery (Wales) and Westonbirt (England), and its species trials included a range of principal conifer species and other conifer species grown at a plot and specimen scale (Reynolds *et al*., 2021). In Scotland, there has been an increase in experimental plots of alternative conifers since 2000, alongside testing of their wood properties (Mason *et al.,* 2018). In Wales, there was a review published after the first 40 years of the Brechfa forest garden (Danby and Mason, 1998), with subsequent additional trial species being planted in 2004 (Mason *et al*., 2018). Species research into alternative conifers has also continued in England at both Bedgebury and Westonbirt, with regular surveys re-evaluating the success or otherwise of either a particular species or genus (Morgan, 1999; Robertshaw, 2020).

Home-grown timber supply and the value chain

1.15 Home-grown industrial timber will play a critical role in helping the UK meet net zero carbon emissions by 2050 (Committee on Climate Change 2019). Given that materials such as steel, cement, plastics, and glass are all highly energy intensive, it can be expected that the construction sector in particular will move to greater use of timber for structure, insulation, cladding and joinery items in its response to targets for reduction in carbon emissions (Royal Society and Royal Academy of Engineering 2018). Furthermore, economic, social, and environmental sustainability demands that GB reduces its heavy dependence on imported softwoods. In 2014, 62% of all softwood used was imported, of which 92% was from the EU and 6% from Russia (Forest Research, 2015). Brexit and the end of the Common Agriculture Policy in GB provides an opportunity to level the playing field in terms of support for agriculture and forestry which may lead to a dramatic increase in new tree planting and the supply of home-grown industrial timber.

1.16 There are a number of resources providing detailed guidance and notes on a wide range of alternative conifers that are currently not widely used for commercial timber production in GB, but which may become suitable given future climatic changes and pest and pathogen risks (EUFORGEN, n.d.; Forest Research, 2021a; Natural Resources Wales, 2015; Royal Forestry Society, 2015; Savill, 2019; Wilson, 2011). Many of these existing sources of guidance on alternative or novel conifer species include content on the ecological and silvicultural requirements of the different tree species. However, the quality of this evidence is very variable amongst species. Furthermore, a key limiting factor preventing wider use of these alternative conifers is a lack of knowledge of their timber properties and suitability for entering into the timber processing value chain.

1.17 This is primarily due to a limited investigation of timber properties commercial tree species in Britain which has been exacerbated by subjective judgments by processors on the desirability of certain tree species. Wood properties vary greatly even within individual sawlogs. Conifer species with potential for resilience currently available to British foresters demonstrate large variations in their wood physical characteristics. For instance, strength class may vary from grade C12 to C35 within and between species (Gil-Moreno *et al.,* 2016). Existing protocols may need adjustment to fully utilise lower value strength grades in UK construction. Current high-speed saw lines are dependent on efficient debarking, and innovative approaches may be necessary to debark novel sawlogs with different bark characteristics to spruce and larch species.

1.18 In addition, there is a lack of an integrated decision making tool spanning the range of factors from ecology, pest and pathogen risks, site requirements, susceptibility to climate change, silvicultural requirements, as well as wood properties, for selecting amongst the identified alternative conifer species the best candidates for increased use in UK plantations.

Aim and research questions

1.19 Welsh Government commissioned Woodknowledge Wales to conduct this review to identify the top five alternative commercial tree species suitable to meet timber utilisation demands of that sector in GB, in light of increasing potential pest and disease pressures as a result of climate change. The overall aim was to produce a detailed review that identifies five alternative conifer tree species which can be incorporated practically into the commercial conifer forest resource across GB. The species chosen must fulfil the criteria of being suitable to either maintain or improve the social, economic, environmental, and cultural benefits currently provided by commercial woodlands in GB. This review centred on answering the following questions:

- What tree pests and pathogens are currently present in France or other countries in continental Europe?
- What conifer species are likely to be resilient to current and future pests and pathogens in GB?
- What conifer species are likely to grow well and provide commercial timber products throughout GB?
- What conifer species have timber properties that might meet grading standards to meet market needs?

Our approach

1.20 It important to have a robust understanding of the science and evidence base relevant to addressing these challenges in order to guide decisions relating to the future health and resilience of GB's forestry resource (Welsh Government, 2020). Yet, the major barrier to adoption of alternative tree species within commercial plantation woodlands is the lack of holistic information that is based on systematic assessment of ecological, silvicultural, economic and timber utilisation considerations. Innovative, reactive yet systematic research protocols will need to be designed to allow different specialist information to be appropriately synthesised. Our approach to identifying the top five alternative tree species for GB has drawn on and collated the existing knowledge base (and the knowledge of expert stakeholders) to address these considerations within this review.

2. Methodology

2.1 We undertook a review of alternative conifer tree species suitable for commercial timber production in GB in the face of growing pest and pathogen pressures. Our review followed two broad stages:

- Ranking of a long list of alternative conifer tree species based on their resilience to current and future pests and pathogens, their suitability for a changing climate and a range of site conditions across GB, and their suitability for producing commercial timber products.
- Extended narrative literature review and characterisation of the top five ranked tree species.

Ranking alternative conifer species

2.2 In the first stage of the review, we used multi-criteria analysis (MCA) to rank alternative conifer species and short-list the top five alternative conifer species for further review. We chose to use an MCA approach because this involved systematically identifying the top five alternative conifer species by reference to an explicit set of objectives for which there were measurable criteria to assess the extent to which these objectives were met by each species. MCA has a number of advantages over other more informal judgement-based approaches:

- It is explicit with regard to the objectives and criteria used to rank options.
- The choice of objectives and criteria is open to analysis and change by decision makers if they are felt to be inappropriate.
- Scores and weightings used to rank options are explicit and developed according to established techniques. They can be amended as necessary if decision makers deem them to be inappropriate or in subsequent iterations of such a review.
- It can provide an important means of including decision makers, experts and wider stakeholders in the process.

2.3 The application of MCA techniques in this study was guided by the use of Multi-criteria analysis: a manual (Department for Communities and Local Government, 2009), which provides guidance for practitioners on how to undertake MCA to appraise policy options and other decisions including those which have implications for the environment.

SMARTER technique

2.4 In this study we used the Simple multi-attribute rating technique exploiting ranks (SMARTER) approach to MCA (Edwards and Barron, 1994). SMARTER is a simplified form of the Simple multi-attribute rating technique (SMART) (Edwards, 1977) and provides a simple and practical way to implement multi-attribute utility theory (MAUT). MAUT states that every choice (e.g., choice of alternative conifer species) has utility across a range of different criteria (e.g., resilience to pests and pathogens, productivity or timber properties). Determining the overall utility of any given choice involves measuring these values one criteria at a time followed by their aggregation across attributes through a weighting procedure.

2.5 The SMARTER technique involves nine steps and is based on a linear additive model. This means that the overall utility of a given option (e.g., a given conifer species) is calculated as the total sum of the performance scores (value) across a range of criteria (attribute). The stages in the analysis (adapted from Edwards and Barron, (1994); Olson, (1996)) were as follows.

Step one: Identify the key decision makers

2.6 The utility of a particular choice depends on who is making the decision. There are a wide range of individuals and organisations involved in forestry, timber production and utilisation in GB, to whom the output of this study will have an impact. In this stage we compiled a list of key individuals and organisations associated with forestry and commercial timber production and utilisation in GB, whose expertise would be drawn on in step six (ranking the evaluation criteria) of the analysis. The list of decision makers was compiled with the guidance of the project steering group. Decision makers from eight broad groups were identified for involvement in this study, they were:

- Academics (forest pathologists, silviculturists, and wood scientists)
- Foresters and forest managers

- Industry bodies and societies (e.g., Trada, CONFOR and the Royal Forestry Society)
- Nursery managers
- Policy makers
- Sawmillers and processors
- Timber marketers and buyers
- Other (consultants or industry commentators).

Step two: Identify the relevant evaluation criteria of the conifer species

2.7 This step involved compiling a list of criteria against which the performance of the conifer species would be evaluated. Criteria are specific ways of measuring values and determining how well options address given objectives. They are the ‘children’ of ‘parent’ objectives, which may be the children of even higher-level parent objectives.

2.8 The overall aim of the study was to *“identify five practical alternative tree species which can be incorporated into the commercial conifer forest resource across GB”*. Given the prescriptive nature of this aim we followed a ‘top down’ approach to determining the relevant criteria (Department for Communities and Local Government, 2009). This was based on the overall aim and the associated high-level objectives of the study outlined in §1 Para 1.19. A ‘top down’ approach to determining criteria involved these high-level objectives being broken down into criteria using a value tree (Table 2.1).

2.9 It is important to limit the criteria used to measure value because having too many criteria makes determining a criteria rank order a difficult task for decision makers (Edwards and Barron, 1994; Olson, 1996). Defining the evaluation criteria (n=12) was done by restating and combining criteria, or by omitting less important criteria in an iterative process with the guidance of the project steering group.

Table 2.1: Value tree for identifying the relevant criteria for evaluation of the conifer species.

Aim	Higher-level objectives	Lower-level objectives	Criteria (n=12)	Criteria type	Rationale
Identify five practical alternative conifer tree species that can be incorporated into the commercial conifer forest resource across GB	The identified tree species should be resilient to future pest and pathogen pressures	The identified tree species should be resilient to pest and pathogens currently prevalent in GB	Resistance to 'high risk'[1] pests and pathogens currently in GB	Quantitative	Tree pests and pathogens can cause significant economic losses to commercial forestry through a combination of sublethal effects on tree growth and in some cases tree mortality (Wainhouse *et al*., 2016). Combined sublethal effects from multiple pests and pathogens can also lead to tree mortality. As the climate in GB changes, the effects of pests and pathogens on forest resources is likely to intensify (Forzieri *et al*., 2018; Wainhouse *et al*., 2016; Wainhouse and Inward, 2016). Current UK Climate Projections (UKCP18) suggest GB will primarily see increases in temperature and greater extremes of rainfall and drought events (Lowe *et al*., 2018). Increase in temperature is the primary climatic variable influencing the reproduction, development and survival of insect pests (Altermatt, 2010; Harvey *et al*., 2020; Jactel *et al*., 2019; Van Asch *et al*., 2013; Wainhouse *et al*., 2016). The reproductive cycles of uni-voltine (one generation per year) insect pests may change with earlier budburst and they may survive for longer periods due to increased temperatures (Altermatt, 2010; Bale *et al*., 2002; Wainhouse and Inward, 2016). Longer warm periods may also lead to much greater abundance of bi-voltine (two generations per year) and multi-voltine insect pests. This may lead to significantly increased damage to trees (Altermatt, 2010; Wainhouse *et al*., 2016). Increases in temperature and moisture are the primary climatic variables influencing the sporulation, dispersal and success of many tree pathogens (Wainhouse *et al*., 2016). In addition, reductions in the frequency and severity of frosts will increase survival of spores over winter. Extreme drought events can also affect the regulation of resistance mechanisms in trees making them more susceptible to outbreaks of tree pathogens (Hennon *et al*., 2020; Hossain *et al*., 2018). Climate driven increases in the susceptibility of trees to pathogens will affect the sustainability of commercial conifer species in GB (Wainhouse *et al*., 2016). Climate change in GB will also lead to the development of a new 'bioclimate envelope' (Pearson and Dawson, 2003), which will support the spread of pests and pathogens whose distribution is currently constrained by low temperatures (Pureswaran *et al*., 2018; Ramsfield *et al*., 2016; Wainhouse *et al*., 2016; Wainhouse and Inward, 2016). As a result, the range of pests and pathogens currently present in GB may increase. In addition, pests and pathogens currently in France or elsewhere in continental Europe may disperse into the more favourable bioclimatic envelope of GB. The resilience of conifer trees (and the plantation forests of which they are a constituent part) to pests and pathogens is a result of a wide range of factors, including not only the choice of tree species but also their management. However, one of the fundamental elements that influences the resilience of tree species to pests and pathogens is genetic resistance (Cavers and Cottrell, 2015; Ennos, 2015). Conifer tree species that are resistant to a number of pests and pathogens currently prevalent in GB, as well as in France or elsewhere in continental Europe, are likely to be more resilient in light of the above climate change-driven pest and pathogen impacts.
			Resistance to 'lower risk'[2] pests and pathogens currently in GB		
		The identified tree species should be resilient to pest and pathogens currently prevalent in France or elsewhere in continental Europe	Resistance to 'high risk'[1] pests and pathogens from France and Europe		
			Resistance to 'lower risk'[2] pests and pathogens from France and Europe		

Aim	Higher-level objectives	Lower-level objectives	Criteria (n=12)	Criteria type	Rationale
	The Identified tree species should grow well throughout GB	The identified tree species should be resilient to future climate change pressures and risks	Drought tolerance	Qualitative	Current climate projections suggest that GB will be subject to hotter and drier summers, most significantly in southern and eastern areas (Lowe *et al*., 2018). Summer droughts can cause significant damage to GB forests (Nicoll, 2016). Soil moisture deficits can cause reduced productivity (Davies *et al*., 2020) and mortality through xylem collapse and cambium cracking (Green and Ray, 2009). Spruce and fir species are particularly susceptible to stem cracking caused by drought (Cameron, 2015); this can reduce the value of timber and render it unsuitable for structural use. Drought can also render trees more vulnerable to pests and pathogens (Anderegg *et al*., 2015; Wainhouse *et al*., 2016). Conifer tree species that are more drought tolerant are likely to be less susceptible to these additional risks.
		The identified species should be suitable for a range of site conditions across GB	Waterlogging tolerance	Qualitative	Waterlogging is common in soils with impeded drainage, typically found across upland areas of GB. Current UK climate projections suggest that GB will be subject to increased rainfall, most significantly in western and north western areas (Lowe *et al*., 2018). Persistently waterlogged soils can have a number of effects on soil physical and chemical properties affecting the quality of soil as a medium for plant growth (Balshaw *et al*., 2014; Nicholson *et al*., 2015). The primary mechanism by which waterlogging reduces the health and growth of trees is oxygen deficits in the rooting environment. This limits the aerobic respiration by roots reducing metabolic energy (Kreuzwieser and Rennenberg, 2014). Unless a tree is tolerant of waterlogging this can lead to root mortality followed by crown decline, increased windthrow risk and potentially tree death. Conifer tree species that are more tolerant of waterlogged soils are likely to be suitable for a wider range of sites across GB, especially those economically favourable for commercial forestry.
			Shade tolerance	Qualitative	There is an increasing shift in British forestry towards resilient and multi-purpose forests. This is linked to a growing interest in the wider use of more diverse silvicultural systems such as continuous cover forestry (CCF) as a means of enhancing the species and structural diversity of forests (Macdonald *et al*., 2010; Mason, 2015; Stokes and Kerr, 2009). A major factor limiting the suitability of alternative conifer species for use in structurally diverse silvicultural systems is their shade tolerance and capacity to grow in the understory (Kerr and Haufe, 2016). Conifer species that are shade tolerant are likely to have use in a wider range of silvicultural systems.
			Exposure tolerance	Qualitative	Site conditions set the limits to what is achievable in a plantation. Climatic factors such as warmth (or accumulated temperature) and windiness have a significant impact on the productivity of trees in a plantation (Toledo *et al*., 2011). Exposed sites are likely to be much cooler, windier and wetter than sheltered sites. Exposed sites are also likely to be subject to late season frosts. Exposure to wind and cold temperatures increases water loss from trees and in some cases leads to desiccation of foliage (Dixon and Grace, 1984; Hadley *et al*., 1986). Conifer species that are tolerant of the climatic effects of exposure are likely to be suitable for a greater range of sites across GB.

Aim	Higher-level objectives	Lower-level objectives	Criteria (n=12)	Criteria type	Rationale
	The identified tree species should provide commercial timber products	The identified tree species should be commercially viable	Potential productivity	Quantitative	The primary purpose of most conifer plantations is to produce timber and other forest products on a commercial basis, i.e., to derive a profit. This profit depends on the biological productivity or growth of trees resulting in the annual increase in timber volume in the plantation. This is also fundamental to the rate of carbon sequestration. The objective of commercial forestry operations is to increase the growth rates of individual trees, maximising the volume of wood in the trees, minimising the rotation length and maximising profit. There are a number of factors that affect the productivity and commercial viability of a plantation. However, species choice is one of the most fundamental (McEwan *et al*., 2020; Sedjo, 1999) because potential growth rates are highly variable across species (Mason *et al*., 2018). Conifer species that can produce high volumes of timber on relatively short rotations, i.e., have large annual increments of timber volume, are likely to be more suitable for commercial conifer plantations.
		The identified tree species should have properties suitable to meet timber grading requirements	Technical suitability of timber (stiffness)	Quantitative	Timber strength grading is based on three key determinants or 'timber properties': strength, stiffness and density (Ridley-Ellis *et al*., 2016). Grading standards set a threshold characteristic value for each strength class (e.g., C14 in the case of bending grades) that timber must meet or exceed to be graded in that class (Ridley-Ellis *et al*., 2016). Timber stiffness is measured by the modulus of elasticity (MOE), which describes the elastic behaviour of wood under dynamic cyclic stress (Kovryga *et al*., 2020). Machine grading of timber operates on the principle that the strength of timber is strongly correlated with one or more of its mechanical properties (Harte, 2009). MOE is the most important properties in machine grading of timber (Kovryga *et al*., 2020; Ridley-Ellis *et al*., 2016; Simic *et al*., 2019). Conifer species with timber that has higher mean MOE values will likely grade into higher strength classes and hence have greater technical suitability for a wider range of structural applications.
		The identified tree species should meet wood processing and market requirements	Suitability for existing processing machinery	Qualitative	There are a wide range of genotypic and phenotypic wood characteristics in conifers that affect their suitability for use in primary processing, these include (but are not limited to) bark characteristics, stem straightness, stem forking, wood density, stiffness, knot size, latewood proportion and spiral grain (Richter, 2015; Zobel and Buijtenen, 1989; Zobel and Jett, 1995). Many of these phenotypic characteristics can be altered through silvicultural protocols and interventions such as initial tree spacing, thinning regimes and underplanting, or through environmental interactions. However, one of the most important genotypic characteristics and limiting factors affecting the use of alternative conifer species within high volume wood processing is the ease with which logs can be debarked before conversion to sawn wood. This is a characteristic that is not altered through silviculture or environmental interaction. The most commonly used debarkers in softwood sawmills are cambio-ring debarkers, in which the log is held between spiked rollers and moved through a debarking ring (Blackwell and Walker, 2006). The debarking ring is formed of a series of blunt knives that press against the log shearing the bark off at the cambium (Blackwell and Walker, 2006). Many alternative conifers are stringy-barked, which presents a problem for sawmills using cambio-ring debarkers because the bark pulls away in long strands and wraps around the debarking arms blocking the machine. Conifer species that are suitable for existing processing machinery are more likely to be accepted by sawmillers.

Aim	Higher-level objectives	Lower-level objectives	Criteria (n=12)	Criteria type	Rationale
			Range of end uses for timber	Quantitative	The primary aim of many conifer plantations is to produce timber and other forest products on a commercial basis, i.e., to derive a profit. This profit depends on the range of end uses for the timber and other forest products. Conifer species with timber that has a wider range of uses are likely to offer more commercially viable options than species with a limited range of end uses.

Table notes

[1] High risk pest and pathogens are defined as having a UK Plant Health Risk Register risk rating of ≥60.

[2] Low risk pest and pathogens are defined as having a UK Plant Health Risk Register risk rating of <60.

Step three: Identify the conifer species to be evaluated

2.10 This step involved a data gathering exercise based on literature review supplemented by expert advice to compile a long list of conifer species. We compiled the initial long list using existing tree species guidance available in GB, particularly relating to non-native commercial timber producing species (EUFORGEN, n.d.; Forest Research, 2021b; Macdonald *et al*., 1957; Natural Resources Wales, 2015, 2017; Parratt, 2018; Royal Forestry Society, 2015; Savill, 2019; SilviFuture, n.d.; TRADA, n.d.; Wilson, 2011). We specified three criteria for including species from the literature on our long list:

- Include tree species that are naturalised in GB (Para 2.11, Parratt, 2018)
- Include tree species that are used or have historically been used for timber production in their natural range
- Exclude tree species that are principal conifer species already widely used in British Forestry (Box 2.1)

Box 2.1: Principal conifer species used in British Forestry

There are eight principal conifer species and one hybrid that contribute 97% of the British commercial coniferous forest resource (Forest Research, 2020). These were excluded from our long list of alternative species.

Scientific name	Common name	Proportion of GB commercial conifer forest resource (%)
Picea sitchensis	Sitka spruce	50.8
Pinus sylvestris	Scots pine	16.6
Larix decidua, Larix kaempferi and *Larix × marschlinsii*	larch (European, Japanese and hybrid)	9.6
Pinus contorta	lodgepole pine	7.6
Picea abies	Norway spruce	4.7
Pinus nigra subsp. *laricio*	Corsican pine	3.5
Pseudotsuga menziesii	Douglas fir	3.5

2.11 The primary criterion for inclusion on our long list was evidence of naturalisation in GB. In this case naturalised species are tree species that have been grown in tree collections and arboreta or exemplar sites across the public and private forest estate in GB and have shown the ability to naturally regenerate (Macdonald *et al*., 1957; Parratt, 2018; Savill, 2019; Wilson, 2011), i.e., the climatic conditions are suitable in the UK for the trees to reproduce without human intervention. Naturalisation as an ecological concept is often used as a proxy for a good climatic match with species selection (Mayer *et al*., 2017) and is also a valuable trait if there is a widespread shift to less intensive silvicultural systems involving natural regeneration, as expected over the next century (Bianchi *et al*., 2018; Macdonald *et al*., 2010; Mason, 2015). Following this protocol our compiled long list contains fifty-six species of coniferous trees (Table 2.3).

Table 2.3: Long list of 56 alternative conifer species.

Scientific name	Common name
Abies alba	European silver fir
Abies amabilis	Pacific silver fir
Abies balsamea	balsam fir
Abies cephalonica	Greek fir
Abies concolor	white fir
Abies fraseri	Fraser fir
Abies grandis	grand fir
Abies koreana	Korean fir
Abies nordmanniana	Nordmann fir
Abies procera	noble fir
Abies spectabilis	East Himalayan fir
Araucaria araucana	monkey puzzle tree/Chilean pine
Calocedrus decurrens	incense cedar
Cedrus atlantica	Atlas cedar
Cedrus atlantica Glauca	blue cedar
Cedrus brevifolia	Cyprus cedar
Cedrus deodara	deodar cedar
Cedrus libani	cedar of Lebanon
Chamaecyparis lawsoniana	Lawson’s cypress
Chamaecyparis obtuse	hinoki
Chamaecyparis pisifera	Sawara cypress
Cryptomeria japonica	Japanese cedar
Cupressus arizonica	Arizona cypress
Cupressus glabra	smooth cypress
Cupressus macrocarpa	Monterey cypress

Scientific name	Common name
Cupressus nootkatensis	Nootka cypress
Cupressus sempervirens	Italian cypress
x Cuprocyparis leylandii	Leyland cypress
Ginkgo biloba	maidenhair tree
Juniperus chinensis	Chinese juniper
Metasequoia glyptostroboides	dawn redwood
Picea engelmannii	Engelmann spruce
Picea glauca	white spruce
Picea omorika	Serbian spruce
Picea orientalis	Oriental spruce
Picea pungens	Colorado blue spruce
Pinus albicaulis	white bark pine
Pinus armandii	Armand's pine
Pinus monticola	Western white pine
Pinus muricata	bishops pine
Pinus peuce	Macedonian pine
Pinus pinaster	maritime/Bournemouth pine
Pinus pinea	Italian stone pine
Pinus ponderosa	Ponderosa pine
Pinus radiata	Monterey/radiata pine
Pinus strobus	Eastern white/Weymouth pine
Pinus wallichiana	Bhutan pine
Platycladus orientalis	Chinese thuja
Sequoia sempervirens	coast redwood
Sequoiadendron giganteum	giant redwood
Taxodium distichum	swamp cypress
Taxus baccata	yew
Thuja plicata	Western red cedar
Tsuga canadensis	Eastern hemlock
Tsuga heterophylla	Western hemlock
Tsuga mertensiana	mountain hemlock

Step four: Develop value-by-criteria matrix

2.12 We collated data collected from the literature available, evaluating how well each of the options performed against each of the criteria using a value-by-criteria matrix. Where physical quantitative data were available for a given criterion, this was used. Other qualitative measures were used where quantitative data for a particular criterion were not available. The values entered into the value-by-criteria matrix were 'raw' values on a range of scales derived from a range of sources. For the specific data sources used in the value by criteria matrix see Table 3.4.

Step five: Develop single-dimension utilities

2.13 The value-by-criteria matrix collated in the prior stage contained a combination of qualitative and quantitative values on a range of scales. In this subsequent stage these values were normalised values onto a common scoring scale (0-100). For the specific normalisation procedures used for each criterion see Table 2.4: . Scores were assigned using a relative 5-point scale for qualitative criteria as outlined in Table 2.4. For these criteria, where a high value is better than a low value, the best possible category was given a score of 100 and the worst possible category was given a score of 0, with all other categories given intermediate scores as appropriate. Scores were assigned using a straight-line function for the quantitative criteria outlined in Table 2.4. For these criteria, where a high value is better than a low value, the formula for converting the value onto a 0-100 scale was as follows:

$$u_{j,k} = 100(value_{j,k})/(max_k - min_k) \qquad \textit{Equation 1}$$

where $u_{j,k}$ is the scaled score for species j on criterion k, $value_{j,k}$ is the un-scaled value for species j on criterion k (from stage 4), max_k is the maximum score of any species for criterion k, min_k is the minimum score of any species for criterion k. Where no data for a species relating to a particular criterion could be found in Step 4, the species scored 0 for that criterion.

Table 2.4: Values and categories for the values-by-criteria matrix, normalisation procedures for single dimension utilities and data sources.

Criteria	Criteria type	Quantitative Values/qualitative categories	Normalisation to common scale (0 to 100)	Data source(s)
Resistance to ‘high risk’[1] pests and pathogens currently in GB	Quantitative	Number of pest and pathogen species that tree *species x* **is not** susceptible to out of the 5 ‘high risk’[3] pests and pathogens currently in GB	Straight-line function using Equation 1	Burns and Honkala (1990) Hansen, Lewis and Chastagner (1997) Nguyen *et al.* (2016) Oszako *et al.* (2017) Forest Research Pest and Diseases Resources, (Forest Research, 2021a) Phillips and Burdekin (1992e, 1992a, 1992b, 1992c, 1992d) Scharpf (1993) Spaulding, (1961) UK Plant Health Risk Register, (Defra, 2021) Wainhouse *et al.* (2016) For more other references see Annex A.
Resistance to ‘lower risk’[2] pests and pathogens currently in GB	Quantitative	Number of pest and pathogen species that tree *species x* **is not** susceptible to out of the 17 ‘lower risk’[4] pests and pathogens currently in GB	Straight-line function using Equation 1	
Resistance to ‘high risk’[1] pests and pathogens from France and Europe	Quantitative	Number of pest and pathogen species that tree *species x* **is not** susceptible to out of the 6 ‘high risk’[5] pests and pathogens from France or elsewhere in continental Europe	Straight-line function using Equation 1	
Resistance to ‘lower risk’[2] pests and pathogens from France and Europe	Quantitative	Number of pest and pathogen species that tree *species x* **is not** susceptible to out of the 5 ‘high risk’[7] pests and pathogens from France or elsewhere in continental Europe	Straight-line function using Equation 1	
Drought tolerance	Qualitative	‘Very intolerant’ ‘Intolerant’ ‘Moderately tolerant’ ‘Tolerant’ ‘Very tolerant’	‘Very intolerant’ = 0 ‘Intolerant’ = 25 ‘Moderately tolerant’ = 50 ‘Tolerant’ = 75 ‘Very tolerant’ = 100	Niinemets and Valladares (2006)
Waterlogging tolerance	Qualitative	‘Very intolerant’ ‘Intolerant’ ‘Moderately tolerant’ ‘Tolerant’ ‘Very tolerant’	‘Very intolerant’ = 0 ‘Intolerant’ = 25 ‘Moderately tolerant’ = 50 ‘Tolerant’ = 75 ‘Very tolerant’ = 100	Niinemets and Valladares (2006)
Shade tolerance	Qualitative	‘Very intolerant’ ‘Intolerant’ ‘Moderately tolerant’ ‘Tolerant’ ‘Very tolerant’	‘Very intolerant’ = 0 ‘Intolerant’ = 25 ‘Moderately tolerant’ = 50 ‘Tolerant’ = 75 ‘Very tolerant’ = 100	Niinemets and Valladares (2006)
Exposure tolerance	Qualitative	‘Very intolerant’ ‘Intolerant’ ‘Moderately tolerant’ ‘Tolerant’ ‘Very tolerant’	‘Very intolerant’ = 0 ‘Intolerant’ = 25 ‘Moderately tolerant’ = 50 ‘Tolerant’ = 75 ‘Very tolerant’ = 100	Burns and Honkala (1990) Forest Research Tree Species Database, (Forest Research, 2021b)
Potential productivity	Quantitative	Average yield class[7] of stands currently growing in GB	Straight line function using Equation 1	SilviFuture database (SilviFuture, n.d.-a) Mason *et al.* (2018)

Criteria	Criteria type	Quantitative Values/qualitative categories	Normalisation to common scale (0 to 100)	Data source(s)
Technical suitability of timber (stiffness)	Quantitative	Modulus of Elasticity (kN/mm^2)	MOE < 7 = 0 (Unlikely to grade to C14) 7 ≤ MOE < 8 = 25 (Likely to grade to C14) 8 ≤ MOE < 9 = 50 (Likely to grade to C16) 9 ≤ MOE < 9.5 = 75 (Likely to grade to C18) MOE ≥ 9.5 = 100 (Likely to grade to C20)	Berard *et al*. (2011) Güray *et al*. (2019) Lavers (1983) Passialis and Kiriazakos (2004) Ramsay and Macdonald (2013) Ross (2010)
Suitability for existing processing machinery	Qualitative	'Unknown' 'Other methods' 'Cambial debarking'	'Unknown' = 0 'Other methods' = 50 'Cambial debarking' = 100	Anecdotal evidence and expert judgement
Range of end uses for timber	Quantitative	Number of common uses for the timber of *species x*	Straight line function using Equation 1	CABI (2019g, 2019f, 2019e, 2019d, 2019c, 2019b, 2019h, 2019a, 2020) Meier (2021) TRADA, (no date) Savill and Mason (2015) Savill *et al*. (2017a) Savill *et al*. (2017b) Wilson *et al.* (2016) For more detailed references see Annex B.

Table notes

[1] High risk pest and pathogen species are defined as having a UK Plant Health Risk Register risk rating of ≥60.

[2] Low risk pest and pathogen species are defined as having a UK Plant Health Risk Register risk rating of <60.

[3] The high risk pest and pathogen species currently in GB include: *Dendrolimus pini, Dosthistroma septosporum, Ips typographus, Phytophthora ramorum and Phytophthora kernoviae.*

[4] The lower risk pest and pathogen species currently in GB include: Conifer aphids, *Armilaria mellea, Dendroctonus mican, Elatobium micans, Heterobasidion annosum, Hylobius abietis, Lymantria dispar, Neonectria neomacrospora, Pestalotiopsis pseudotsugae, Phomopsis sp., Rhizosphaera sp, Phytophthora lateralis, Sphaeropsis sp., Polyporous schweinilzii and Sicroccus tsugae.*

[5] The high risk pest and pathogen species from France or elsewhere in continental Europe include: *Bursaphelenchus xylophilus, Choristoneura sp., Dendrolimus sibiriicus, Lecanostica acicula, Thaumetopoea pityocampa and Xylella fastidiosa.*

[6] The lower risk pest and pathogen species from France or elsewhere in continental Europe include: *Carulepsis juniperi, Cronartium ribicola, Malacosoma Neustria, Fusarium circinatum and Rhyacionia buoliana.*

[7] Yield class is a measurement of incremental growth (i.e., the amount of solid stem wood added to an area of woodland) in cubic meters per hectare per year (m^3/ha/yr) expressed in intervals of 2. Different species of conifers will have different potential maximum yield classes, with higher values indicating higher growth rates and productivity.

Step six: Swing weighting

2.14 This step involved determining the rank order of the criteria (i.e., ranking them from most to least important), this was done through a process of 'stakeholder engagement'. We held an initial stakeholder meeting on Friday 5th March 2021, where the project objectives, ranking methodology and the online survey were introduced to participants. This event provided an opportunity for participants to ask any questions about the project or highlight anything the research team had missed. The meeting was followed up by an online survey, which was open from Friday 5th March 2021 to Monday 15th March 2021. Attendance at the online event was not a prerequisite for taking part in the survey.

2.15 In the online survey participants were invited to rank the 12 evaluation criteria in order of importance. This was undertaken by presenting decision makers with the 12 criteria and asking them:

> *"Imagine a tree species that has the worst performance across all of the 12 criteria, the worst possible species that could exist. You can improve the performance of one criterion from its current worst value to the best possible level. Which of the 12 criteria values would you improve?"*

2.16 Each participant selected which of the 12 criteria values they would improve first. The next question asked the participant which of the 12 criteria values (other than the one they selected before) they would then prefer, to be changed from the worst possible value to the best possible value. This continued until a rank ordering (from highest importance to lowest importance) of all criteria by each participant was obtained. For an overview of the survey questions see Annex C.

2.17 Survey responses were collated and the criterion that received the most votes amongst participants in response to each of the successive questions was deemed to be the preferred criterion. The criterion that was deemed to be preferred in response to the first question was ranked 1 (i.e., the most important), the criterion that was deemed to be preferred in response to the last question was ranked 12 (i.e., the least important). Criteria that were most popular in earlier questions and ranked in those positions were subsequently disregarded in the responses to the remaining questions. Following this process, the researchers placed the criteria into an importance order: e.g., Criterion 1 is more important than Criterion 2, which is more important than Criterion 3, which is more important than Criterion 4 and so on.

Step seven: Multi-attribute utility elicitation

2.18 This step involved obtaining the weights for each criterion. While the SMART technique involves a ‘hard’ step of eliciting judgemental weights from decision makers, the simpler SMARTER technique replaces this with a calculation to generate weights based on the rank order of criteria from the previous step. This process of generating weights is more appropriate and practicable than eliciting weights from decision makers or stakeholders, especially when the rank order of criteria is an outcome from a group who are likely to be more confident with ranking of the criteria rather than judging their relative weighting (Barron and Barrett, 1996).

2.19 There are a number of methods for generating weights from rankings. We used the rank order centroid (ROC) method (Barron and Barrett, 1996; Roberts and Goodwin, 2002), which assigns weights to each criterion based on its position in the rank order determined in the previous step. The ROC method assigns weights as follows: w_1 is the weight of the most important criterion, w_2 is the weight of the next most important criterion, and so on. For k criteria the calculation of the weights was as follows:

$$\begin{aligned} w_1 &= (1 + 1/2 + 1/3 + \ldots + 1/k)/k \\ w_2 &= (0 + 1/2 + 1/3 + \ldots + 1/k)/k \\ w_k &= (0 + 0 + \ldots + 0 + 1/k)/k \end{aligned}$$

Equation 2

The sum of these weights will equal 1.0. This approach minimises maximum error by identifying the centroid of all possible weights that maintain the rank order of the criterion.

Step eight: Calculate multi-attribute utilities for options

2.20 The multi-attribute utilities for each of the options (i.e., conifer species) were calculated using the following formula:

$$U_j = \sum_k w_k u_{jk}$$ *Equation 3*

where U_j is the utility value for option j, w_k is the normalised weight for attribute k and u_{jk} is the score for option j on criteria k. The u_{jk} values were generated in step five and the w_k values were obtained from the step seven.

Step nine: Ranking

2.21 To identify the top five alternative conifer species, we rank-ordered the options in the order of U_j from highest to lowest. The five alternative conifer species with the highest value for U_j were selected for further review.

Characterisation of top five alternative conifer species

2.22 In the second stage of the review, we carried out an extended narrative literature review and characterisation of the top five ranked tree species. The literature reviewed in compiling these characterisations was sourced from searches using the Elsevier Scopus Abstract and Citation database, Clarivate Web of Science Abstract and Citation Database, Google Scholar, and other literature sources available to the authors. The common (English) and scientific (Latin) names of the species identified were used as search strings. Due to the time available for this review only papers published in the English language were included in the characterisations. In addition, 'grey' unpublished literature was included when it was known to, or could be located by, the authors. Stakeholders were also given an opportunity to contribute literature they felt was relevant to the review. The extended characterisations focussed on answering the following questions for each of the top five ranked species:

- What is their native range and genetic diversity?
- What is their ecology and silviculture?
- What are the threats that they face from pests and pathogens?
- What is the utilisation potential of their timber?

3. Findings

Current and future pests in GB

3.1 One of the primary research questions this review set out to address was which conifer tree species are likely to be resilient to current and future pests and pathogens in GB. This involved identifying:

1. Pests and pathogens currently prevalent in GB
2. Pests and pathogens currently prevalent in France and elsewhere in continental Europe

Table 3.1: The pest and pathogen species affecting conifers that are currently prevalent in GB.

Scientific name	Common name	Category	Risk
Dendrolimus pini	pine tree lappet moth	Insect	High
Dothistroma septosporum	red band needle blight	Fungus	High
Ips typographus	European spruce bark beetle	Insect	High
Phytophthora kernoviae		Phytophthora	High
Phytophthora ramorum	Ramorum disease	Phytophthora	High
	conifer aphids	Insect	Low
Armilaria mellea	honey fungus	Fungus	Low
Dendroctonus micans	giant spruce beetle	Insect	Low
Elatobium abietinum	green spruce aphid	Insect	Low
Heterobasidion annosum	Fomes annosus	Fungus	Low
Hylobius abietis	large pine weevil	Insect	Low
Lymantria dispar	gypsy moth	Insect	Low
Neonectria neomacrospora		Fungus	Low
Pestalotiopsis funereal		Fungus	Low
Phomopsis pseudotsugae		Fungus	Low
Phomopsis sp.		Fungus	Low
Rhizosphaera sp.	Rhizosphaera needle cast	Fungus	Low
Phytophthora austrocedri		Phytophthora	Low
Phytophthora lateralis		Phytophthora	Low
Sphaeropsis sp.	Diplodia tip blight	Fungus	Low
Polyporus schweinilzii		Fungus	Low
Sirococcus tsugae		Fungus	Low

Source: Defra (2021); Forest Research (2021)
Table notes
[1] High risk pests and pathogens are defined as having a UK Plant Health Risk Register risk rating of ≥60 and Low risk pests and pathogens are defined as having a UK Plant Health Risk Register risk rating of <60.

3.2 The pests and pathogen species currently prevalent in France or elsewhere in continental Europe (Table 3.2) are considered a threat to GB because of the potential for their range expansion due to climate change.

Table 3.2: Pest and pathogen species affecting conifers that are currently absent from GB but prevalent in France or elsewhere in continental Europe.

Scientific name	Common name	Category	Risk
Bursaphelenchus xylophilus	pine wood nematode	Insect	High
Choristoneura sp.	budworms	Insect	High
Dendrolimus sibiiricus	Siberian silk moth	Insect	High
Lecanostica acicola	brown spot needle blight	Fungus	High
Thaumetopoea pityocampa	pine processionary moth	Insect	High
Xylella fastidiosa	Xylella	Bacterium	High
Carulepsis juniperi	juniper scale	Insect	Low
Cronartium ribicola	white pine blister rust	Fungus	Low
Malacosoma neustria	forest tent caterpillar	Insect	Low
Fusarium circinatum	pine pitch canker	Fungus	Low
Rhyacionia buoliana	European pine shoot moth	Insect	Low

Source: Defra (2021); Forest Research (2021a)
Table notes
[1] High risk pests and pathogens are defined as having a UK Plant Health Risk Register risk rating of ≥60 and Low risk pests and pathogens are defined as having a UK Plant Health Risk Register risk rating of <60.

3.3 The lists of pests and pathogens affecting conifers that are currently in GB, France and elsewhere in continental Europe used in this study are unlikely to be comprehensive and should be considered just to be representative of the major threats. Many recent forest disease outbreaks have been from pathogens that were unknown in their native range and only discovered after establishment in a non-native ecosystem. Examples include Dutch elm disease, sudden oak death, *Phytophthora alni* of alder and box blight (Brasier, 2008).

3.4 Anticipating pests and pathogens that are unknown or that have not yet caused observed symptoms in affected trees is problematic (Srivastava *et al*, 2021; Robinet *et al*., 2020). Given that an estimated 7-10% of species of fungi are currently identified (Crous and Groenwald, 2005) it seems likely that approximately 90% of fungal pathogens are currently unknown to science (Brasier, 2008). It is estimated that there are between 100 and 500 undiscovered species of Phytophthora, which due to co-evolution will not show symptoms until they escape their native range (Brasier, 2005). With this in mind, there is a significant level of uncertainty with undertaking such an exercise and readers should be cognisant of this when interpreting the results.

Ranking alternative conifer species

Value-by-criteria matrix

3.5 The value-by-criteria matrix (Table 3.3) contains a mix of qualitative and quantitative data on a range of scales. For most of the alternative species, data to evaluate their performance were readily available. However, for a number of species there were insufficient data available to evaluate their performance in relation to some of the criteria.

3.6 The primary data gaps relate to the environmental tolerances of some of the cypresses, cedars and pines. Another significant data gap related to the potential productivity of some of the alternative conifer species. While many are grown in pineta or arboreta some have yet to be grown in single-species stands from which yield class could be estimated.

3.7 Sufficient data were available to evaluate the resistance of all of the alternative conifer species to both ‘high’ and ‘lower’ risk pests and pathogens currently in GB or in France or elsewhere in continental Europe (Table 3.1 and 3.2). The value-by-criteria matrix evaluating how well each of the alternative conifer species perform against each of the 12 evaluation criteria is shown in Table 3.3.

3.8 Specific data sources used to construct the value-by-criteria matrix are outlined in §2 Table 2.4. For further information on how the values for the four pest and pathogen criteria, and the end uses for timber criterion, were derived see Annexes A and B.

Table 3.3: Value-by-criteria matrix.

Scientific name	Common name	Criteria value											
		Resistance to 'high risk' pests and pathogens currently in GB[1]	Resistance to 'lower risk' pests and pathogens currently in GB[2]	Resistance to 'high risk' pests and pathogens from France and Europe[3]	Resistance to 'lower risk' pests and pathogens from France and Europe[4]	Drought tolerance	Waterlogging tolerance	Shade tolerance	Exposure tolerance	Potential productivity – yield class (m^3/ha/yr)	Technical suitability of timber (stiffness) – MOE (kN/mm^2)	Suitability for existing processing machinery	Range of end uses for timber[5]
Abies alba	European silver fir	4 out of 5	11 out of 17	3 out of 6	5 out of 5	moderate	low	very high	intolerant	16	9.8	cambial debarking	6
Abies amabilis	Pacific silver fir	4 out of 5	12 out of 17	3 out of 6	5 out of 5	low	low	very high	very intolerant	20	11.3	cambial debarking	6
Abies balsamea	balsam fir	4 out of 5	11 out of 17	3 out of 6	5 out of 5	very low	moderate	very high	intolerant		9.7	cambial debarking	6
Abies cephalonica	Greek fir	4 out of 5	12 out of 17	3 out of 6	5 out of 5						8.1	cambial debarking	0
Abies concolor	white fir	4 out of 5	10 out of 17	3 out of 6	5 out of 5	low	low	very high			10.3	cambial debarking	6
Abies fraseri	Fraser fir	4 out of 5	12 out of 17	3 out of 6	5 out of 5	moderate	moderate	very high				cambial debarking	0
Abies grandis	grand fir	3 out of 5	12 out of 17	3 out of 6	5 out of 5	moderate	low	very high		20	7	cambial debarking	6
Abies koreana	Korean fir	4 out of 5	12 out of 17	3 out of 6	5 out of 5							cambial debarking	6
Abies nordmanniana	Nordmann fir	4 out of 5	12 out of 17	3 out of 6	5 out of 5	low	low	very high	very intolerant		5.9	cambial debarking	6
Abies procera	noble fir	3 out of 5	11 out of 17	3 out of 6	5 out of 5	moderate	low	moderate	tolerant	16	8.1	cambial debarking	6
Abies spectabilis	East Himalayan fir	3 out of 5	11 out of 17	3 out of 6	5 out of 5							cambial debarking	0
Araucaria araucana	monkey puzzle tree/Chilean pine	5 out of 5	14 out of 17	4 out of 6	5 out of 5							unknown	5
Calocedrus decurrens	incense cedar	5 out of 5	14 out of 17	4 out of 6	5 out of 5	high	low	high			7.2	other methods	5
Cedrus atlantica	Atlas cedar	4 out of 5	13 out of 17	3 out of 6	5 out of 5				very intolerant		10.1	cambial debarking	6
Cedrus atlantica Glauca	Blue cedar	4 out of 5	13 out of 17	3 out of 6	5 out of 5				very intolerant			cambial debarking	6
Cedrus brevifolia	Cyprus cedar	4 out of 5	13 out of 17	4 out of 6	5 out of 5							cambial debarking	6
Cedrus deodara	deodar cedar	4 out of 5	13 out of 17	4 out of 6	5 out of 5	high	low	moderate				cambial debarking	6
Cedrus libani	cedar of Lebanon	4 out of 5	13 out of 17	4 out of 6	5 out of 5	moderate	low	low	very intolerant		5.8	cambial debarking	6
Chamaecyparis lawsoniana	Lawson's cypress	5 out of 5	11 out of 17	4 out of 6	4 out of 5	moderate	low	high	very intolerant	14	5.4	other methods	4

Scientific name	Common name	Criteria value											
		Resistance to 'high risk' pests and pathogens currently in GB[1]	Resistance to 'lower risk' pests and pathogens currently in GB[2]	Resistance to 'high risk' pests and pathogens from France and Europe[3]	Resistance to 'lower risk' pests and pathogens from France and Europe[4]	Drought tolerance	Waterlogging tolerance	Shade tolerance	Exposure tolerance	Potential productivity – yield class (m^3/ha/yr)	Technical suitability of timber (stiffness) – MOE (kN/mm^2)	Suitability for existing processing machinery	Range of end uses for timber[5]
Chamaecyparis obtuse	hinoki	5 out of 5	13 out of 17	4 out of 6	4 out of 5	moderate	low	very high			11.72	other methods	4
Chamaecyparis pisifera	Sawara cypress	5 out of 5	13 out of 17	4 out of 6	4 out of 5							other methods	4
Cryptomeria japonica	Japanese cedar	5 out of 5	14 out of 17	4 out of 6	5 out of 5	moderate	moderate	high	moderate	16	9.6	other methods	4
Cupressus arizonica	Arizona cypress	5 out of 5	11 out of 17	4 out of 6	4 out of 5	very high	low	low				other methods	2
Cupressus glabra	smooth cypress	5 out of 5	12 out of 17	4 out of 6	4 out of 5							other methods	0
Cupressus macrocarpa	Monterey cypress	5 out of 5	12 out of 17	4 out of 6	4 out of 5							other methods	4
Cupressus nootkatensis	Nootka cypress	5 out of 5	11 out of 17	4 out of 6	4 out of 5							other methods	6
Cupressus sempervirens	Italian cypress	5 out of 5	12 out of 17	4 out of 6	4 out of 5	very high	low	low				other methods	4
x Cuprocyparis leylandii	Leyland cypress	5 out of 5	12 out of 17	4 out of 6	4 out of 5				moderate	20	5.9	other methods	4
Ginkgo biloba	maidenhair tree	5 out of 5	14 out of 17	4 out of 6	5 out of 5	high	low	low				unknown	4
Juniperus chinensis	Chinese juniper	4 out of 5	10 out of 17	4 out of 6	3 out of 5	very high	low	low				other methods	7
Metasequoia glyptostroboides	dawn redwood	5 out of 5	14 out of 17	4 out of 6	5 out of 5	moderate	low	high	Intolerant			other methods	8
Picea engelmannii	Engelmann spruce	4 out of 5	10 out of 17	3 out of 6	5 out of 5	moderate	low	very high			8.9	cambial debarking	5
Picea glauca	white spruce	4 out of 5	10 out of 17	3 out of 6	5 out of 5	moderate	low	very high			9.6	cambial debarking	4
Picea omorika	Serbian spruce	3 out of 5	10 out of 17	3 out of 6	5 out of 5	moderate	low	very high	tolerant	10	7.6	cambial debarking	4
Picea orientalis	Oriental spruce	4 out of 5	10 out of 17	3 out of 6	5 out of 5				moderate	14	8.2	cambial debarking	7
Picea pungens	Colorado blue spruce	4 out of 5	9 out of 17	3 out of 6	5 out of 5	moderate	low	high				cambial debarking	3
Pinus albicaulis	white bark pine	2 out of 5	9 out of 17	1 out of 6	3 out of 5	very high	low	low				cambial debarking	0
Pinus armandii	Armand's pine	2 out of 5	9 out of 17	1 out of 6	3 out of 5							cambial debarking	0
Pinus monticola	Western white pine	2 out of 5	9 out of 17	1 out of 6	2 out of 5	moderate	low	moderate	intolerant	12	10.1	cambial debarking	5
Pinus muricata	bishops pine	2 out of 5	9 out of 17	1 out of 6	2 out of 5	moderate	low	moderate				cambial debarking	7

Scientific name	Common name	Criteria value											
		Resistance to 'high risk' pests and pathogens currently in GB[1]	Resistance to 'lower risk' pests and pathogens currently in GB[2]	Resistance to 'high risk' pests and pathogens from France and Europe[3]	Resistance to 'lower risk' pests and pathogens from France and Europe[4]	Drought tolerance	Waterlogging tolerance	Shade tolerance	Exposure tolerance	Potential productivity – yield class (m^3/ha/yr)	Technical suitability of timber (stiffness) – MOE (kN/mm^2)	Suitability for existing processing machinery	Range of end uses for timber[5]
Pinus peuce	Macedonian pine	2 out of 5	9 out of 17	1 out of 6	3 out of 5				moderate	10	4.8	cambial debarking	2
Pinus pinaster	maritime/ Bournemouth pine	2 out of 5	9 out of 17	1 out of 6	3 out of 5				intolerant	14	8.9	cambial debarking	4
Pinus pinea	Italian stone pine	2 out of 5	9 out of 17	1 out of 6	3 out of 5						6.6	cambial debarking	4
Pinus ponderosa	Ponderosa pine	2 out of 5	9 out of 17	1 out of 6	3 out of 5	very high	low	low			7.6	cambial debarking	7
Pinus radiata	Monteray/ radiata pine	1 out of 5	9 out of 17	1 out of 6	3 out of 5	moderate	low	moderate	tolerant	16	8.3	cambial debarking	5
Pinus strobus	Eastern white/ Weymouth pine	2 out of 5	9 out of 17	1 out of 6	2 out of 5	moderate	low	high	moderate	12	5.5	cambial debarking	3
Pinus wallichiana	Bhutan pine	2 out of 5	9 out of 17	1 out of 6	3 out of 5	moderate	low	low				cambial debarking	7
Platycladus orientalis	Chinese thuja	5 out of 5	14 out of 17	4 out of 6	5 out of 5							other methods	7
Sequoia sempervirens	coast redwood	5 out of 5	14 out of 17	4 out of 6	5 out of 5	moderate	very low	very high	very intolerant	20	7.6	other methods	5
Sequoiadendron giganteum	giant redwood	5 out of 5	14 out of 17	4 out of 6	5 out of 5	moderate	low	high	moderate	16	8.9	other methods	5
Taxodium distichum	swamp cypress	5 out of 5	14 out of 17	4 out of 6	5 out of 5	high	very high	moderate			9.9	other methods	5
Taxus baccata	yew	5 out of 5	13 out of 17	5 out of 6	5 out of 5	high	low	very high				other methods	2
Thuja plicata	Western red cedar	5 out of 5	11 out of 17	5 out of 6	4 out of 5	moderate	low	very high	very intolerant	18	7	other methods	3
Tsuga canadensis	Eastern hemlock	5 out of 5	13 out of 17	4 out of 6	5 out of 5	low	low	very high			8.3	cambial debarking	5
Tsuga heterophylla	Western hemlock	4 out of 5	12 out of 17	3 out of 6	5 out of 5	low	very low	very high	very intolerant	18	8	cambial debarking	5
Tsuga mertensiana	mountain hemlock	5 out of 5	13 out of 17	3 out of 6	5 out of 5	low	very low	very high		12	9.2	cambial debarking	5

Table notes

A blank cell indicates that no relevant data could be found to evaluate that individual species against a particular criterion.

[1] See Annex A for the matrix outlining the susceptibility/resistance of the alternative conifer species to 'high risk' pests and pathogens currently in GB.

[2] See Annex A for the matrix outlining the susceptibility/resistance of the alternative conifer species to 'lower risk' pests and pathogens currently in GB.

[3] See Annex A for the matrix outlining the susceptibility/resistance of the alternative conifer species to 'high risk' pests and pathogens in France or elsewhere in continental Europe.

[4] See Annex A for the matrix outlining the susceptibility/resistance of the alternative conifer species to 'high risk' pests and pathogens in France or elsewhere in continental Europe.

[5] See Annex B for the matrix outlining the range of end uses for the timber of the alternative conifer species.

Single-dimension utilities

3.9 Annex D outlines the single-dimension utility scores for each of the alternative conifer species against the 12 evaluation criteria. These scores normalise the raw values from Table 3.3 onto a common 0 to 100 scale allowing the qualitative and quantitative data to be aggregated using criteria weightings derived from stakeholder input. It should be noted that many of the zero scores are not due to poor performance of the particular conifer species, but rather due to lack of suitable data to evaluate their performance against that particular criterion. Availability of additional data would be likely to affect the rankings, elevating the position of the least well-known species.

Swing weighting

3.10 To determine the rank order of the criteria (i.e., ranking them from most to least important), a process of stakeholder engagement was undertaken using an online survey, which was open from the Friday 5th March 2021 to Monday 15th March 2021. In the online survey participants were invited to rank the 12 criteria outlined in §2 Table 2.1 in order of importance. We received 38 survey responses from a broad invitation to around 100 invited stakeholders (covering the range of stakeholders identified in §2). The breakdown of survey respondents by category of decision maker is shown in Figure 3.1.

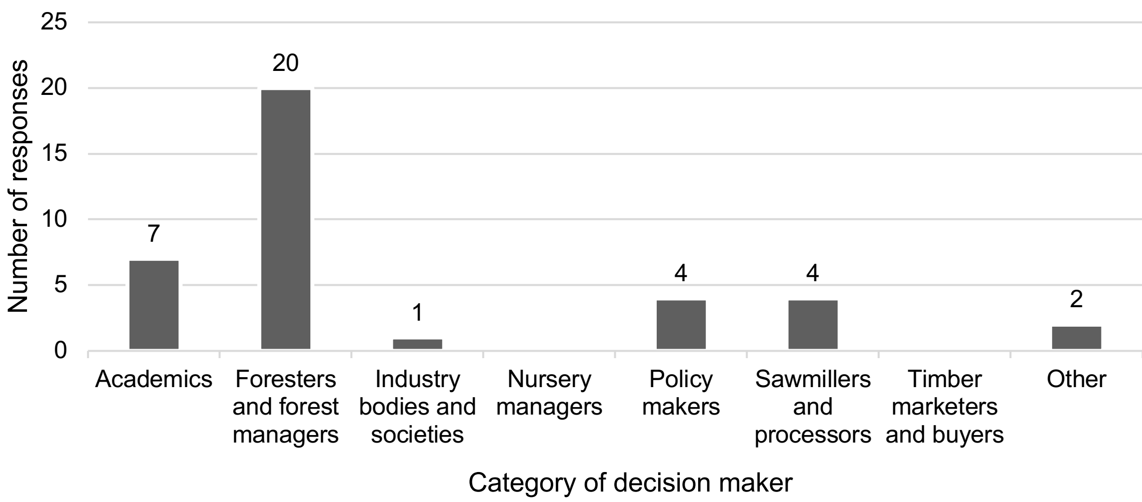

Figure 3.1: Breakdown of survey responses by category of decision maker.

3.11 Responses were primarily from foresters and forest managers followed by academics. No responses were received from nursery managers or timber marketers and buyers. Survey responses were collated, and the resulting rank order of the criteria is shown in Table 3.4.

Table 3.4: Stakeholder swing weighting and rank order of the evaluation criteria.

Ranking	Criterion	Weight
1st	Resistance to 'high risk' pests and pathogens from France and Europe	0.2586
2nd	Resistance to 'high risk' pests and pathogens currently in GB	0.1753
3rd	Potential productivity	0.1336
4th	Drought tolerance	0.1058
5th	Resistance to 'lower risk' pests and pathogens from France and Europe	0.0850
6th	Resistance to 'lower risk' pests and pathogens currently in GB	0.0683
7th	Range of end uses for timber	0.0544
7th	Exposure tolerance	0.0425
9th	Suitability for existing processing machinery	0.0321
10th	Shade tolerance	0.0229
11th	Technical suitability of timber (stiffness)	0.0145
12th	Waterlogging tolerance	0.0069

3.12 Criteria relating high risk pests and pathogens present in France or elsewhere in continental Europe followed by those present in GB were deemed to be the most important, with productivity, drought tolerance and resistance to lower risk pests and pathogens making up the four next most important criteria. Criteria relating to site tolerances, processing and markets were deemed to be less important and formed the lower end of the rank order.

Multi-attribute utility elicitation

3.13 Using the criteria rank order, the criteria weights were calculated using the rank order centroid (ROC) method and are shown in the final column of Table 3.4.

Multi-attribute utilities and overall ranking

3.14 The multi-attribute utility scores and overall ranking of the alternative conifer species are shown in Table 3.5. These weighted scores are calculated using the scores from Annex D and the criteria weightings from Table 3.4.

Table 3.5: Weighted scores, multi-attribute utilities and overall ranking of the alternative conifer species.

Scientific name	Common name	Weighted criteria score												Total (multi-attribute utility value)
		Resistance to 'high risk' pests and pathogens currently in GB	Resistance to 'lower risk' pests and pathogens currently in GB	Resistance to 'high risk' pests and pathogens from France and Europe	Resistance to 'lower risk' pests and pathogens from France and Europe	Drought tolerance	Waterlogging tolerance	Shade tolerance	Exposure tolerance	Potential productivity	Technical suitability of timber (stiffness)	Suitability for existing processing machinery	Range of end uses for timber	
Sequoia sempervirens	coast redwood	17.53	6.83	20.69	8.50	5.29	0.00	2.29	0.00	13.36	0.36	3.21	3.40	81.46
Cryptomeria japonica	Japanese cedar	17.53	6.83	20.69	8.50	5.29	0.35	1.71	2.13	10.69	1.45	3.21	2.72	81.10
Thuja plicata	Western red cedar	17.53	5.37	25.86	6.80	5.29	0.17	2.29	0.00	12.02	0.36	3.21	2.04	80.94
Sequoiadendron giganteum	giant redwood	17.53	6.83	20.69	8.50	5.29	0.17	1.71	2.13	10.69	0.73	3.21	3.40	80.88
Abies alba	European silver fir	14.02	5.37	15.52	8.50	5.29	0.17	2.29	1.06	10.69	1.45	3.21	4.08	71.65
Taxodium distichum	swamp cypress	17.53	6.83	20.69	8.50	7.94	0.69	1.14	0.00	0.00	1.45	3.21	3.40	71.39
Chamaecyparis lawsoniana	Lawson's cypress	17.53	5.37	20.69	6.80	5.29	0.17	1.71	0.00	9.35	0.00	1.61	2.72	71.24
Abies amabilis	Pacific silver fir	14.02	5.86	15.52	8.50	2.65	0.17	2.29	0.00	13.36	1.45	3.21	4.08	71.10
Taxus baccata	yew	17.53	6.34	25.86	8.50	7.94	0.17	2.29	0.00	0.00	0.00	1.61	0.68	70.91
Cupressus arizonica	Arizona cypress	17.53	5.86	20.69	6.80	0.00	0.00	0.00	2.13	13.36	0.00	1.61	2.72	70.68
Metasequoia glyptostroboides	dawn redwood	17.53	6.83	20.69	8.50	5.29	0.17	1.71	1.06	0.00	0.00	3.21	5.44	70.44
Calocedrus decurrens	incense cedar	17.53	6.83	20.69	8.50	7.94	0.17	1.71	0.00	0.00	0.36	3.21	3.40	70.35
Abies grandis	grand fir	10.52	5.86	15.52	8.50	5.29	0.17	2.29	0.00	13.36	0.36	3.21	4.08	69.15
Tsuga mertensiana	mountain hemlock	17.53	6.34	15.52	8.50	2.65	0.00	2.29	0.00	8.02	1.09	3.21	3.40	68.54
Abies procera	noble fir	10.52	5.37	15.52	8.50	5.29	0.17	1.14	3.19	10.69	0.73	3.21	4.08	68.40
Tsuga heterophylla	Western hemlock	14.02	5.86	15.52	8.50	2.65	0.00	2.29	0.00	12.02	0.73	3.21	3.40	68.19
Ginkgo biloba	maidenhair tree	17.53	6.83	20.69	8.50	7.94	0.17	0.57	0.00	0.00	0.00	1.61	2.72	66.56
Chamaecyparis obtuse	hinoki	17.53	6.34	20.69	6.80	5.29	0.17	2.29	0.00	0.00	1.45	3.21	2.72	66.49
Cupressus glabra	smooth cypress	17.53	5.37	20.69	6.80	10.58	0.17	0.57	0.00	0.00	0.00	3.21	1.36	66.28
Tsuga canadensis	Eastern hemlock	17.53	6.34	20.69	8.50	2.65	0.17	2.29	0.00	0.00	0.73	3.21	3.40	65.50

Scientific name	Common name	Weighted criteria score												Total (multi-attribute utility value)
		Resistance to 'high risk' pests and pathogens currently in GB	Resistance to 'lower risk' pests and pathogens currently in GB	Resistance to 'high risk' pests and pathogens from France and Europe	Resistance to 'lower risk' pests and pathogens from France and Europe	Drought tolerance	Waterlogging tolerance	Shade tolerance	Exposure tolerance	Potential productivity	Technical suitability of timber (stiffness)	Suitability for existing processing machinery	Range of end uses for timber	
Cupressocyparis leylandii	leyland cypress	17.53	5.86	20.69	6.80	10.58	0.17	0.57	0.00	0.00	0.00	0.00	2.72	64.92
Cedrus deodara	deodar cedar	14.02	6.34	20.69	8.50	7.94	0.17	1.14	0.00	0.00	0.00	1.61	4.08	64.49
Juniperus chinensis	Chinese juniper	14.02	4.88	20.69	5.10	10.58	0.17	0.57	0.00	0.00	0.00	3.21	4.76	63.99
Platycladus orientalis	Chinese thuja	17.53	6.83	20.69	8.50	0.00	0.00	0.00	0.00	0.00	0.00	3.21	4.76	61.52
Picea orientalis	oriental spruce	14.02	4.88	15.52	8.50	0.00	0.00	0.00	2.13	9.35	0.73	1.61	4.76	61.49
Cedrus libani	cedar of Lebanon	14.02	6.34	20.69	8.50	5.29	0.17	0.57	0.00	0.00	0.00	1.61	4.08	61.28
Araucaria araucana	monkey puzzle tree/Chilean pine	17.53	6.83	20.69	8.50	0.00	0.00	0.00	0.00	0.00	0.00	3.21	3.40	60.16
Picea omorika	Serbian spruce	10.52	4.88	15.52	8.50	5.29	0.17	2.29	3.19	6.68	0.36	0.00	2.72	60.12
Picea glauca	white spruce	14.02	4.88	15.52	8.50	5.29	0.17	2.29	0.00	0.00	1.45	3.21	2.72	58.05
Cupressus sempervirens	Italian cypress	17.53	5.37	20.69	6.80	0.00	0.00	0.00	0.00	0.00	0.00	3.21	4.08	57.68
Chamaecyparis pisifera	sawara cypress	17.53	6.34	20.69	6.80	0.00	0.00	0.00	0.00	0.00	0.00	3.21	2.72	57.29
Cedrus brevifolia	Cyprus cedar	14.02	6.34	20.69	8.50	0.00	0.00	0.00	0.00	0.00	0.00	3.21	4.08	56.85
Cupressus nootkatensis	nootka cypress	17.53	5.86	20.69	6.80	0.00	0.00	0.00	0.00	0.00	0.00	3.21	2.72	56.80
Picea engelmannii	engelmann spruce	14.02	4.88	15.52	8.50	5.29	0.17	2.29	0.00	0.00	0.73	1.61	3.40	56.40
Abies concolor	white fir	14.02	4.88	15.52	8.50	2.65	0.17	2.29	0.00	0.00	1.45	1.61	4.08	55.16
Abies fraseri	Fraser fir	14.02	5.86	15.52	8.50	5.29	0.35	2.29	0.00	0.00	0.00	3.21	0.00	55.03
Picea pungens	Colorado blue spruce	14.02	4.39	15.52	8.50	5.29	0.17	1.71	0.00	0.00	0.00	3.21	2.04	54.86
Abies nordmanniana	nordmann fir	14.02	5.86	15.52	8.50	2.65	0.17	2.29	0.00	0.00	0.00	1.61	4.08	54.69
Abies balsamea	balsam fir	14.02	5.37	15.52	8.50	0.00	0.35	2.29	1.06	0.00	1.45	1.61	4.08	54.24
Cedrus atlantica	atlas cedar	14.02	6.34	15.52	8.50	0.00	0.00	0.00	0.00	0.00	1.45	3.21	4.08	53.13

Scientific name	Common name	Weighted criteria score												Total (multi-attribute utility value)
		Resistance to 'high risk' pests and pathogens currently in GB	Resistance to 'lower risk' pests and pathogens currently in GB	Resistance to 'high risk' pests and pathogens from France and Europe	Resistance to 'lower risk' pests and pathogens from France and Europe	Drought tolerance	Waterlogging tolerance	Shade tolerance	Exposure tolerance	Potential productivity	Technical suitability of timber (stiffness)	Suitability for existing processing machinery	Range of end uses for timber	
Cupressus macrocarpa	Monterey cypress	17.53	5.86	20.69	6.80	0.00	0.00	0.00	0.00	0.00	0.00	1.61	0.00	52.48
Cedrus atlantica Glauca	blue cedar	14.02	6.34	15.52	8.50	0.00	0.00	0.00	0.00	0.00	0.00	3.21	4.08	51.67
Abies koreana	Korean fir	14.02	5.86	15.52	8.50	0.00	0.00	0.00	0.00	0.00	0.00	3.21	4.08	51.19
Abies cephalonica	Greek fir	14.02	5.86	15.52	8.50	0.00	0.00	0.00	0.00	0.00	0.73	1.61	0.00	46.22
Pinus radiata	Monterey/radiata pine	3.51	4.39	5.17	5.10	5.29	0.17	1.14	3.19	10.69	0.73	1.61	3.40	44.39
Abies spectabilis	East Himalayan fir	10.52	5.37	15.52	8.50	0.00	0.00	0.00	0.00	0.00	0.00	3.21	0.00	43.11
Pinus strobus	Eastern white/ Weymouth pine	7.01	4.39	5.17	3.40	5.29	0.17	1.71	2.13	8.02	0.00	3.21	2.04	42.55
Pinus monticola	Western white pine	7.01	4.39	5.17	3.40	5.29	0.17	1.14	1.06	8.02	1.45	1.61	3.40	42.12
Pinus ponderosa	ponderosa pine	7.01	4.39	5.17	5.10	10.58	0.17	0.57	0.00	0.00	0.36	3.21	4.76	41.34
Pinus pinaster	maritime/ Bournemouth pine	7.01	4.39	5.17	5.10	0.00	0.00	0.00	1.06	9.35	0.73	3.21	2.72	38.75
Pinus albicaulis	white bark pine	7.01	4.39	5.17	5.10	10.58	0.17	0.57	0.00	0.00	0.00	1.61	0.00	34.61
Pinus wallichiana	Bhutan pine	7.01	4.39	5.17	5.10	5.29	0.17	0.57	0.00	0.00	0.00	1.61	4.76	34.08
Pinus peuce	Macedonian pine	7.01	4.39	5.17	5.10	0.00	0.00	0.00	2.13	6.68	0.00	1.61	1.36	33.45
Pinus muricata	bishops pine	7.01	4.39	5.17	3.40	5.29	0.17	1.14	0.00	0.00	0.00	1.61	4.76	32.95
Pinus pinea	Italian stone pine	7.01	4.39	5.17	5.10	0.00	0.00	0.00	0.00	0.00	0.00	3.21	2.72	27.61
Pinus armandii	Armand's pine	7.01	4.39	5.17	5.10	0.00	0.00	0.00	0.00	0.00	0.00	3.21	0.00	24.89

The top five alternative conifer species

3.15 Based on the overall ranking outlined in Table 3.5, the five highest scoring species are shown in Table 3.6. The five top ranked species scored well overall as they are relatively resistant to a range of high and low risk pests and pathogens, they are tolerant of a range of site conditions, there is evidence of their high potential productivity when grown in GB and their timber is suitable for a range of end uses and are likely to grade to strength classes required for use in construction.

Table 3.6: Top five ranked alternative conifer species.

Ranking	Scientific name	Common name	Multi-attribute utility value
1st	*Sequoia sempervirens*	coast redwood	81.46
2nd	*Cryptomeria japonica*	Japanese cedar	81.10
3rd	*Thuja plicata*	Western red cedar	80.94
4th	*Sequoiadendron giganteum*	giant redwood	80.88
5th	*Abies alba*	European silver fir	71.65

3.16 The primary aim of this review was to identify five practical alternative conifer tree species which can be incorporated into the commercial conifer forest resource across GB. It should be noted that there is a significant drop in the multi-attribute utility value score from the fourth to the fifth ranked species, whose score is much closer to those ranked below it in the list. The results show that there are clearly four 'outstanding' species followed by a large set of very similar scoring species (Table 3.5).

3.17 While the top five ranked species score well and are likely to be suitable for a broad range of site conditions across GB, they are not ideal everywhere. Therefore, we recommend that the diversity of productive conifers considered for future use across GB should be broader. The results indicate that there are 11 other alternative conifer species that perform well in relation to being resistant to pests and pathogens, being suitable for a range of site conditions and able to produce commercial timber products, which are worthy of active consideration. These 11 species all have multi-attribute utility within four units of value of the 5th placed species.

3.18 Table 5.7 outlines these 11 species that are worthy of further investigation as they may be suitable for site types that the top five may not be. However, it was beyond the scope of this review to consider their suitability in more detail.

Table 3.7: Other alternative conifer species with merit.

Ranking	Scientific name	Common name	Multi-attribute utility value
6th	*Taxodium distichum*	swamp cypress	71.39
7th	*Chamaecyparis lawsoniana*	Lawson's cypress	71.24
8th	*Abies amabilis*	Pacific silver fir	71.10
9th	*Taxus baccata*	yew	70.91
10th	*Cupressus arizonica*	Arizona cypress	70.68
11th	*Metasequoia glyptostroboides*	dawn redwood	70.44
12th	*Calocedrus decurrens*	incense cedar	70.35
13th	*Abies grandis*	grand fir	69.15
14th	*Tsuga mertensiana*	mountain hemlock	68.54
15th	*Abies procera*	noble fir	68.40
16th	*Tsuga heterophylla*	Western hemlock	68.19

Characterisation of the top five alternative conifer species

3.19 The following section provides further characterisation and review of the top five ranked alternative conifer species in relation to their native range and genetic diversity, their ecology and silviculture, their major pest and pathogen threats, and potential utilisation of their timber.

Native range and genetic diversity of the top five ranked species

3.20 The native ranges of the top five alternative conifer species identified by this study differ greatly. The size of the geographical range is an important indicator of the range of climatic and soil conditions a species can tolerate (Bansal *et al.,* 2016). There is an assumption that a tree with a large native geographical distribution range (and by extension range of provenances) displays a large range within its tolerance and growth traits (Pötzelsberger *et al.,* 2020). This is useful for the species to be suitable for planting across the range of climatic and soil conditions in GB. The provenance chosen can result in either a successful, healthy crop or a complete failure (Lines, 1987).

Ideally, new alternative species adopted for widespread planting would have already undergone structured trials of a range of provenances and origins (Jink and Kerr, 2016). However, for many alternative conifer species this information is not available.

3.21 **Coast redwood** has a native range covering a small strip of coastal land, known as the 'fog belt', between the most southerly grove in California and the most northerly in Oregon, USA (Savill, 2019), totalling an approximate area of 647,500 hectares (Olsen *et al.,* 1990). The altitude of this native range is normally between 30 and 450 m (Savill, 2019). However, this species is sometimes found significantly stunted, as high as 900 m (Farjon, 2005). The native ranges' mountain climate is characterised by wet winters and misty summers with annual precipitation of between 640 and 3100 mm and a mean annual temperature of 10-16 ºC (Olsen *et al.,* 1990).

3.22 As minimum winter temperatures rarely go below -9 ºC (Wilson et al., 2016) in its native range this species is not regarded as very cold hardy and is likely to be most suitable for climatic regions in the west of GB from Argyll to the south west of England (Forest Research, 2016). Of the two redwoods in the top five alternative species, the coast redwood has been shown to have more genetic diversity with the more northerly provenances generally considered to be more frost hardy but still be sensitive to late spring frosts (Breidenbach *et al.,* 2020; Jinks and Kerr, 2016).

3.23 **Japanese red cedar** was thought to have a native range covering Japan and China but is now known to have been exported to China from Japan (Numata *et al.,* 1972). Later genetic analysis confirmed that even the oldest stands found in China were descended from Japanese trees (Chen *et al.,* 2008). The Chinese stands are commonly known as sugi trees (as is sometimes the case for Japanese stands) and have become a distinct variety known as *Cryptomeria japonica* var. *sinensis,* previously thought of as a separate species, *Cryptomeria fortune* (Chen *et al.,* 2008). The genetic diversity of the *Cryptomeria japonica* var. *sinensis* population is significantly less than the whole Japanese national metapopulation due to a combination of genetic drift, inbreeding and a significantly restricted gene pool (Cai *et al.,* 2020; Tsumura *et al.,* 2020).

3.24 In Japan, the species is divided into two varieties var. *japonica* and var. *radicans,* with *japonica* found on the Pacific Ocean side of the archipelago and *radicans* in the east, and this variation may imply some genetically based range of tolerance to different moisture regimes (Cai *et al.,* 2020). In GB, very limited provenance trialling of this species has occurred (Forest Research, 2016), although it has been suggested that Chinese provenances may do well in GB (Wilson, 2010). However, more recent analysis of material planted by Forest Research in 1958, which included Chinese vegetatively propagated material, found that the most successful trees came from mid-latitudes of Honshu (34-38 °N) (Parratt *et al.,* 2017).

3.25 **Giant redwood** has a native range confined to a very small area, approximately 14,400 hectares, of the western Sierra Nevada, California, USA (Sillett *et al.,* 2019). Historically, this species had a larger range, stretching from North America, over Eurasia and as far as New Zealand and Australia (Barnett, 2010) as evidenced by fossil and pollen records (Eckenwalder, 2009), which was dramatically reduced by the last ice-age (Noss, 1999). Genetic research has revealed a lack of genetic diversity in its native range when compared with many other conifer species, even the closely related coast redwood (Libby, 1986).

3.26 It is believed that, due to the current small native range of this species and the fact that isolated trees have a lower fecundity than those in larger groups, inbreeding has occurred (Guinon *et al.,* 1982). Provenance trials in Europe and New Zealand have shown that trees grown from seeds collected from the most southerly grove found in Sequoia-Kings Canyon National Park or from the natural groves situated at the highest altitudes have significantly better frost resistance and performance (Guinon *et al*., 1982). The giant redwood trials established in GB stalled at the plot stage, although this species was and continues to be widely planted in gardens and parks (Macdonald *et al.,*1957).

3.27 **Western red cedar** is one of the most widespread trees in its native range of the Pacific Northwest of the United States and is distributed from sea level to approximately 2300 m altitude (Minore, 1990). Western red cedar was introduced into GB in 1853 (Savill, 2019) and has historically been researched more than the other alternative species (Zehetmayr, 1954; Wood, 1955; Macdonald *et al.,* 1957; Aldous and Low, 1974; Monore, 1990; Lines, 1987; Oliver *et al.,* 1988; Pyatt *et al.,* 2001; Jinks, 2017). It had been previously noted that the genetic diversity of this species is lower than that of other north-western conifer species and that the Olympic Peninsula, Washington had the best seed origin for use in GB commercial plantations (Minore 1990). However, western Washington or Vancouver Island or Washington and British Columbian origins (46°N and 50°N) are now recommended as the most suited to the GB climate (Lines, 1987; Forest Research, 2019).

3.28 **European silver fir** is found throughout the mountainous regions of Europe, from Normandy to the Balkans (De Rigo *et al.,* 2016) and usually occurs at an altitude of 500-2000 m (Dobrowolska *et al.,* 2017). It was the first true fir to be introduced to GB being planted in about 1603 (Macdonald *et al.,*1957). It has been infrequently planted since but historically has grown well across GB, most notably in Scotland (Macdonald *et al.,* 1957). As this species has a relatively large native range, there are a wider range of provenances available and phenotypic variability resulting from natural selection and past demography (Herr *et al.,* 2018). Provenance recommendations for GB vary, with some sources recommending Czech Republic region provenances (Forest Research, 2016) and others suggesting that seeds from Swiss Jura (Lines, 1987) or Calabria, Italy should be first choice (Kerr *et al.,* 2015). Silver fir has a broad range of tolerances (Kerr *et al.,* 2015) with recent genetic analysis revealing that it shows moderate genetic variability, similar to other European fir species (Mosca *et al.,* 2019).

Ecology and silviculture of the top five ranked species

3.29 The top five alternative conifer species have varied ecology and consequently silvicultural requirements, as summarised in this section.

3.30 **Coast redwood** is long-lived, fast-growing, and shade-tolerant with the ability to regrow shoots from coppiced stumps (Macdonald *et al.,* 1957) as well as naturally producing root suckers (Mabberley, 2017). This makes vegetative propagation relatively straightforward (Savill, 2019). Seed production usually takes place between 10 and 15 years, when the cones start to develop in winter and resemble flowers (Becking, 1982). Mature trees produce thousands of cones containing 90-150 seeds (Becking, 1982), although viability is poor with less than 10% survival rate being reported (Savill, 2019). This tree was identified as having promise for timber production almost a century ago, but commercial scale production has been restricted by the low seed viability (Savill, 2019).

3.31 A coast redwood is currently the World's tallest tree and has been recorded in excess of 110 m height (Wilson *et al.,* 2016). In GB, the most successful sites have been in moister areas in the west, although some impressive specimens can be found in the eastern lowlands (Savill, 2019). The species prefers warm, moist temperate regions without summer drought, or frost exposure, and preferred soils are poor to moderately fertile brown earths (Wilson *et al*., 2016), but it does not tolerate acidic soils (Savill, 2013). This species is more shade tolerant than the giant redwood but suffers more from exposure and frost, and atmospheric pollution (Savill, 2019). The large scale-like leaves are arranged radially around the stems and the needles are similar in appearance to those of a yew (Johnson and Owen, 2004).

3.32 **Japanese red cedar** is a monoecious, evergreen tree with a slender straight trunk (Farjon, 2012). The solitary cones are globular in shape and 1.5-2 cm in length (Johnson and Owen, 2004). Seed production from British stands is reported as inconsistent (Savill, 2015). Flowering is in spring with the seeds maturing in September-October the same year, although seeds are notoriously poor germinators, with less than 12% surviving (Savill, 2015). The tree is good at self-pruning, can regrow from coppice stumps and from root suckers, and regenerates naturally (Macdonald *et al.,* 1957).

3.33 Japanese red cedar is tolerant of a range of site conditions (Macdonald *et al.,* 1957), but the best growth recorded in GB is in areas with more than 1200 mm of precipitation annually and in reasonably sheltered sites, as it can suffer foliage scorch in high winds (Savill, 2015). The preferred soil conditions are deep well-drained loams, and it is reported that soils with very poor nutrition, peats and sites with heather should all be avoided (Savill, 2015). In its native range it occurs in both pure and mixed stands at elevations of 1100-2500 m (Savill, 2015) and is described as moderately drought tolerant (Ray *et al.,* 2010). In GB it has been shown to grow over 30 m tall (Savill, 2015) and is shade tolerant enough to be suitable for continuous cover forestry (CCF) systems. It has been shown to flourish in mixed stands with western hemlock, Douglas fir and western red cedar (Hemery and Simblet, 2014).

3.34 **Giant redwood** have soft red bark and its leaves are sharp radial scales on a cord-like shoot and have an aniseed smell (Johnson and More, 2004). It is a fast-growing species that reaches amongst the largest tree sizes in the World, the record holder currently being 95 m tall (Flint 2002). Another tree, known as General Grant, holds the record for the largest stem diameter at breast height of any tree in the world at 8.8 m. The range of maximum height of this species is between 50-85 m, depending on the soil nutritional status (Flint, 2002). This species is generally found in groves mixed with other species, where the mean annual precipitation is between 900 and 1400 mm and the climate has generally dry summers (Savill, 2019).

3.35 Giant redwoods have the potential for extreme longevity, with the oldest recorded, using dendrochronology, as being approximately 3200 years old (Harvey *et al.,* 1986). Giant redwoods are monecious, the male and female cone buds form in April-May and fertilisation normally occurs in August, with cones maturing the following year (Weatherspoon, 1990). The cones are 4-6 cm long and unremarkable (Johnson and More, 2004). The tree is not tolerant of shade (Savill *et al.,* 2019), and natural regeneration is particularly light demanding and vegetative propagation can occur easily (Wilson *et al.,* 2019). In GB, this species seems to tolerate late frosts and exposure better than the coast redwood (Macdonald *et al.,* 1957), although it is less shade tolerant than coast redwood (Savill, 2019). Giant redwood has been found to grow reliably on most soils in GB, with the exception of waterlogged acid soils, and is slightly tolerant of atmospheric pollution compared with coast redwood (Savill, 2019). The species is slow to establish and often needs repeated weed control for the first years after planting (Savill, 2019)

3.36 **Western red cedar** is considered more tolerant of both frost and drought than coast redwood, although it remains intolerant of exposure, which can cause leaf scorch (Wilson *et al.,* 2016). It is a shade-tolerant species, often vigorous, although sometimes slow to establish (Jinks, 2017). It is best suited to areas with annual rainfall greater than 800 mm (Minore, 1990). It is considered cold hardy and both drought and frost tolerant but does not tolerate exposed sites (Jinks, 2017) and thus should not be planted above 200 m (Savill, 2019). It generally grows in neutral soils with medium to high nutritional status and will tolerate calcareous soils, but not infertile sandy soils (Savill, 2019).

3.37 In its native range western red cedar often associates with both Douglas fir and western hemlock, and it is also thought of as a riparian tree growing in flooded forests and on riverbanks (Stewart, 2009). It can be grown in mixtures with conifers or broadleaves (Kerr, 2019) and is a shade tolerant species, with a narrow crown particularly useful to mix with broadleaves or underplanting (Gil-Moreno, 2018). In the past it was considered hard to propagate due to infection by the fungus *Didymascella thujina,* which is now successfully treated with fungicide (Savill, 2019). The flowers form in spring, usually after 25 years, and the seeds ripen in September (Savill, 2019). These can be sown directly in March, without the need for temperature treatment, so natural regeneration is often prolific (Aldous, 1972).

3.38 **European silver fir** is considered one of the most shade-tolerant fir species, it can be sensitive to late spring frosts and atmospheric pollution but copes with exposure (Savill, 2019). This species grows well on heavy and deep soils, but not so well on sandy, dry, or peaty soils; it also does not grow well on soils near heathers (Savill, 2019). Establishment can be slow and close spacing needs to be considered as heavy branching can occur, although self-pruning does occur eventually (Savill, 2019). The tree flowers May-June, usually after 25 to 30 years age, and seeds ripen in September (Johnson and More 2004) in large numbers, normally every three years (Savill, 2019). European silver fir grows best in moist climates with a mean annual precipitation of 700-1800 mm (Tinner *et al.,* 2013) and it can reach an age of 600 years with a maximum height of more than 60 m (Nagel and Svoboda, 2008). In Europe, it is normally associated with European beech (*Fagus* *sylvatica*) (Dobrowolska *et al.,* 2017) and Norway spruce (*Picea abies*) (Ellenberg, 1988).

Threats from pests, pathogens that the top five ranked species might face

3.39 Through our structured systematic ranking exercise, we have tried to identify five alternative conifer species that are likely to be resilient to current and potential future pests and pathogens in GB. That being said, there are no conifer species that combine being (i) susceptible to no pests and pathogens, (ii) capable of growing on a range of site conditions and (iii) producing merchantable timber. With that in mind, the following paragraphs outline some of the pest and pathogen threats that our top five ranked species may face in GB and some threats from their native range.

3.40 **Coast redwood** is noted to have no insect pests or pathogens of major concern in GB (Forest Research, 2021a). In its native range it is commonly reported to have fewer foliar pathogens than any other major tree species. However, *Phytophthora ramorum*, the cause of ramorum blight on coast redwood trees and many other tree species, has been confirmed on coast redwood in California (Davidson *et al*., 2008; Fichtner *et al*., 2007; Maloney *et al*., 2002). *Phytophthora cinnamomi* (which causes root and crown rot), canker pathogens including *Botryosphaeria dothidea*, *B*. *ribis*, and *Cytospora* sp., as well as various wood decay and needle blight pathogens, can infect stressed coast redwood trees (Scharpf 1993). A twig branch canker (*Coryneum* sp.), which girdles stems and branches, could become damaging in plantations (Bega, 1978; Hepting, 1971). Several insects, including a flatheaded twig borer and girdler *(Anthaxia aeneogaster),* two redwood bark beetles *(Phloeosinus sequoiae* and *P. cristatus),* and the sequoia pitch moth *(Vespamima sequoiae*), are found on coast redwood, but none are known to cause significant damage at present (Furniss and Carolin, 1977).

3.41 **Japanese red cedar** is susceptible to Phytophthora root diseases, including *Phytophthora cinnamomi* (SilviFuture, n.d.-b). It is also considered to be susceptible to *Armillaria* root rot (honey fungus) (SilviFuture, n.d.-b). Elsewhere, it has been reported to be affected by Juniper blight (*Phomopsis* *juniperovora*), which is present in Britain and already widespread on juniper (Savill, 2015).

3.42 **Giant redwood** is known to have fewer troublesome pathogens in its native range than most other tree species, although at least nine fungi have been found associated with decayed giant sequoia wood. Of these, *Heterobasidion annosum, Armillaria mellea, Poria incrassata,* and *P. albipellucida* probably are the most significant in terms of risk of pathogenicity (Bega, 1964; Piirto *et al.,* 1984), with the first two being serious root pathogens. Branch canker caused by *Seiridium* spp. has also been reported on giant redwoods (Aćimović *et al.*, 2018). Insect depredations are not known to do serious harm to giant redwoods older than about 2 years, although sometimes they may reduce vigour (Parmeter, 1986).

3.43 **Western red cedar** suffers little damage from insects but is quite susceptible to *Armillaria* (honey fungus) and to *Heterobasidion* (fomes root and butt rot) resulting in decay and death (Hepting, 1971). Cypress aphid (*Cinara cupressivora*) is a common cause of foliage browning on western red cedar (Wilson *et al*., 2016). Newly planted seedlings are sometimes damaged by a weevil (*Steremnius carinatus*) in British Columbia, and larger trees are killed by a bark beetle (*Phloeosinus sequoiae*) on poor sites in southeastern Alaska (Burns and Honkala, 1990). Overall, the root and butt rots, including *Phellinus weiri, Armillaria mellea, Poria subacida, Poria asiatica* and *P. albipellucida*, are considered the biggest potential pathogen issues in the native range of western red cedar (Boyd, 1965).

3.44 **European silver fir** is known to suffer significant damage from a woolly aphid (*Adelges nordmanniana*) causing defoliation, which can lead to dieback or mortality (Varty, 1956). The effects of site conditions and silviculture on the severity of attack from woolly aphids is not clear, but stands on cool moist sites with suitable soils are thought to recover better than stands on dry warm sites with poor soils (Savill *et al*., 2016). European silver fir is also known to be vulnerable to *Heterobasidion annosum,* but some provenances from central Europe have been found to be resistant (Capretti *et al*., 1990). *Heterobasidion abietinum* is a potential threat, although it is not currently found in GB (Forest Research, 2021a).

Utilisation potential of timber from the top five ranked species

3.45 The sawn timber of these five species is suitable for a similar range of uses (including construction timber) as the widely utilised principal conifer species in GB.

- **Coast and giant redwood** timber is moderately naturally durable (Wilson *et al*., 2016) and is typically suitable for external cladding, joinery, furniture and construction timber (Meier, 2021). While giant redwood is considered to be suitable for structural uses, this is not the case for coast redwood. There is often a distinct visual difference between the heartwood and sapwood of these two species, with the outer paler sapwood being much less durable, so this is often discarded by processors (Wilson *et al*., 2016). However, if demand for massive wood panels increases, the potentially stiffer sapwood may find new markets.
- **Japanese cedar** timber is rot resistant, strong and very durable, and has been used extensively for construction in Japan and China (Farjon, 2012; Fu *et al.,* 1999). Other uses include interior and exterior joinery, along with other applications such as boxes, pallets or roundwood for poles and piles.
- **Western red cedar** timber is suitable for use as exterior decorative carpentry, cladding and shingles that exploits its visual appeal and natural durability (Morgan, 2008). It is often considered not suitable for use as structural timber based on current grading requirements (Wilson *et al.*, 2016), but anecdotal evidence suggests wet sites typically lead to lower stiffness timber. The natural durability of western red cedar is typically lower in plantation-grown material than in old growth material from its native range (Wilson *et al.*, 2016).
- **European silver fir** has white timber which is very similar to Norway spruce and, in continental Europe, it is utilised alongside Norway spruce as 'European whitewood', primarily for construction and pulp or paper (Savill *et al*., 2016). It is widely used for heavy construction framing in alpine areas of Europe (Savill *et al*., 2016) and is increasingly used as internal components in large cross-laminated timber construction systems (Wilson, 2011).

3.46 The wood from four of the top five species (coast redwood, Japanese cedar, giant redwood, and western red cedar) is not generally considered suitable for industrial particle board and pulp manufacturing due to its colour and chemistry. However, western red cedar is a major supplier of feedstock for chemical pulping in North America (Wilson *et al.*, 2016). There is currently no such mill in GB, but should such a technology be adopted, western red cedar is a suitable feedstock. The white timber of European silver fir is very similar to Norway spruce and as such is suitable for pulp and paper (Savill *et al*., 2016).

3.47 The use of sawn timber for structural purposes in construction depends on a combination of mechanical properties relating to bending (strength and stiffness) and density. Stiffness measures the deflection of a length of wood under load. Stiffness of British timber is the limiting property that determines grading to current strength classes (Gil-Moreno *et al.*, 2016). The C16 strength class is the commonly specified strength class for use in UK construction (CEN, 2016) and sets a threshold stiffness, or modulus of elasticity (MOE), value of 8 kN/mm^2.

3.48 Timber from three out of the five species (Japanese cedar, giant redwood and European silver fir) has demonstrated stiffness characteristics in lab experiments that suggest it might grade to the C16 strength class or higher (Mean modulus of elasticity ≥ 8.0 kN/mm^2, Table 3.8). However, timber from coast redwood and western red cedar has demonstrated lower stiffness characteristics that suggest it might not grade to C16 and is potentially less suitable for structural applications as solid sawn timber.

Table 3.8: Mean modulus of elasticity (MOE) values of the top five alternative conifer species.

Ranking	Scientific name	Common name	Mean modulus of elasticity (kN/mm^2)	Reference
1st	*Sequoia sempervirens*	coast redwood	7.6	Ramsay and Macdonald (2013)
2nd	*Cryptomeria japonica*	Japanese cedar	9.6	Ramsay and Macdonald (2013)
3rd	*Sequoiadendron giganteum*	giant redwood	8.9	Ramsay and Macdonald (2013)
4th	*Thuja plicata*	Western red cedar	7.0	Lavers (1983)
5th	*Abies alba*	European silver fir	9.8	Lavers (1983)

3.49 These results must be treated with caution due to the serious lack of information about the wood properties of these five species when grown under British conditions and the relatively small number of small defect-free samples tested (Gil-Moreno *et al.*, 2016). While these results must be treated with caution, they suggest that when grown in Britain, these five species could produce a mix of structural and special-purpose timber such as material for exterior carpentry, cladding, roofing. However, there is potential for all five species to be used structurally with modern engineering technologies such as glulam or cross-laminated timber (Dauksta, 2014).

3.50 There is generally little experience of processing home-grown timber from these five species in high-volume sawmills, as they are typically sawn by mobile, estate or specialist processors in GB (Savill, 2015; Savill *et al.*, 2016; Wilson *et al.*, 2016). The stringy bark of four of the five species (coast redwood, Japanese cedar, giant redwood, and western red cedar) poses an issue for high-volume sawmills where cambial debarking is widely used. However, the period between further trials, adoption and harvesting timber at the end of the first rotation should provide sufficient time for technology to be developed to receive a wider range of species with various bark characteristics. The bark of European silver fir should pose no issues for debarking with cambial ring debarkers.

4. Discussion

4.1 Our review has identified five alternative conifer species, which are likely to be suitable for a range of (but not all) climatic and soil conditions found across GB and are likely to survive until the end of a rotation and produce marketable timber. In this section of the review, we discuss some of the wider issues surrounding the identification of five alternative conifer species for GB, these are:

- Development of a full evidence base for species selection and key evidence gaps
- Risks of expanding plantation area of alternative species
- Increasing forest resilience

Development of a full evidence base for species selection and key evidence gaps.

4.2 History teaches us that the five alternative conifer species identified by this research are likely, as others previously, to have a period of unprecedented growth and yield, before a non-native or native species of pest or pathogen starts damaging the crop. Once the damage starts then this period tends to be followed by one of decreasing success and yields (Wingfield *et al*., 2015; Burgess and Wingfield, 2017).

4.3 This knowledge should result in a strategic research program to revisit the previous species trials conducted since the 1800's in GB and assess the longer-term resilience of the five identified species.

4.4 Due to the coarse nature of the scoring criteria based on considerations at national scale and the short project time frame, there are a number of other important considerations that were beyond the scope of this study. The provenance of the planting stock, where you grow each species (location) and how to identify a complementary set of species to cover the full range of site types that are economically suited to plantation forestry in GB, how you grow it (silviculture) and what you do with it (alternative processing) are important considerations that need further investigation.

Provenance

4.5 Genetic variation between individuals of the same species is a well-established factor in the success of non-native tree introductions. Forest Research have carried out over 400 trials since the 1920's (Samuel, 2007), resulting in recommendations for choosing species provenances of principal conifer species in GB as documented by Lines (1987). The genetic variation within species is associated with the area and range of environmental conditions of their native range but the relationship is complex because of the role of historical biogeography. For example, Douglas fir has a large native distribution range, growing from Canada to Mexico leading to a high level of variation in both its tolerance and growth traits (Pötzelsberger *et al.,* 2020).

4.6 Successful species introduction programs for commercial forestry are characterised by the availability of data from trials of multiple provenances of each species before their widespread adoption (Burdon, 2001). This approach reduces the inherent risks of introducing unsuitable provenances (Brus *et al*., 2019).

4.7 Considering the potential provenances of the alternative species and their suitability for different sites across GB was beyond the remit of this study, however we recommend an assessment of current available evidence to determine if there are major gaps that constitute a priority for future research.

Location and the identification of a complementary set of species

4.8 The relationship between forest productivity and site characteristics has long been the subject of research in forest science (Johnstone and Samuel, 1978; Aertsen *et al.,* 2010). Recent research across a range of climatic conditions suggests that, for Douglas fir as an example, its growth is directly correlated with the soil nutrition, water retention and climate of the planting site (Eckhart *et al.,* 2019). Conditions will also differ within the site, for example exposure, light and moisture regimes vary from the edge to inside a forest block (Harper *et al.,* 2005). Given this environmental heterogeneity across a range of spatial scales, in the absence of detailed information about suitability of alternative provenances, then the best advice for selection of the most appropriate species may be to choose those that have a large natural range and therefore tolerance across a broad range of environmental conditions.

4.9 Great Britain, although a relatively small island, has high climatic and soil variability. The top five ranked species in this study can all be characterised as moderately tolerant of a wide range of site conditions and, as such, should feature strongly in a future strategy for plantation forestry in GB. However, there are many specific site types that are economically suited to plantation forestry in GB (e.g., on acidic soils) where none of these five species are likely to be the best suited amongst the long list of alternative species considered in this study.

4.10 Therefore, we recommend that a bigger list of alternative species be considered by forest planners and managers to identify a complementary set of species to cover the full range of forestry site types. In particular, we recommend that the 11 species ranked 6th-16th in our study (Table 3.7) be further researched for inclusion in this set. This would provide an enhanced evidence base for the ecological site classification (Ray, 1995), and other decision-support tools that are used for site-level decisions of identifying the most suitable plantation tree species, including considerations of future climate projections (Broadmeadow *et al.,* 2005) or species distribution modelling (SDM) (Pecchi *et al*., 2019).

Silviculture

4.11 The future of forest management and silviculture is far from certain, but it can have a significant effect on the species selection for a given forest (Macpherson *et al.,* 2017). For example, the widespread use of CCF techniques would increase the need for shade tolerant species and those that can grow well in species mixtures (Mason and Kerr, 2004). The key to future management of forests is likely to be adaptability as the bioclimatic conditions and socio-economic objectives change (Yousefpour *et al.,* 2017).

4.12 It was beyond the scope of this review to consider the implications of silvicultural systems in the species ranking exercise. However, the literature review component exposed significant gaps in knowledge for most of the species about their suitability for a range of silvicultural systems, e.g., mixed species stands. Therefore, there is a need for further research into the suitability and performance of the alternative conifer species across a range of silvicultural systems and their performance when grown in a range of species mixtures. Detailed investigation of knowledge based on the experience of forest management within the native range of each species (much of it not reported in the standard scientific literature) is likely to produce valuable information.

Timber properties and future wood products

4.13 The selection of the criteria assessing wood utilisation could not incorporate the unpredictable ways in which the wood supply chain may develop. New engineered wood products are already increasingly substituting for more traditional wood building materials, and this is leading to a change in the required species, form, tree size, timber properties, processing equipment and harvesting technologies (Eriksson *et al*., 2007). New technologies and developments in wood science will continue to influence the forest products markets (Hurmekoski and Hetemaki 2013; McEwan *et al.,* 2020; Philips, 2013; Trømborg *et al*., 2000), and there is a complex relationship between change in market demand for different types of wood *versus* adaptation of the supply chain to the wood material that is available now and projected in the future.

4.14 The top five alternative conifer species identified in this review are broadly suitable for a range of uses in current markets in the short and medium term. However, further evidence is needed about the suitability of a wider set of alternative species to meet anticipated longer-term future market needs as other wood-based technologies become more mainstream. A particular priority is to identify whether future markets will require timber that conforms to a narrow set of properties or whether the increasing breadth of material (and chemical) ‘biorenewable’ products derived from wood will favour the growing of a broader range of tree species, with a wider range of wood properties.

4.15 In the shorter term, information about the timber properties of the five identified species is not at the level required for reliable strength grading according to current standards. More research into the timber properties of structural-sized pieces of timber is required.

Risks of expanding the area planted with new alternative exotic tree species

Biosecurity risk

4.16 Modelling the risks of new invasive pests and pathogens arriving in GB is extremely complex (Srivastava *et al*, 2021; Robinet *et al*., 2020), but through biosecurity measures these risks can be managed (White *et al.,* 2010). It is known that a major pathway for the introduction of non-native pathogens is imported plants, including trees (Liebhold *et al*., 2012; Brasier, 2008). The presence of non-native relatives of native species can increase the threat of new pathogen strains to which native trees have less resistance (Piotrowska, 2018). Insects are also known to be accidentally imported in or with live plants, wood-based and food items as 'hitchhikers' (Meurisse *et al.,* 2019).

4.17 It is therefore critical for the success of the strategy of introducing alternative tree species in GB forestry to use seeds sourced from GB parent trees and grown exclusively in GB nurseries (Spence, 2020). Great Britain has an opportunity post-Brexit to introduce stricter transboundary biosecurity legislation with targeted management and public awareness campaigns to reduce the risk of new pest colonisation (Black, 2018; Black and Bartlett, 2020).

Invasiveness and threats to biodiversity

4.18 A serious risk associated with planting non-native tree species in GB is that they can become invasive themselves and, if they do, become expensive to control (Richardson and Rejmánek, 2011; Nunez *et al.,* 2017). The risk of species escaping from plantations and becoming a problem in native ecosystems (Essle *et al.,* 2010), including reduction in biodiversity by altering the soil biota and belowground processes (Peltzer, 2018), is linked to their capacity for seed set, dispersal, germination and establishment (all components of a species capacity to ‘naturalise’).

4.19 The use of exotic conifers in plantations and their potential to colonise and outcompete local native flora can also lead to a decrease in native fauna species, by replacing natural food species or by fragmenting suitable habitat (Fady, 2003). Non-native conifers also have the potential to reduce both soil pH and organic matter content as well as altering biogeochemical cycling (Desie *et al*.,2019; Vanguelova and Pitman, 2019) and the soil microbial community (Lyu *et al*, 2019).

4.20 It is, however, often overlooked that exotic conifer plantations do also have the potential to benefit some native species by providing habitat, including that required for the natural colonisation of a number of native tree species (Fady, 2003). There has been considerable research in the UK over many decades showing how conifer plantations can be designed and managed to maximise their value for biodiversity (e.g., Peterken et al. 1992; Ratcliffe & Peterken 1995; Wallace & Good 1995) and this has been incorporated into the UK Forest Standard, the success of which was supported in a recent review (Harris 2020).

4.21 The introduction of novel alternative conifer species at a landscape scale therefore requires monitoring for effects on biodiversity, soil functioning and the range of ecosystem services to assess the impact and rapidly feedback evidence to inform decisions about whether to further expand the area planted to each species.

Increasing forest resilience

4.22 The alternative conifer species identified by this research are based on scoring against criteria that account for the perceived risk of known pests and pathogens. It is relatively easy to score the resistance/susceptibility of tree species to known pests and pathogens that are either already in GB or are in Europe and heading north or west. However, it is far harder to assess the threat posed by pests and pathogens that are unknown or have not yet led to observed symptoms (the ‘unknown unknowns’) (Srivastava *et al*, 2021; Robinet *et al*., 2020).

4.23 A potential mitigation strategy against the risk of a new unknown pest or pathogen causing environmental and economic losses is to ensure that all new forests planted are resilient. Forest resilience can be ensured in a number of ways.

Increasing species diversity

4.24 The use of mixtures of species has been widely heralded as another potential mitigation, and this is supported by research evidence (Roberts et al. 2020), although it is also accepted that this presents silvicultural problems and can reduce yield of the most valuable crop species, and the cost of forest operations, thus reducing economic viability (Roberds and Bishir, 1997). Tree species diversity can be achieved at a range of spatial scales from individual tree mixtures up to small monoculture blocks of different species (Liebhold *et al.,* 2017), thus reducing the forest's initial susceptibility (Macpherson *et al.,* 2017). There is a lack of good evidence of the trade-offs of ecological and economic resilience across these scales of mixture (Roberts et al. 2020). This strategy would require utilisation of more alternative species than the top five identified by this study.

Genetic improvement

4.25 The objective set for this study, to identify five alternative species, assumes that there is serious risk of the ecological and economic viability of the current principal timber producing species in GB declining in the future. However, in many countries' programs of forest tree genetic improvement (Box 4.1) have been successfully established as an alternative mitigation measure through tree selection and breeding, increasingly using new developments in genetic technology (Garattapaglia *et al.,* 2018). This approach has recently been accelerated in the UK through the *Sitka Spruced* project (Depardieu *et al.,* 2021).

4.26 Further genetic improvement of existing principal conifer species using modern molecular approaches has potential to improve their future viability. However, it is also advisable to go beyond the current focus on *Picea sitchensis* and include the alternative conifer species with potential to be successful timber producing species in GB that have been identified in the present study, some of which are included in the current work of the Conifer Breeding Co-operative (Box 4.1).

Box 4.1 Genetic improvement

Tree selection and breeding

Tree breeding was first suggested in GB by Macdonald (1930), although the Forestry Commission's Genetics sub-committee was not formed until 1946, as it was delayed by WWII (Forestry Commission, 2006). In 1948 the sub-committee established a Genetics Research Station at Alice Holt Lodge, Hampshire, the main purpose of which was to develop trees with better vigour, resistance to pests and pathogens, improved form, and improved timber properties (EWM, 1969; Pötzelsberger *et al.,* 2020). This research continued into the 1960's and conifers investigated by the section included Scots pine, Corsican pine, Douglas fir, European and Japanese larch, western red cedar, western hemlock and Norway spruce (Seal *et al*., 1965; Faulkner, 1967).

In the 1950's a series of seed orchards were established to produce Scots pine and Douglas fir seeds and continued to be operated until the 1990s (Lee, 1997). By the 1960's it was decided to concentrate efforts on Sitka spruce, lodgepole pine, Scots pine, Corsican pine and hybrid larch as these were by then established as the most economically important species. These programs were labour intensive and expensive, the surveys were used to select trees based on criteria developed for Sitka spruce, then used for other conifer species (Fletcher and Faulkner, 1972; Shelbourne, 1974). In 1998, after 50 years of tree-selection and breeding in Britain, the Forestry Commission produced a report which stated that the original objectives of the Genetics sub-committee had been achieved and as a result investment dwindled (Forestry Commission, 1998).

GB's tree selection and breeding program did produce increases in yield of both Sitka spruce and Scots pine (Forestry Commission, 1998). However, this was at the expense of genetic diversity due to the few trees used as seed stands and the use of clonal propagation (Ingvarsson and Dahlberg, 2019). Conventional tree breeding has also been successful internationally in increasing pathogen resistance (Sniezko and Koch, 2017). More recently the Conifer Breeding Co-operative, a collaboration between Forest Research, private forestry companies, academic institutions and tree nurseries aims to improve Douglas fir, Norway spruce, hybrid spruce and Scots pine. They are also considering including some of the minor conifer species in future programs including western hemlock, western red cedar, Douglas fir, noble fir, and grand fir and possibly coast redwood (Conifer Breeding Program, 2020).

Modern genetics technologies

Modern genetics technologies including existing approaches to genetic modification and current developments in gene editing are increasingly being considered for genetic improvement of trees (Naidoo *et al*., 2019), as this can drastically reduce the timescales involved in genetic selection for desirable phenotypic traits (Peña, and Séguin, 2001). These techniques have already been used to alter flowering times (Meilan *et al.,* 2001) and drought resistance (Polle *et al.,* 2019), although there has been limited commercial use in practice (Chang *et al*., 2018). Recent developments in gene editing offer the potential for major new advances.

Pest and pathogen control

4.27 Biological control through the introduction of predators, parasites or pathogens of pest species are sometimes deployed in order to control non-native pests (Lacey *et al*., 2015). For example, in southern Europe the oak processionary moth is controlled by use of predators that were not previously present in the areas that suffer defoliation (Forest Research, 2021a). There is also a growing research area investigating the potential control of forest pathogens using a variety of techniques including chitosan oligomers, propolis (Correa-Pacheco *et al*., 2019) and nano-silver (Matei *et al*., 2018), and further advances in this field are expected over the coming decades (Chen *et al.,* 2019).

4.28 It is also generally accepted that management of increasing populations of mammal pest species in GB (particular grey squirrels and deer) is essential if forests are to continue to provide useful timber, reach the end of a rotation and then regenerate (Crowley *et al.,* 2018; Fattorini *et al*., 2020; Mill *et al*., 2020).

4.29 There is currently a knowledge gap about the susceptibility of the five alternative conifer species identified in this study, when grown at the scale of plantation forest stands, to these mammal pest species prevalent in GB. In addition, there is a lack of knowledge about the potential of biological control to mitigate the threat of invertebrate pest and pathogen species most likely to attack these five species. These knowledge gaps are also a priority for future research.

Mycorrhizal fungi

4.30 The success of a particular tree species on a site is sometimes dependent on the presence of the correct species of microbial symbionts, particularly mycorrhizal fungi and, for a small proportion of trees in temperate forests, nitrogen (N)-fixing associations (Nuñez and Dickie, 2014). If there is no recent history of the tree species being grown in the area, the appropriate symbiont species are not always present in a given plantation site, or even common in the region, and therefore in some cases they may need to be translocated with the trees (Nuñez *et al.,* 2009). The introduction of non-native symbiotic partners such as mycorrhizal fungi or N-fixing bacteria with non-native trees is often encouraged to ensure productive commercial forests (Nuñez and Dickie, 2014). Without this, the tree species can sometimes struggle to establish or flourish (Nuñez *et al.,* 2009), but the introduced symbionts themselves can also become invasive by forming complex interactions with native or non-native species (Wandrag *et al*., 2013; Wood *et al*., 2015; Zenni *et al*., 2017).

4.31 Some GB-based research has shown that native species of mycorrhizal fungi are retained in the soil under non-native plantations and that no significant differences in species diversity could be found between native forest and non-native plantation (Trocha *et al*., 2012; Johnson *et al.,* 2014). Research in Poland found that several species of rare, red-listed native fungi can form relationships with the non-native conifer tree species, suggesting generalisations are ill-advised and that more research is required in this field (Damszwel *et al.,* 2020).

4.32 Specifically, there is a gap in knowledge of the mycorrhizal symbioses of the five alternative conifer species identified in the present study, the extent to which they depend on specific symbiont species, whether those symbionts are present in potential plantation sites in GB, or whether the tree species can form successful symbioses with the microbial species already present (e.g. those associated with the current principal conifer tree species or native broadleaved species). These are all future research priorities.

5. Conclusions

5.1 The Welsh Government commissioned Woodknowledge Wales to conduct this review to identify the top five alternative commercial conifer tree species suitable to meet timber utilisation demands of the sector, in light of increasing potential pest and disease pressures as a result of new introductions and climate change. The major barrier to adoption of alternative conifer tree species within commercial plantation woodlands is the lack of holistic information. This needs to be supported by a robust evidence base that is produced through systematic assessment of ecological, silvicultural, economic and timber utilisation considerations.

5.2 The overall aim of the review was to identify five practical alternative conifer tree species which can be incorporated into the commercial conifer forest resource across GB. It was important to have a robust understanding of the science and evidence base relating to the potential of alternative conifer species to address these objectives in order to guide the identification of the top five species. We designed a systematic research protocol to allow different specialist information to be appropriately synthesised. Using multi-criteria analysis, we collated the existing knowledge base (including expertise from expert stakeholders) to identify the top five alternative conifer tree species for GB.

5.3 Using this approach, we identified the following five as the top ranked alternative conifer tree species based on their potential suitability for commercial timber production in GB in the face of growing pest and pathogen pressures:

- coast redwood (*Sequoia sempervirens*)
- Japanese cedar (*Cryptomeria japonica*)
- giant redwood (*Sequioadendron giganteum*)
- Western red cedar (*Thuja plicata*)
- European silver fir (*Abies alba*)

5.4 While our approach did not account for every consideration that may be required for site-level selection of tree species, our ranking method covered the broad range of ecological, silvicultural, economic, and timber utilisation considerations appropriate for strategic national level exercises such as this. In addition to identifying the top five alternative conifer species, this review provides an overview of over 50 other alternative conifer species. Within this we identified the next 11 most recommended alternative species that should be the focus for future forest policy and management. We identified the need to look beyond the species with tolerance of a broad range of site conditions, to build a larger set of complementary species that would be suitable for the full set of site environmental conditions across GB. This will be important to provide an enhanced evidence base for the Ecological Site Classification decision support system and some of the knowledge gaps that exist in relation to alternative conifers in GB.

5.5 This review also identified some of the most important gaps in existing evidence that is required for the rigorous selection of a full set of complementary alternative tree species, and to inform their selection for individual sites and silvicultural systems. These indicate the priorities for future research to best equip the GB forestry sector to address the threats created by future climate change and increasing pest and pathogen risks. It also indicates the opportunities created by future markets for wood products, as summarised by the following recommendations.

6. Recommendations

6.1 This review led to eight key recommendations:

- Maintain, restart or set up species trials to test the suitability of the five identified alternative conifer species, as well as the second set of 11 highest priority complementary species.
- Evaluate (or in some cases re-evaluate) the potential provenances of the top five species and their suitability for different sites across GB.
- Extend the analysis presented in this report to evaluate the suitability and performance of alternative broadleaf species.
- Investigate the suitability and performance of the alternative tree species across a range of silvicultural systems and when grown in a range of species mixtures.
- Assess potential long-term future market needs as new wood-based technologies become more mainstream.
- Evaluate the timber properties of structural-sized pieces of timber from the identified top five alternative conifer species.
- Investigate the potential for novel methods, *e.g.*, biological control or silvicultural approaches, to mitigate the threat of invertebrate pest and pathogen species most likely to attack the five identified species.
- Investigate the extent to which the five species depend on specific mycorrhizal microbial symbiont species or can associate with microbial species already abundant in current and future plantation sites in GB.

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Annex A

Pests and pathogens by species matrices

In the matrices that follow + indicates that *species x* is susceptible to *pest/pathogen y* and – indicates that *species x* is not susceptible to *pest/pathogen y*.

Table A1: Susceptibility and resistance of the alternative conifer species to high risk pests and pathogens currently in GB.

Scientific name	Common name	Fungus [1]	Phytophthora [1]		Insect pest [1]		Total (susceptible to)	Total (resistant to)
		Red band needle blight	Ramorum disease		European spruce bark beetle	Pine tree lappet moth		
		Dothistroma septosporum [2]	*Phytophthora ramorum* [3]	*Phytophthora kernoviae* [3]	*Ips Typographus*	*Dendrolimus pini*		
Abies alba	European silver fir	-	-	-	-	+	1	4
Abies amabilis	Pacific silver fir	-	-	-	-	+	1	4
Abies balsamea	balsam fir	-	-	-	-	+	1	4
Abies cephalonica	Greek fir	-	-	-	-	+	1	4
Abies concolor	white fir	-	-	-	-	+	1	4
Abies fraseri	Fraser fir	-	-	-	-	+	1	4
Abies grandis	grand fir	-	+	-	-	+	2	3
Abies koreana	Korean fir	-	-	-	-	+	1	4
Abies nordmanniana	Nordmann fir	-	-	-	-	+	1	4
Abies procera	noble fir	-	+	-	-	+	2	3
Abies spectabilis	East Himalayan fir	-	+	-	-	+	2	3
Araucaria araucana	monkey puzzle tree/Chilean pine	-	-	-	-	-	0	5
Calocedrus decurrens	incense cedar	-	-	-	-	-	0	5
Cedrus atlantica	Atlas cedar	-	-	-	-	+	1	4
Cedrus atlantica Glauca	Blue cedar	-	-	-	-	+	1	4
Cedrus brevifolia	Cyprus cedar	-	-	-	-	+	1	4
Cedrus deodara	deodar cedar	-	-	-	-	+	1	4
Cedrus libani	cedar of Lebanon	-	-	-	-	+	1	4
Chamaecyparis lawsoniana	Lawson's cypress	-	-	-	-	-	0	5
Chamaecyparis obtuse	hinoki	-	-	-	-	-	0	5
Chamaecyparis pisifera	Sawara cypress	-	-	-	-	-	0	5

Scientific name	Common name	Fungus [1]	Phytophthora [1]		Insect pest [1]		Total (susceptible to)	Total (resistant to)
		Red band needle blight	Ramorum disease	*Phytophthora kernoviae* [3]	European spruce bark beetle	Pine tree lappet moth		
		Dothistroma septosporum [2]	*Phytophthora ramorum* [3]		*Ips Typographus*	*Dendrolimus pini*		
Cryptomeria japonica	Japanese cedar	-	-	-	-	-	0	5
Cupressus arizonica	Arizona cypress	-	-	-	-	-	0	5
Cupressus glabra	smooth cypress	-	-	-	-	-	0	5
Cupressus macrocarpa	Monterey cypress	-	-	-	-	-	0	5
Cupressus nootkatensis	Nootka cypress	-	-	-	-	-	0	5
Cupressus sempervirens	Italian cypress	-	-	-	-	-	0	5
x Cuprocyparis leylandii	Leyland cypress	-	-	-	-	-	0	5
Ginkgo biloba	maidenhair tree	-	-	-	-	-	0	5
Juniperus chinensis	Chinese juniper	-	-	-	-	+	1	4
Metasequoia glyptostroboides	dawn redwood	-	-	-	-	-	0	5
Picea engelmannii	Engelmann spruce	-	-	-	+	-	1	4
Picea glauca	white spruce	-	-	-	+	-	1	4
Picea omorika	Serbian spruce	+	-	-	+	-	2	3
Picea orientalis	Oriental spruce	-	-	-	+	-	1	4
Picea pungens	Colorado blue spruce	-	-	-	+	-	1	4
Pinus albicaulis	white bark pine	+	-	-	+	+	3	2
Pinus armandii	Armand's pine	+	-	-	+	+	3	2
Pinus monticola	Western white pine	+	-	-	+	+	3	2
Pinus muricata	bishops pine	+	-	-	+	+	3	2
Pinus peuce	Macedonian pine	+	-	-	+	+	3	2
Pinus pinaster	maritime/ Bournemouth pine	+	-	-	+	+	3	2
Pinus pinea	Italian stone pine	+	-	-	+	+	3	2
Pinus ponderosa	Ponderosa pine	+	-	-	+	+	3	2
Pinus radiata	radiata pine	+	-	+	+	+	4	1
Pinus strobus	Eastern white/Weymouth pine	+	-	-	+	+	3	2
Pinus wallichiana	Bhutan pine	+	-	-	+	+	3	2
Platycladus orientalis	Chinese thuja	-	-	-	-	-	0	5
Sequoia sempervirens	coast redwood	-	-	-	-	-	0	5

Scientific name	Common name	Fungus [(1)]	Phytophthora [(1)]		Insect pest [(1)]		Total (susceptible to)	Total (resistant to)
		Red band needle blight	Ramorum disease	*Phytophthora kernoviae* [(3)]	European spruce bark beetle	Pine tree lappet moth		
		Dothistroma septosporum [(2)]	*Phytophthora ramorum* [(3)]		*Ips Typographus*	*Dendrolimus pini*		
Sequoiadendron giganteum	giant redwood	-	-	-	-	-	0	5
Taxodium distichum	swamp cypress	-	-	-	-	-	0	5
Taxus baccata	yew	-	-	-	-	-	0	5
Thuja plicata	Western red cedar	-	-	-	-	-	0	5
Tsuga canadensis	Eastern hemlock	-	-	-	-	-	0	5
Tsuga heterophylla	Western hemlock	-	+	-	-	-	1	4
Tsuga mertensiana	mountain hemlock	-	-	-	-	-	0	5

Table notes

[1] General references (Burns and Honkala, 1990; Defra, 2021; Forest Research, 2021a; Hansen *et al*., 1997; Nguyen *et al*., 2016; Oszako *et al*., 2017; Phillips and Burdekin, 1992d, 1992a, 1992b, 1992c, 1992e; Scharpf, 1993; Spaulding, 1961; Wainhouse *et al*., 2016).

[2] Red band needle blight (*Dothistroma septosporum*) specific references (Adamson *et al*., 2018; Brown et al., 2003; Brown and Webber, 2008; Mullett *et al*., 2021; Piotrowska *et al*., 2018).

[3] *Phytophthora sp*. specific references (Denman *et al*., 2005; Hamm and Hansen, 1982; Hansen *et al*., 1999; Newhook, 1959; Schlenzig *et al*., 2017).

Table A2: Susceptibility and resistance of the alternative conifer species to lower risk pests and pathogens currently in GB.

Scientific name	Common name	Fungus (1)										Phytophthora (1)		Insect pest (1)					Total (susceptible to)	Total (resistant to)
		Honey fungus / *Armillaria mellea*	Fomes annosus / *Heterobasidion annosum* (3)	*Neonectria neomacrospora*	*Pestalotiopsis funereal*	*Phomopsis sp.* (2)	*Phomopsis pseudotsugae* (2)	*Polyporus schweinilzii* (4)	Rhizosphaera needle cast / *Rhizosphaera sp.*	*Sirococcus tsugae*	Diplodia Tip Blight / *Sphaeropsis sp.*	*Phytophthora austrocedri* (5)	*Phytophthora lateralis* (5)	Conifer aphids	Giant spruce beetle / *Dendroctonus micans*	Green spruce aphid / *Elatobium abietinum*	*Lymantria dispar*	*Hylobius abietis*		
Abies alba	European silver fir	+	-	+	-	-	+	-	+	-	+	-	-	+	-	-	-	-	6	11
Abies amabilis	Pacific silver fir	+	-	+	-	-	+	-	+	-	-	-	-	+	-	-	-	-	5	12
Abies balsamea	balsam fir	+	-	+	-	-	+	-	+	-	+	-	-	+	-	-	-	-	6	11
Abies cephalonica	Greek fir	+	-	+	-	-	+	-	+	-	-	-	-	+	-	-	-	-	5	12
Abies concolor	white fir	+	+	+	-	-	+	-	+	-	+	-	-	+	-	-	-	-	7	10
Abies fraseri	Fraser fir	+	-	+	-	-	+	-	+	-	-	-	-	+	-	-	-	-	5	12
Abies grandis	grand fir	+	-	+	-	-	+	-	+	-	-	-	-	+	-	-	-	-	5	12
Abies koreana	Korean fir	+	-	+	-	-	+	-	+	-	-	-	-	+	-	-	-	-	5	12
Abies nordmanniana	Nordmann fir	+	-	+	-	-	+	-	+	-	-	-	-	+	-	-	-	-	5	12
Abies procera	noble fir	+	-	+	-	-	+	-	+	-	+	-	-	+	-	-	-	-	6	11
Abies spectabilis	East Himalayan fir	+	-	+	-	-	+	-	+	-	+	-	-	+	-	-	-	-	6	11
Araucaria araucana	monkey puzzle tree/Chilean pine	+	-	-	-	-	-	-	+	-	-	-	-	+	-	-	-	-	3	14
Calocedrus decurrens	incense cedar	+	-	-	-	-	-	-	+	-	-	-	-	+	-	-	-	-	3	14
Cedrus atlantica	Atlas cedar	+	-	-	-	-	-	-	+	+	-	-	-	+	-	-	-	-	4	13
Cedrus atlantica Glauca	Blue cedar	+	-	-	-	-	-	-	+	+	-	-	-	+	-	-	-	-	4	13
Cedrus brevifolia	Cyprus cedar	+	-	-	-	-	-	-	+	+	-	-	-	+	-	-	-	-	4	13
Cedrus deodara	deodar cedar	+	-	-	-	-	-	-	+	+	-	-	-	+	-	-	-	-	4	13
Cedrus libani	cedar of Lebanon	+	-	-	-	-	-	-	+	+	-	-	-	+	-	-	-	-	4	13
Chamaecyparis lawsoniana	Lawson's cypress	+	-	-	+	-	-	-	+	-	-	+	+	+	-	-	-	-	6	11
Chamaecyparis obtuse	hinoki	+	-	-	+	-	-	-	+	-	-	-	-	+	-	-	-	-	4	13
Chamaecyparis pisifera	Sawara cypress	+	-	-	+	-	-	-	+	-	-	-	-	+	-	-	-	-	4	13

Scientific name	Common name	Fungus (1)										Phytophthora (1)		Insect pest (1)					Total (susceptible to)	Total (resistant to)
		Honey fungus	Fomes annosus						Rhizosphaera needle cast		Diplodia Tip Blight				Giant spruce beetle	Green spruce aphid				
		Armillaria mellea	*Heterobasidion annosum* (3)	*Neonectria neomacrospora*	*Pestalotiopsis funereal*	*Phomopsis sp.* (2)	*Phomopsis pseudotsugae* (2)	*Polyporus schweinilzii* (4)	*Rhizosphaera sp.*	*Sirococcus tsugae*	*Sphaeropsis sp.*	*Phytophthora austrocedri* (5)	*Phytophthora lateralis* (5)	Conifer aphids	*Dendroctonus micans*	*Elatobium abietinum*	*Lymantria dispar*	*Hylobius abietis*		
Cryptomeria japonica	Japanese cedar	+	-	-	-	-	-	-	+	-	-	-	-	+	-	-	-	-	3	14
Cupressus arizonica	Arizona cypress	+	-	-	+	-	-	-	+	-	+	+	-	+	-	-	-	-	6	11
Cupressus glabra	smooth cypress	+	-	-	+	-	-	-	+	-	+	-	-	+	-	-	-	-	5	12
Cupressus macrocarpa	Monterey cypress	+	-	-	+	-	-	-	+	-	+	-	-	+	-	-	-	-	5	12
Cupressus nootkatensis	Nootka cypress	+	-	-	+	-	-	-	+	-	+	+	-	+	-	-	-	-	6	11
Cupressus sempervirens	Italian cypress	+	-	-	+	-	-	-	+	-	+	-	-	+	-	-	-	-	5	12
x Cuprocyparis leylandii	Leyland cypress	+	-	-	+	-	-	-	+	-	+	-	-	+	-	-	-	-	5	12
Ginkgo biloba	maidenhair tree	+	-	-	-	-	-	-	+	-	-	-	-	+	-	-	-	-	3	14
Juniperus chinensis	Chinese juniper	+	-	-	+	-	-	-	+	-	+	+	-	+	-	-	+	-	7	10
Metasequoia glyptostroboides	dawn redwood	+	-	-	-	-	-	-	+	-	-	-	-	+	-	-	-	-	3	14
Picea engelmannii	Engelmann spruce	+	-	-	-	+	-	+	+	-	-	-	-	+	+	+	-	-	7	10
Picea glauca	white spruce	+	-	-	-	+	-	+	+	-	-	-	-	+	+	+	-	-	7	10
Picea omorika	Serbian spruce	+	-	-	-	+	-	+	+	-	-	-	-	+	+	+	-	-	7	10
Picea orientalis	Oriental spruce	+	-	-	-	+	-	+	+	-	-	-	-	+	+	+	-	-	7	10
Picea pungens	Colorado blue spruce	+	-	-	-	+	-	+	+	-	+	-	-	+	+	+	-	-	8	9
Pinus albicaulis	white bark pine	+	+	-	-	-	-	+	+	-	+	-	-	+	+	-	-	+	8	9
Pinus armandii	Armand's pine	+	+	-	-	-	-	+	+	-	+	-	-	+	+	-	-	+	8	9
Pinus monticola	Western white pine	+	+	-	-	-	-	+	+	-	+	-	-	+	+	-	-	+	8	9
Pinus muricata	bishops pine	+	+	-	-	-	-	+	+	-	+	-	-	+	+	-	-	+	8	9
Pinus peuce	Macedonian pine	+	+	-	-	-	-	+	+	-	+	-	-	+	+	-	-	+	8	9
Pinus pinaster	maritime/Bournemouth pine	+	+	-	-	-	-	+	+	-	+	-	-	+	+	-	-	+	8	9

Scientific name	Common name	Fungus (1)										Phytophthora (1)		Insect pest (1)					Total (susceptible to)	Total (resistant to)
		Honey fungus	Fomes annosus						Rhizosphaera needle cast		Diplodia Tip Blight				Giant spruce beetle	Green spruce aphid				
		Armillaria mellea	*Heterobasidion annosum* (3)	*Neonectria neomacrospora*	*Pestalotiopsis funereal*	*Phomopsis sp.* (2)	*Phomopsis pseudotsugae* (2)	*Polyporus schweinilzii* (4)	*Rhizosphaera sp.*	*Sirococcus tsugae*	*Sphaeropsis sp.*	*Phytophthora austrocedri* (5)	*Phytophthora lateralis* (5)	Conifer aphids	*Dendroctonus micans*	*Elatobium abietinum*	*Lymantria dispar*	*Hylobius abietis*		
Pinus pinea	Italian stone pine	+	+	-	-	-	-	+	+	-	+	-	-	+	+	-	-	+	8	9
Pinus ponderosa	Ponderosa pine	+	+	-	-	-	-	+	+	-	+	-	-	+	+	-	-	+	8	9
Pinus radiata	radiata pine	+	+	-	-	-	-	+	+	-	+	-	-	+	+	-	-	+	8	9
Pinus strobus	Eastern white/Weymouth pine	+	+	-	-	-	-	+	+	-	+	-	-	+	+	-	-	+	8	9
Pinus wallichiana	Bhutan pine	+	+	-	-	-	-	+	+	-	+	-	-	+	+	-	-	+	8	9
Platycladus orientalis	Chinese thuja	+	-	-	-	-	-	-	+	-	-	-	-	+	-	-	-	-	3	14
Sequoia sempervirens	coast redwood	+	-	-	-	-	-	-	+	-	-	-	-	+	-	-	-	-	3	14
Sequoiadendron giganteum	giant redwood	+	-	-	-	-	-	-	+	-	-	-	-	+	-	-	-	-	3	14
Taxodium distichum	swamp cypress	+	-	-	-	-	-	-	+	-	-	-	-	+	-	-	-	-	3	14
Taxus baccata	yew	+	-	-	-	-	-	-	+	-	-	-	-	+	-	-	+	-	4	13
Thuja plicata	Western red cedar	+	-	-	+	-	-	-	+	-	+	-	-	+	-	-	+	-	6	11
Tsuga canadensis	Eastern hemlock	+	-	-	-	-	-	-	+	+	-	-	-	+	-	-	-	-	4	13
Tsuga heterophylla	Western hemlock	+	-	-	-	-	-	-	+	+	-	-	-	+	-	-	-	+	5	12
Tsuga mertensiana	mountain hemlock	+	-	-	-	-	-	-	+	+	-	-	-	+	-	-	-	-	4	13

Table notes
[1] General references (Burns and Honkala, 1990; Defra, 2021; Forest Research, 2021a; Hansen *et al*., 1997; Nguyen *et al*., 2016; Oszako *et al*., 2017; Phillips and Burdekin, 1992d, 1992a, 1992b, 1992c, 1992e; Scharpf, 1993; Spaulding, 1961; Wainhouse *et al*., 2016).
[2] *Phomopsis sp*. specific references (Wilson, 1925).
[3] *Heterobasidium annosum* specific references (Asiegbu *et al*., 2005).
[4] *Polyporus schweinilzii* specific references (Barrett and Uscuplic, 1971).
[5] *Phytophthora sp*. specific references (Denman *et al*., 2005; Hamm and Hansen, 1982; Hansen *et al*., 1999; Newhook, 1959; Schlenzig *et al*., 2017).

Table A3: Susceptibility and resistance of the alternative conifer species to high risk pests and pathogens from France or elsewhere in Europe.

Scientific name	Common name	Fungus [1]	Bacterium [1]	Insect pests [1]				Total (susceptible to)	Total (resistant to)
		Brown spot needle blight		Siberian silk moth	Budworms	Pine processionary moth	Pine wood nematode		
		Lecanosticta acicola	*Xylella fastidiosa*	*Dendrolimus sibiiricus*	*Choristoneura sp.*	*Thaumetopoea pityocampa*	*Bursaphelenchus xylophilus*		
Abies alba	European silver fir	-	+	+	-	-	+	3	3
Abies amabilis	Pacific silver fir	-	+	+	-	-	+	3	3
Abies balsamea	balsam fir	-	+	+	-	-	+	3	3
Abies cephalonica	Greek fir	-	+	+	-	-	+	3	3
Abies concolor	white fir	-	+	+	-	-	+	3	3
Abies fraseri	Fraser fir	-	+	+	-	-	+	3	3
Abies grandis	grand fir	-	+	+	-	-	+	3	3
Abies koreana	Korean fir	-	+	+	-	-	+	3	3
Abies nordmanniana	Nordmann fir	-	+	+	-	-	+	3	3
Abies procera	noble fir	-	+	+	-	-	+	3	3
Abies spectabilis	East Himalayan fir	-	+	+	-	-	+	3	3
Araucaria araucana	monkey puzzle tree/Chilean pine	-	+	-	-	-	+	2	4
Calocedrus decurrens	incense cedar	-	+	-	-	-	+	2	4
Cedrus atlantica	Atlas cedar	-	+	-	-	+	+	3	3
Cedrus atlantica Glauca	Blue cedar	-	+	-	-	+	+	3	3
Cedrus brevifolia	Cyprus cedar	-	+	-	-	-	+	2	4
Cedrus deodara	deodar cedar	-	+	-	-	-	+	2	4
Cedrus libani	cedar of Lebanon	-	+	-	-	-	+	2	4
Chamaecyparis lawsoniana	Lawson's cypress	-	+	-	-	-	+	2	4
Chamaecyparis obtuse	hinoki	-	+	-	-	-	+	2	4
Chamaecyparis pisifera	Sawara cypress	-	+	-	-	-	+	2	4
Cryptomeria japonica	Japanese cedar	-	+	-	-	-	+	2	4
Cupressus arizonica	Arizona cypress	-	+	-	-	-	+	2	4
Cupressus glabra	smooth cypress	-	+	-	-	-	+	2	4
Cupressus macrocarpa	Monterey cypress	-	+	-	-	-	+	2	4

Scientific name	Common name	Fungus [1]	Bacterium [1]	Insect pests [1]				Total (susceptible to)	Total (resistant to)
		Brown spot needle blight		Siberian silk moth	Budworms	Pine processionary moth	Pine wood nematode		
		Lecanosticta acicola	*Xylella fastidiosa*	*Dendrolimus sibiiricus*	*Choristoneura sp.*	*Thaumetopoea pityocampa*	*Bursaphelenchus xylophilus*		
Cupressus nootkatensis	Nootka cypress	-	+	-	-	-	+	2	4
Cupressus sempervirens	Italian cypress	-	+	-	-	-	+	2	4
x Cuprocyparis leylandii	Leyland cypress	-	+	-	-	-	+	2	4
Ginkgo biloba	maidenhair tree	-	+	-	-	-	+	2	4
Juniperus chinensis	Chinese juniper	-	+	-	-	-	+	2	4
Metasequoia glyptostroboides	dawn redwood	-	+	-	-	-	+	2	4
Picea engelmannii	Engelmann spruce	-	+	+	-	-	+	3	3
Picea glauca	white spruce	-	+	+	-	-	+	3	3
Picea omorika	Serbian spruce	-	+	+	-	-	+	3	3
Picea orientalis	Oriental spruce	-	+	+	-	-	+	3	3
Picea pungens	Colorado blue spruce	-	+	+	-	-	+	3	3
Pinus albicaulis	white bark pine	+	+	+	-	+	+	5	1
Pinus armandii	Armand's pine	+	+	+	-	+	+	5	1
Pinus monticola	Western white pine	+	+	+	-	+	+	5	1
Pinus muricata	bishops pine	+	+	+	-	+	+	5	1
Pinus peuce	Macedonian pine	+	+	+	-	+	+	5	1
Pinus pinaster	maritime/ Bournemouth pine	+	+	+	-	+	+	5	1
Pinus pinea	Italian stone pine	+	+	+	-	+	+	5	1
Pinus ponderosa	Ponderosa pine	+	+	+	-	+	+	5	1
Pinus radiata	radiata pine	+	+	+	-	+	+	5	1
Pinus strobus	Eastern white/Weymouth pine	+	+	+	-	+	+	5	1
Pinus wallichiana	Bhutan pine	+	+	+	-	+	+	5	1
Platycladus orientalis	Chinese thuja	-	+	-	-	-	+	2	4
Sequoia sempervirens	coast redwood	-	+	-	-	-	+	2	4
Sequoiadendron giganteum	giant redwood	-	+	-	-	-	+	2	4
Taxodium distichum	swamp cypress	-	+	-	-	-	+	2	4
Taxus baccata	yew	-	+	-	-	-	-	1	5

Scientific name	Common name	Fungus (1)	Bacterium (1)	Insect pests (1)				Total (susceptible to)	Total (resistant to)
		Brown spot needle blight		Siberian silk moth	Budworms	Pine processionary moth	Pine wood nematode		
		Lecanosticta acicola	*Xylella fastidiosa*	*Dendrolimus sibiiricus*	*Choristoneura sp.*	*Thaumetopoea pityocampa*	*Bursaphelenchus xylophilus*		
Thuja plicata	Western red cedar	-	+	-	-	-	-	1	5
Tsuga canadensis	Eastern hemlock	-	+	-	-	-	+	2	4
Tsuga heterophylla	Western hemlock	-	+	-	-	+	+	3	3
Tsuga mertensiana	mountain hemlock	-	+	-	-	+	+	3	3

Table notes
[1] General references (Burns and Honkala, 1990; Defra, 2021; Forest Research, 2021a; Hansen *et al*., 1997; Nguyen *et al*., 2016; Oszako *et al*., 2017; Phillips and Burdekin, 1992d, 1992a, 1992b, 1992c, 1992e; Scharpf, 1993; Spaulding, 1961; Wainhouse *et al*., 2016).

Table A4: Susceptibility and resistance of the alternative conifer species to lower risk pests and pathogens from France and elsewhere in Europe.

Scientific name	Common name	Fungus [1]		Insect pests [1]			Total (susceptible to)	Total (resistant to)
		Pine pitch canker	White pine blister rust	European pine shoot moth	Forest tent caterpillar	Juniper scale		
		Fusarium circinatum [4]	*Cronartium ribicola*	*Rhyacionia buoliana*	*Malacosoma neustria*	*Carulaspis juniperi*		
Abies alba	European silver fir	-	-	-	-	-	0	5
Abies amabilis	Pacific silver fir	-	-	-	-	-	0	5
Abies balsamea	balsam fir	-	-	-	-	-	0	5
Abies cephalonica	Greek fir	-	-	-	-	-	0	5
Abies concolor	white fir	-	-	-	-	-	0	5
Abies fraseri	Fraser fir	-	-	-	-	-	0	5
Abies grandis	grand fir	-	-	-	-	-	0	5
Abies koreana	Korean fir	-	-	-	-	-	0	5
Abies nordmanniana	Nordmann fir	-	-	-	-	-	0	5
Abies procera	noble fir	-	-	-	-	-	0	5
Abies spectabilis	East Himalayan fir	-	-	-	-	-	0	5
Araucaria araucana	monkey puzzle tree/Chilean pine	-	-	-	-	-	0	5
Calocedrus decurrens	incense cedar	-	-	-	-	-	0	5
Cedrus atlantica	Atlas cedar	-	-	-	-	-	0	5
Cedrus atlantica Glauca	Blue cedar	-	-	-	-	-	0	5
Cedrus brevifolia	Cyprus cedar	-	-	-	-	-	0	5
Cedrus deodara	deodar cedar	-	-	-	-	-	0	5
Cedrus libani	cedar of Lebanon	-	-	-	-	-	0	5
Chamaecyparis lawsoniana	Lawson's cypress	-	-	-	-	+	1	4
Chamaecyparis obtuse	hinoki	-	-	-	-	+	1	4
Chamaecyparis pisifera	Sawara cypress	-	-	-	-	+	1	4
Cryptomeria japonica	Japanese cedar	-	-	-	-	-	0	5
Cupressus arizonica	Arizona cypress	-	-	-	-	+	1	4
Cupressus glabra	smooth cypress	-	-	-	-	+	1	4
Cupressus macrocarpa	Monterey cypress	-	-	-	-	+	1	4

Scientific name	Common name	Fungus (1)		Insect pests (1)			Total (susceptible to)	Total (resistant to)
		Pine pitch canker	White pine blister rust	European pine shoot moth	Forest tent caterpillar	Juniper scale		
		Fusarium circinatum (4)	*Cronartium ribicola*	*Rhyacionia buoliana*	*Malacosoma neustria*	*Carulaspis juniperi*		
Cupressus nootkatensis	Nootka cypress	-	-	-	-	+	1	4
Cupressus sempervirens	Italian cypress	-	-	-	-	+	1	4
x Cuprocyparis leylandii	Leyland cypress	-	-	-	-	+	1	4
Ginkgo biloba	maidenhair tree	-	-	-	-	-	0	5
Juniperus chinensis	Chinese juniper	-	-	-	+	+	2	3
Metasequoia glyptostroboides	dawn redwood	-	-	-	-	-	0	5
Picea engelmannii	Engelmann spruce	-	-	-	-	-	0	5
Picea glauca	white spruce	-	-	-	-	-	0	5
Picea omorika	Serbian spruce	-	-	-	-	-	0	5
Picea orientalis	Oriental spruce	-	-	-	-	-	0	5
Picea pungens	Colorado blue spruce	-	-	-	-	-	0	5
Pinus albicaulis	white bark pine	+	-	+	-	-	2	3
Pinus armandii	Armand's pine	+	-	+	-	-	2	3
Pinus monticola	Western white pine	+	+	+	-	-	3	2
Pinus muricata	bishops pine	+	+	+	-	-	3	2
Pinus peuce	Macedonian pine	+	-	+	-	-	2	3
Pinus pinaster	maritime/ Bournemouth pine	+	-	+	-	-	2	3
Pinus pinea	Italian stone pine	+	-	+	-	-	2	3
Pinus ponderosa	Ponderosa pine	+	-	+	-	-	2	3
Pinus radiata	radiata pine	+	-	+	-	-	2	3
Pinus strobus	Eastern white/Weymouth pine	+	+	+	-	-	3	2
Pinus wallichiana	Bhutan pine	+	-	+	-	-	2	3
Platycladus orientalis	Chinese thuja	-	-	-	-	-	0	5
Sequoia sempervirens	coast redwood	-	-	-	-	-	0	5
Sequoiadendron giganteum	giant redwood	-	-	-	-	-	0	5
Taxodium distichum	swamp cypress	-	-	-	-	-	0	5
Taxus baccata	yew	-	-	-	-	-	0	5

Scientific name	Common name	Fungus (1)		Insect pests (1)			Total (susceptible to)	Total (resistant to)
		Pine pitch canker	White pine blister rust	European pine shoot moth	Forest tent caterpillar	Juniper scale		
		Fusarium circinatum (4)	*Cronartium ribicola*	*Rhyacionia buoliana*	*Malacosoma neustria*	*Carulaspis juniperi*		
Thuja plicata	Western red cedar	-	-	-	-	+	1	4
Tsuga canadensis	Eastern hemlock	-	-	-	-	-	0	5
Tsuga heterophylla	Western hemlock	-	-	-	-	-	0	5
Tsuga mertensiana	mountain hemlock	-	-	-	-	-	0	5

Table notes

[1] General references (Burns and Honkala, 1990; Defra, 2021; Forest Research, 2021a; Hansen *et al*., 1997; Nguyen *et al*., 2016; Oszako *et al*., 2017; Phillips and Burdekin, 1992d, 1992a, 1992b, 1992c, 1992e; Scharpf, 1993; Spaulding, 1961; Wainhouse *et al*., 2016).

[2] Pine pitch canker (*Fusarium circinatum*) specific references (Gordon *et al*., 2015; MartÍnez-Álvarez *et al*., 2011).

Annex B

Common end uses of timber by species matrix

In the matrix that follows + indicates that timber from species x is commonly used in that category.

Table B1: Range of end uses for the timber of the alternative conifer species.

Scientific name	Common name	Use category											Total	Reference
		Cladding	Decking	Flooring	Furniture	Joinery - exterior	Joinery - interior	Other [1]	Pulp	Sheet material	Sleepers	Structural use		
Abies alba	European silver fir			+		+	+		+	+		+	6	TRADA, (no date)
Abies amabilis	Pacific silver fir			+		+	+		+	+		+	6	TRADA, (no date)
Abies balsamea	balsam fir			+		+	+		+	+		+	6	Meier (2021)
Abies cephalonica	Greek fir												0	Meier (2021)
Abies concolor	white fir			+		+	+		+	+		+	6	Meier (2021)
Abies fraseri	Fraser fir												0	Meier (2021)
Abies grandis	grand fir			+		+	+		+	+		+	6	Meier (2021)
Abies koreana	Korean fir												6	Meier (2021)
Abies nordmanniana	Nordmann fir			+		+	+		+	+		+	6	Meier (2021)
Abies procera	noble fir			+		+	+		+	+		+	6	Meier (2021)
Abies spectabilis	East Himalayan fir												0	Meier (2021)
Araucaria araucana	monkey puzzle tree/Chilean pine				+	+	+	+	+				5	Meier (2021)
Calocedrus decurrens	incense cedar				+	+		+		+		+	5	Meier (2021)
Cedrus atlantica	Atlas cedar	+			+	+	+	+				+	6	Meier (2021)
Cedrus atlantica Glauca	Blue cedar	+			+	+	+	+				+	6	Meier (2021)
Cedrus brevifolia	Cyprus cedar	+			+	+	+	+				+	6	Meier (2021)
Cedrus deodara	deodar cedar	+			+	+	+	+				+	6	Meier (2021)
Cedrus libani	cedar of Lebanon	+			+	+	+	+				+	6	Meier (2021)
Chamaecyparis lawsoniana	Lawson's cypress		+		+	+		+					4	Meier (2021)
Chamaecyparis obtuse	hinoki	+			+	+	+						4	CABI (2019a)
Chamaecyparis pisifera	Sawara cypress				+	+	+	+				+	4	CABI (2019b)

Scientific name	Common name	Use category											Total	Reference
		Cladding	Decking	Flooring	Furniture	Joinery - exterior	Joinery - interior	Other [1]	Pulp	Sheet material	Sleepers	Structural use		
Cryptomeria japonica	Japanese cedar					+	+	+				+	4	Meier (2021)
Cupressus arizonica	Arizona cypress					+		+					2	CABI (2019c)
Cupressus glabra	smooth cypress												0	Meier (2021)
Cupressus macrocarpa	Monterey cypress	+			+	+		+					4	Meier (2021)
Cupressus nootkatensis	Nootka cypress		+	+	+	+		+				+	6	Meier (2021)
Cupressus sempervirens	Italian cypress				+	+	+	+					4	Meier (2021)
x Cuprocyparis leylandii	Leyland cypress				+	+	+	+					4	Meier (2021)
Ginkgo biloba	maidenhair tree	+			+		+	+					4	CABI (2019d)
Juniperus chinensis	Chinese juniper	+		+	+	+	+	+	+				7	Meier (2021)
Metasequoia glyptostroboides	dawn redwood				+	+	+	+	+	+	+	+	8	CABI (2019e)
Picea engelmannii	Engelmann spruce							+	+	+	+	+	5	Meier (2021)
Picea glauca	white spruce							+	+	+		+	4	Meier (2021)
Picea omorika	Serbian spruce							+	+	+		+	4	Savill *et al*. (2017a)
Picea orientalis	Oriental spruce			+	+	+	+	+	+			+	7	Savill *et al*. (2017b)
Picea pungens	Colorado blue spruce							+	+			+	3	Meier (2021)
Pinus albicaulis	white bark pine												0	Meier (2021)
Pinus armandii	Armand's pine												0	Meier (2021)
Pinus monticola	Western white pine				+		+	+		+		+	5	Meier (2021)
Pinus muricata	bishops pine	+				+	+	+	+	+		+	7	CABI (2019f)
Pinus peuce	Macedonian pine				+							+	2	Savill and Mason (2015)
Pinus pinaster	maritime/ Bournemouth pine			+				+	+			+	4	TRADA, (no date)
Pinus pinea	Italian stone pine					+	+	+		+			4	CABI (2020)
Pinus ponderosa	Ponderosa pine			+	+	+	+	+		+		+	7	TRADA, (no date)
Pinus radiata	radiata pine				+			+	+	+		+	5	TRADA, (no date)
Pinus strobus	Eastern white/ Weymouth pine						+	+				+	3	Meier (2021)

Scientific name	Common name	Use category											Total	Reference
		Cladding	Decking	Flooring	Furniture	Joinery - exterior	Joinery - interior	Other [1]	Pulp	Sheet material	Sleepers	Structural use		
Pinus wallichiana	Bhutan pine				+	+	+	+	+		+	+	7	CABI (2019g)
Platycladus orientalis	Chinese thuja				+	+	+	+	+			+	7	CABI (2019h)
Sequoia sempervirens	coast redwood		+		+	+	+					+	5	Meier (2021)
Sequoiadendron giganteum	giant redwood		+		+	+	+					+	5	Meier (2021)
Taxodium distichum	swamp cypress				+	+	+	+				+	5	Meier (2021)
Taxus baccata	yew							+					1	Meier (2021)
Thuja plicata	Western red cedar	+				+		+					3	Wilson *et al.* (2016)
Tsuga canadensis	Eastern hemlock					+	+	+		+		+	5	Meier (2021)
Tsuga heterophylla	Western hemlock					+	+	+		+		+	5	TRADA, (no date)
Tsuga mertensiana	mountain hemlock					+	+	+		+		+	5	Meier (2021)

Table notes
[1] Other includes (but not limited to) pallets, boxes, turning, boatbuilding, musical instruments, tool handles and roundwood (piles, poles, pit props or telegraph poles)

Annex C

Stakeholder survey

The following provides a transcript of the survey text presented in the online survey to stakeholders that ran from the 5th March 2021 to 15th March 2021.

Survey introduction

Woodknowledge Wales together with a consortium of researchers has been commissioned to undertake a detailed study to identify the top five alternative conifer tree species in GB. As part of this project, we are inviting a broad range of stakeholders across GB to help rank the relative importance of varying criteria for identifying suitable alternative conifer tree species for use in British commercial forestry.

We would highly appreciate your participation in this online survey which will run from 5-14 March 2021.

To include a broad range of stakeholders across academia, forestry and processing, we invite you to forward the link to this survey to relevant parties in your network.

PURPOSE

We are undertaking this review of alternative commercial tree species suitable for timber production in GB in the face of growing pest and pathogen pressures, using a multi-criteria analysis method for ranking alternative conifer tree species. Our review will focus on their resilience to current and future pest and pathogens, their suitability for a changing climate and a range of site conditions across GB, and their suitability for producing commercial timber products.

The purpose of the survey is to gather evidence and views from expert stakeholders on the appropriateness and suitability of the 12 criteria we will use to identify suitable conifer tree species and to establish their relative importance.

Participation is voluntary. However, your views and experiences are important in order to help inform Welsh Government policies.

METHODOLOGY

As part of this review, we will be using multi-criteria analysis to rank alternative conifer tree species. You can find more information on our approach in this video https://vimeo.com/519916201. Find presentations on scope and objectives; methodology, long list findings, main pests and pathogens (from 7:30'); stakeholder questions and answers (from 20:55').

DATA

All data gathered through this project will be reported in an anonymised format. It will not contain your contact details and any identifiable information in open-ended answers will be removed. Woodknowledge Wales will use the data to produce a report for Welsh Government. This report will not include any information that could be used to identify individual participants.

CONTACT

If you have any queries about the review or survey please contact: <insert contacts>

Information about yourself

In order to evaluate the survey results, we need to understand who participated in the ranking of criteria.

Which of the following options characterises your position best?

Academia/Policy/Forester/Processor/Other

How would you describe your area of expertise or practice?

Survey questions

Evaluating the suitability of alternative conifer tree species. The overall ranking of a trees species is a function of:

- Their resistance to current and future pest and pathogens.
- Their suitability for a changing climate and a range of site conditions across GB.
- Their suitability for producing commercial timber products.

Based on these three considerations we have identified 12 broad criteria which we will use for the purpose of this study to rank the suitability of alternative conifer species for commercial timber production in GB. Find out more about the criteria and the rationale behind their selection in this document: https://bit.ly/30f3hAY.

RANKING THE CRITERIA

As part of the multi-criteria analysis, we need to establish the relative importance of these criteria. To help us allocate a weighting to each, we are asking you to rank these 12 criteria in order of their importance based on your individual expertise and experience.

The following 12 questions will guide you through ranking the criteria outlined below. We are using an iterative approach to help you weigh the relative importance of each criterion on the list. Please bear with us throughout these 12 steps. Thank you for your time and perseverance!

For further information on the methodology and criteria, you can watch the video from the stakeholder meeting here: https://vimeo.com/519916201

Table C1: Criteria for evaluating the suitability of alternative conifer tree species for commercial timber production across GB.

Criterion	Criterion number
Resistance to 'high risk' pests and pathogens currently in GB	1
Resistance to 'lower risk' pests and pathogens currently in GB	2
Resistance to 'high risk' pests and pathogens from France and Europe	3
Resistance to 'lower risk' pests and pathogens from France and Europe	4
Drought tolerance	5
Waterlogging tolerance	6
Shade tolerance	7
Exposure tolerance	8
Potential productivity	9
Technical suitability of timber (stiffness)	10
Suitability for existing processing machinery	11
Range of end uses for timber	12

Table C1: Survey questions.

	Question
1	Imagine a tree species that has the worst performance across all of the 12 criteria outlined in Table C1, the worst possible species that could exist. You can improve that tree species' performance on one criterion from its current worst value to the best possible level. Which of the 12 criteria would you improve that tree species' performance on first?
2	Imagine that same tree species with the worst performance across all of the 12 criteria (outlined in Table C1), the worst possible species that could exist. You can improve that tree species' performance on one criterion (other than the one you have already chose) from its current worst value to the best possible level. Which of the remaining 11 criteria would you improve that tree species' performance on next?

3	Imagine that same tree species with the worst performance across all of the 12 criteria (outlined in Table C1), the worst possible species that could exist. You can improve that tree species' performance on one criterion (other than the two you have already chosen) from its current worst value to the best possible level. Which of the remaining 10 criteria would you improve that tree species performance on next?
4	Imagine that same tree species with the worst performance across all of the 12 criteria (outlined in Table C1), the worst possible species that could exist. You can improve that tree species' performance on one criterion (other than the three you have already chosen) from its current worst value to the best possible level. Which of the remaining nine criteria would you improve that tree species' performance on next?
5	Imagine that same tree species with the worst performance across all of the 12 criteria (outlined in Table C1), the worst possible species that could exist. You can improve that tree species' performance on one criterion (other than the four you have already chosen) from its current worst value to the best possible level. Which of the remaining eight criteria would you improve that tree species' performance on next?
6	Imagine that same tree species with the worst performance across all of the 12 criteria (outlined in Table C1), the worst possible species that could exist. You can improve that tree species' performance on one criterion (other than the five you have already chosen) from its current worst value to the best possible level. Which of the remaining seven criteria would you improve that tree species' performance on next?
7	Imagine that same tree species with the worst performance across all of the 12 criteria (outlined in Table C1), the worst possible species that could exist. You can improve that tree species' performance on one criterion (other than the six you have already chosen) from its current worst value to the best possible level. Which of the remaining six criteria would you improve that tree species' performance on next?
8	Imagine that same tree species with the worst performance across all of the 12 criteria (outlined in Table C1), the worst possible species that could exist. You can improve that tree species' performance on one criterion (other than the seven you have already chosen) from its current worst value to the best possible level. Which of the remaining five criteria would you improve that tree species' performance on next?
9	Imagine that same tree species with the worst performance across all of the 12 criteria (outlined in Table C1), the worst possible species that could exist. You can improve that tree species' performance on one criterion (other than the eight you have already chosen) from its current worst value to the best possible level. Which of the remaining four criteria would you improve that tree species' performance on next?
10	Imagine that same tree species with the worst performance across all of the 12 criteria (outlined in Table C1), the worst possible species that could exist. You can improve that tree species' performance on one criterion (other than the nine you have already chosen) from its current worst value to the best possible level. Which of the remaining three criteria would you improve that tree species' performance on next?
11	Imagine that same tree species with the worst performance across all of the 12 criteria (outlined in Table C1), the worst possible species that could exist. You can improve that tree species' performance on one criterion (other than the 10 you have already chosen) from its current worst value to the best possible level. Which of the remaining two criteria would you improve that tree species' performance on next?
12	Imagine that same tree species with the worst performance across all of the 12 criteria (outlined in Table C1), the worst possible species that could exist. Which one criterion would you improve that tree species' performance on last?

Thank you for participating in this short online survey. The results of our study will inform further areas for research to establish a basket of future tree species suitable across a range of land types available in GB. We appreciate your time and input into this project.

Please provide any further comments or questions on the topic here.

Do you have unpublished data or research findings you'd like us to include in our study? Please list these here or share with us via email to <insert contacts>

Annex D

Single dimension utility scores

The following single dimension utility scores normalise the raw criteria values (from Table 3.3) onto a common scoring scale (0 to 100).

Table D1: Single dimension utility scores for the alternative conifer species.

Scientific name	Common name	Criteria score											
		Resistance to 'high risk' pests and pathogens currently in GB	Resistance to 'lower risk' pests and pathogens currently in GB	Resistance to 'high risk' pests and pathogens from France and Europe	Resistance to 'lower risk' pests and pathogens from France and Europe	Drought tolerance	Waterlogging tolerance	Shade tolerance	Exposure tolerance	Potential productivity	Technical suitability of timber (stiffness)	Suitability for existing processing machinery	Range of end uses for timber
Abies alba	European silver fir	80	86	60	80	50	25	100	25	80	100	100	75
Abies amabilis	Pacific silver fir	80	86	60	100	25	25	100	0	100	100	100	75
Abies balsamea	balsam fir	80	86	60	80	0	50	100	25	0	100	50	75
Abies cephalonica	Greek fir	80	86	60	100	0	0	0	0	0	50	50	0
Abies concolor	white fir	80	79	60	80	25	25	100	0	0	100	50	75
Abies fraseri	Fraser fir	80	86	60	100	50	50	100	0	0	0	100	0
Abies grandis	grand fir	60	86	60	100	50	25	100	0	100	25	100	75
Abies koreana	Korean fir	80	86	60	100	0	0	0	0	0	0	100	75
Abies nordmanniana	Nordmann fir	80	86	60	100	25	25	100	0	0	0	50	75
Abies procera	noble fir	60	86	60	80	50	25	50	75	80	50	100	75
Abies spectabilis	East Himalayan fir	60	86	60	80	0	0	0	0	0	0	100	0
Araucaria araucana	monkey puzzle tree/ Chilean pine	100	100	80	100	0	0	0	0	0	0	100	63
Calocedrus decurrens	incense cedar	100	100	80	100	75	25	75	0	0	25	100	63

Scientific name	Common name	Criteria score											
		Resistance to ‘high risk’ pests and pathogens currently in GB	Resistance to ‘lower risk’ pests and pathogens currently in GB	Resistance to ‘high risk’ pests and pathogens from France and Europe	Resistance to ‘lower risk’ pests and pathogens from France and Europe	Drought tolerance	Waterlogging tolerance	Shade tolerance	Exposure tolerance	Potential productivity	Technical suitability of timber (stiffness)	Suitability for existing processing machinery	Range of end uses for timber
Cedrus atlantica	Atlas cedar	80	93	60	100	0	0	0	0	0	100	100	75
Cedrus atlantica Glauca	Blue cedar	80	93	60	100	0	0	0	0	0	0	100	75
Cedrus brevifolia	Cyprus cedar	80	93	80	100	0	0	0	0	0	0	100	75
Cedrus deodara	deodar cedar	80	93	80	100	75	25	50	0	0	0	50	75
Cedrus libani	cedar of Lebanon	80	93	80	100	50	25	25	0	0	0	50	75
Chamaecyparis lawsoniana	Lawson’s cypress	100	79	80	80	50	25	75	0	70	0	50	50
Chamaecyparis obtuse	hinoki	100	93	80	80	50	25	100	0	0	100	100	50
Chamaecyparis pisifera	Sawara cypress	100	93	80	80	0	0	0	0	0	0	100	50
Cryptomeria japonica	Japanese cedar	100	100	80	100	50	50	75	50	80	100	100	50
Cupressus arizonica	Arizona cypress	100	93	80	60	0	0	0	50	100	0	50	50
Cupressus glabra	smooth cypress	100	93	80	60	100	25	25	0	0	0	100	25
Cupressus macrocarpa	Monterey cypress	100	93	80	60	0	0	0	0	0	0	50	0
Cupressus nootkatensis	Nootka cypress	100	93	80	60	0	0	0	0	0	0	100	50
Cupressus sempervirens	Italian cypress	100	86	80	60	0	0	0	0	0	0	100	75
x Cuprocyparis leylandii	Leyland cypress	100	93	80	60	100	25	25	0	0	0	0	50
Ginkgo biloba	maidenhair tree	100	100	80	100	75	25	25	0	0	0	50	50
Juniperus chinensis	Chinese juniper	80	79	80	40	100	25	25	0	0	0	100	88
Metasequoia glyptostroboides	dawn redwood	100	100	80	100	50	25	75	25	0	0	100	100
Picea engelmannii	Engelmann spruce	80	71	60	100	50	25	100	0	0	50	50	63

Scientific name	Common name	Criteria score											
		Resistance to 'high risk' pests and pathogens currently in GB	Resistance to 'lower risk' pests and pathogens currently in GB	Resistance to 'high risk' pests and pathogens from France and Europe	Resistance to 'lower risk' pests and pathogens from France and Europe	Drought tolerance	Waterlogging tolerance	Shade tolerance	Exposure tolerance	Potential productivity	Technical suitability of timber (stiffness)	Suitability for existing processing machinery	Range of end uses for timber
Picea glauca	white spruce	80	71	60	100	50	25	100	0	0	100	100	50
Picea omorika	Serbian spruce	60	71	60	100	50	25	100	75	50	25	0	50
Picea orientalis	Oriental spruce	80	71	60	100	0	0	0	50	70	50	50	88
Picea pungens	Colorado blue spruce	80	71	60	80	50	25	75	0	0	0	100	38
Pinus albicaulis	white bark pine	40	64	20	60	100	25	25	0	0	0	50	0
Pinus armandii	Armand's pine	40	64	20	60	0	0	0	0	0	0	100	0
Pinus monticola	Western white pine	40	64	20	40	50	25	50	25	60	100	50	63
Pinus muricata	bishops pine	40	64	20	40	50	25	50	0	0	0	50	88
Pinus peuce	Macedonia n pine	40	64	20	60	0	0	0	50	50	0	50	25
Pinus pinaster	maritime/ Bournemou th pine	40	64	20	60	0	0	0	25	70	50	100	50
Pinus pinea	Italian stone pine	40	64	20	60	0	0	0	0	0	0	100	50
Pinus ponderosa	Ponderosa pine	40	64	20	60	100	25	25	0	0	25	100	88
Pinus radiata	radiata pine	20	64	20	60	50	25	50	75	80	50	50	63
Pinus strobus	Eastern white/ Weymouth pine	40	64	20	40	50	25	75	50	60	0	100	38
Pinus wallichiana	Bhutan pine	40	64	20	60	50	25	25	0	0	0	50	88
Platycladus orientalis	Chinese thuja	100	100	80	100	0	0	0	0	0	0	100	88
Sequoia sempervirens	coast redwood	100	100	80	100	50	0	100	0	100	25	100	63
Sequoiadend ron giganteum	giant redwood	100	100	80	100	50	25	75	50	80	50	100	63
Taxodium distichum	swamp cypress	100	100	80	100	75	100	50	0	0	100	100	63

Scientific name	Common name	Criteria score											
		Resistance to 'high risk' pests and pathogens currently in GB	Resistance to 'lower risk' pests and pathogens currently in GB	Resistance to 'high risk' pests and pathogens from France and Europe	Resistance to 'lower risk' pests and pathogens from France and Europe	Drought tolerance	Waterlogging tolerance	Shade tolerance	Exposure tolerance	Potential productivity	Technical suitability of timber (stiffness)	Suitability for existing processing machinery	Range of end uses for timber
Taxus baccata	yew	100	93	100	100	75	25	100	0	0	0	50	25
Thuja plicata	Western red cedar	100	86	100	60	50	25	100	0	90	25	100	38
Tsuga canadensis	Eastern hemlock	100	93	80	100	25	25	100	0	0	50	100	63
Tsuga heterophylla	Western hemlock	80	86	60	100	25	0	100	0	90	50	100	63
Tsuga mertensiana	mountain hemlock	100	93	60	100	25	0	100	0	60	75	100	63