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Increasing resistance and resilience of forests, a case study of Great Britain

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The forests of Great Britain (GB) are an important resource, which are under threat from climate change and exotic pests and diseases. The forest sector has been proactive in launching initiatives and supporting activities to improve the resistance and resilience of forests in GB. These interventions can be directed at forests at a range of scales, from genetic to national. This review describes the range of potential and actual actions focused on adapting Britain's forests to climate change and damage from pests and diseases. However, there are also barriers to improving the resilience of forests in GB and these are also discussed.

Keywords: Forests, Great Britain, Resistance, Resilience, Climate Change, Pests and Pathogens

Introduction

This review aims to describe the actual and potential actions taken in Great Britain (GB) to improve the resistance and resilience of forests to damaging agents. The forests of GB represent a valuable environmental, economic and social resource, the total value of products and services from forests in the United Kingdom (UK) in 2017 was estimated at £129.7 billion, with £8.9 billion being the value of timber (Office for National Statistics 2020). However, the forests of Britain are under threat from two major environmental developments. Accelerated climate change (ACC) is the main concern and the Climate Change Risk Assessment UK for the Forestry Sector identified over 30 associated threats to the forests of Britain (Moffat et al. 2012). These were evaluated in terms of their importance and four main areas of hazards were identified: (i) the action of pests and pathogens; (ii) changes in forest productivity; (iii) the impact of increased drought in parts of GB; and (iv) the likelihood of increased damage from forest fires. A fifth important predicted impact was more frequent and severe damage from wind (Ray 2008a, 2008b). All these impacts are anticipated to become amplified under ACC.

Predictions for future climates have been generated for the UK (Jenkins et al. 2009) with the latest being the UK Climate Programme 2018 (UKCP18 – Met Office 2020). The greatest change predicted in precipitation is a significant decrease in southern England in the summer, while over the whole country there is an increase in winter precipitation. While there is a general warming of the climate, the most change in temperature is in southern England in summer (Met Office 2020). Based on predictions generated by a previous climate change programme (UKCIP02), Forest Research have made forecasts of change to moisture deficit and accumulated temperature, two climatic variables that strongly influence tree growth. These are described for England in Ray et al. (2010), for Scotland in Ray (2008a) and for Wales in Ray (2008b). In general, it is predicted that the greatest impact of ACC will be in the southeast of England, with a considerable increase in moisture deficits and accumulated temperatures, which is analogous to a Mediterranean climate. A study by Petr et al. (2014) predicted that drought related to ACC would reduce the productivity of three important tree species: Scots pine (*Pinus sylvestris*), Sitka spruce (*Picea sitchensis*) and oak (*Quercus* spp.) in Great Britain, with greatest effect in the lowlands. Using the IPCC A1F1 emissions scenario and applying its climatic predictions to the state forest resource they found that potential production for all three species in the 2080s is estimated to decrease due to drought by an average of 42% in the lowlands and 32% in the uplands. Furthermore, other abiotic disturbances to forests are likely to increase. In Atlantic parts of Europe, including Great Britain, forests are likely to be subjected to greater damage from wind, with fire being likely to become more prevalent in northern parts of Britain (Siedl et al. 2014).

The second important threat is the introduction of exotic pests and diseases. The damage inflicted by insect pests (Leather 2014), but more so by pathogens on forests has increased significantly over the last two decades (Logan et al. 2003, Sturrock et al. 2011, Freer-Smith & Webber 2017). Important productive exotic trees have been affected in Britain; larches (*Larix spp.*) are no longer planted in most of GB due to the impact of *Phythpophthora ramorum* (Forestry Commission 2014a), while planting of Corsican pine (*Pinus nigra* ssp. *laricio*) has ceased because of damage from *Dothistroma septosorum* (Brown & Webber 2008). Native tree species have also been impacted, for example ash by the introduction of the organism responsible for ash dieback (*Hymenoscyphus fraxineus* – Thomas 2016) and *Phythophthora austrocedrae* on juniper (*Juniperus communis* – Green et al. 2015).

The actual and potential impact of these

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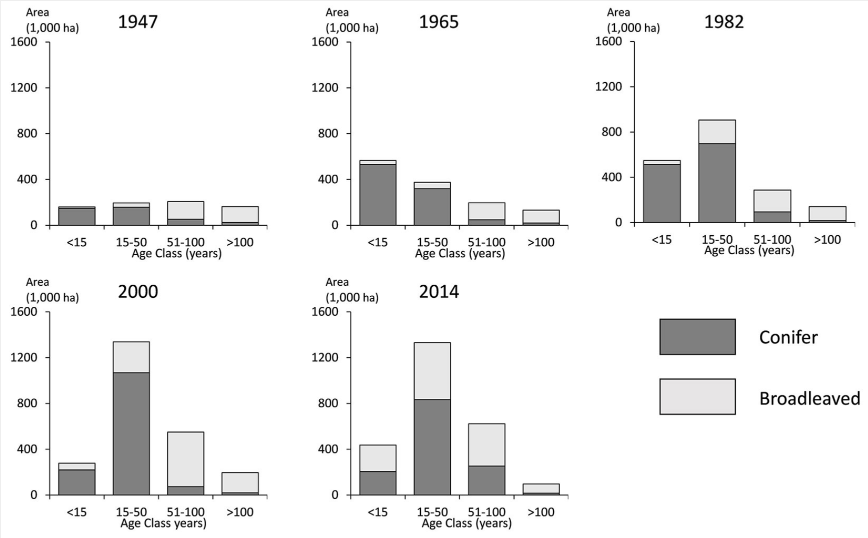

Fig. 1 - Age class distribution of forests in GB since 1947 (Mason 2007, National Forest Inventory pers. comm.).

threats is recognised and management interventions have been developed to build resistance and resilience of the forests of GB. Most of these activities are not described in peer-reviewed publications but in other types of documents, ranging from articles in professional journals, government information papers and documentation produced by non-governmental forestry organisations. This article collates and summarises relevant information from a wide range of sources and makes it available to an academic audience.

This review of the literature takes the form of a narrative literature review (Stratton 2019) and is based on literature collected by the authors over several years. The authors have conducted regular searches on academic search engines on the topic and collected material published by government agencies, professional bodies and other forestry organisations. The strength of the narrative approach is that it can include material from these diverse types of sources and that it allows a broader approach when collecting information. The disadvantage of this type of review is that they can be biased, do not involve a systematic approach to selecting information and can be unstructured (Stratton 2019). For this topic, where much of the information is not peer-reviewed this was considered an appropriate structure to adopt. The aims of this review were fourfold:

- To review the current situation of forests in GB.
- To identify and describe the main threats to the forests in GB.
- To draw together for the first-time information on woodland management and silviculture for resilience, from peer reviewed publications and from other literature.
- To describe approaches that could be adopted to develop resistance and resilience in forests in GB but also elsewhere.

The present situation of forests in GB

The forest cover of GB (defined as comprising blocks of forest over 5 ha in area and over 20 m in width) was estimated in 2019 to be 3,179 million ha, or 13% of the total land area (Forest Research 2019a). Since 1919 when the Forestry Commission was founded with the purpose of expanding the forest resource (Aldhous 1997, Mason 2007) the area of forest has more than doubled, with 60% being under 40 years old (Forest Research 2019b – Fig. 1). However, despite this expansion the forests remain fragmented and there is generally poor connectivity (De Albaquerque & Rueda 2010, Fuentes-Montemayor et al. 2012) and individual trees and small patches of woodland make a significant contribution to tree cover. A study of three English counties found that trees outside woodlands represented 7% of the land area (Brown & Fisher 2009). The considerable differences in forest cover, type and composition in the three countries that comprise Great Britain (Tab. 1), reflect different forest histories and woodland establishment policies.

The forests of GB exhibit a moderately diversified species composition when compared with other European countries (Tab. 2). Currently conifers make up about half of the forest area of GB. However, there are major differences across the country with about one quarter of England's woodland being conifer, compared with two thirds of Scotland's (Forestry Commission 2023a – Tab. 1). This reflects the emphasis on lowland forestry in England and upland forestry in Scotland. A study (Beauchamp 2016) using the Shannon's Diversity Index to compare species evenness and species richness of the forests in England, Scotland and Wales found that England's were the most diverse, followed by Wales and then Scotland.

In GB there is a reliance on exotic tree species in production forestry and over the last century there has been a reduction in the diversity of conifers planted in Great Britain, but conversely an increase in the diversity of broadleaves (Forestry Commission 2003). In conifer plantations two thirds of the area comprises two species; Sitka spruce (44%) and Scots pine (14%) (Forestry Commission 2023a). However, there is a greater concentration on a few productive species in some other temperate countries. For example, 87% of the area of productive forests in New Zealand comprise Monterey pine (*Pinus radiata* – New Zealand Forest Owners Association 2015). In productive forests of boreal countries in Europe such as Sweden and Finland, there is also a concentration on a few species, with Norway Spruce, Scots pine and birch making up 93% (Swedish University of Agricultural Sciences 2016) and 99% of the forest area respectively (Natural Resource Finland 2011).

Provision of grants and tax incentives over more than a century has encouraged private forest ownership, with approximately 75% now being owned privately (Forestry Commission 2023a). While there is a similar area of conifer woodland in private and public ownership (860,000 ha *vs.* 642,000 ha) there is twelve times the area of broadleaves in private ownership than public (14,760 ha *vs.* 166,000 ha – Forestry Commission 2023a). Most forests today in GB are managed for objectives other than investment, with reasons such as nature conservation, personal pleasure and protecting the landscape being important (Hemery et al. 2018).

Tab. 1 - Comparison of the forests in England, Scotland and Wales. (1): remaining % area is broadleaved; (2): remaining % area is publicly owned (data from Forestry Commission 2023a).

Country	% area forest	Area forest (1000 ha)	% area conifer(1)	% area privately owned(2)
England	10	1326	23	84
Scotland	19	1494	71	69
Wales	15	312	45	63

Increasing resistance and resilience at different scales

Resistance can be defined as remaining unchanged in the face of disturbances (Grimm & Wissel 1997), while a simple definition of resilience is the relative ability of a system to return to its original state following disturbance (Holling 1973). For forests the definition of ecosystem resilience is particularly appropriate being defined as the "capacity of an ecosystem to absorb disturbance without shifting to an alternative state and losing function and services" (Côté & Darling 2010) and therefore, focuses on maintaining a flow of desired goods or services. This shift might however result in forest ecosystems of a very different composition and structure (Gunderson 2000).

Building resilience can involve a wide range of approaches. Some relate to traditional rotational forestry, but there is a growing interest in close to nature forestry involving lower impact approaches to silviculture (Pommerening et al. 2021). This has been supported by European organisations such as Pro Silva (Pro Silva 2024), while an example of promotion of such approaches in GB is the recent campaign by the Soil Association focused on "regenerative forestry" (Soil Association 2022). Resistance and resilience can be developed in forests at a range of scales. Tab. 3 describes silvicultural and forest management interventions that could or are being applied to forest across a range of scales, from genetic to national and indicates the threats (Moffat et al. 2012) moderated by each intervention. Using this as a structure, we describe initiatives and activities that have been undertaken or could be applied in Britain at these varying scales of management to improve forest resistance and resilience.

National

The guidelines in the UK Forestry Standard (UKFS – Forestry Commission 2023b) and associated standards described in the UK Woodland Assurance Scheme (UKWAS 2018) provide a framework for sustainable forest management. In the UKFS, resistance or resilience is mentioned 36 times (Forestry Commission 2023b) whereas in UKWAS they are mentioned 12 times (UKWAS 2018) and in the chapter of the UKFS on forest and climate change there are twenty guidelines specifically relating to adaptation of forests, however many in other sections also enhance the robustness of forests to damaging agents. To support the Standard a UKFS Practice Guide on adapting woodland management to climate change was published in 2022 and contains useful guidance and directs the reader to additional more detailed advice (Forest Research 2022). There have been other recent policy developments focused on increasing resilience of forests. England, Scotland and Wales have all recently published forestry strategies (Welsh Forestry Commission 2018, Scottish Government 2019, UK Government 2021) which include broad plans for enhancing adaptation of forests to future threats and increasing forest cover.

Tab. 2 - The percentage cover of the five most abundant tree species and percentage areas of the five main species in Germany, Denmark and the UK. (1): Forstwirtschaft in Deutschland (2021); (2): Forestry Commission (2023a); (3): Bastrup-Birk (2010)

-	Germany(1)	GB(2)	Denmark(3)
Cover of most abundant 5 tree species (%)	78.2	47.5	60.8
1st species	Norway Spruce (26.0)	Sitka Spruce (21.3)	Norway Spruce (19.6)
2nd species	Scots Pine (22.9)	Birch (7.5)	Beech (13.4)
3rd species	Beech (15.8)	Oak (7.0)	Scots Pine(12.4)
4th species	Oak (10.6)	Scots pine (6.6)	Oak (9.3)
5th species	Larch (2.9)	Ash (5.0)	Sitka Spruce (6.2)

Exotic pests and diseases are recognised as a major threat (Barham et al. 2016). In the British Woodlands Survey 2015 the management of pests and pathogens was given the highest priority in terms of building resistance and resilience (Hemery et al. 2015). The UK Government's strategy for controlling pests and diseases has three main principles: (i) to exclude exotic pests and pathogens; (ii) to eradicate any that have entered the country; and (iii) if that fails to limit the damage from a new pest or pathogen. Actions are focused on specific pests and diseases based on a pest risk analysis ranking pests and diseases on the likelihood of introduction combined with the seriousness of damage. The risk associated with 962 pests and diseases is presented on the web pages of the UK Plant Health Risk Register (DEFRA 2019). A novel approach used in surveillance and monitoring of new pest and diseases in GB has been the use of plant health citizen science projects such as OPAL (Opal Explore Nature 2022) and Observatree (2022).

Landscape

GB has a highly fragmented forest resource (De Albaquerque & Rueda 2010, Fuentes-Montemayor et al. 2012) and has a small proportion of ancient woodland, important for conserving biodiversity. Landscape ecology principles need to be applied (Bailey 2007, Fuentes-Montemayor et al. 2012) and developing habitat networks has been acknowledged as being crucial to conserving biodiversity in semi natural woodlands (Welsh Assembly Forestry Commission 2006, DEFRA 2011, Scottish Government 2013). Petrokofsky et al. (2010) con-

Tab. 3 - Potential forest management and silvicultural interventions to increase resistance and resilience. These are cross-referenced to the five main threats identified in Moffat et al. (2012). (1) Pests and diseases, (2) changes in productivity, (3) increased drought, (4) forest fires and (5) wind.

Genetic	Maintain genetic variation within species (EUFORGEN) (1, 2) Adoption of provenances suited to new climates (eg Sitka spruce - Washington provenances) (1, 2) Develop tree populations resistant to pests and diseases (inc use of genomics eg ash) (1) Genetic improvement and modification (*e.g.*, elm/ Abertay university - American chestnut) to resist new pests and diseases (1)
Species	Increase range of species and provenances used in forestry (1,2) Assisted migration of species (2) Development of hybrids with desirable characteristics of both parents (1, 2, 3)
Stand	Increase use of mixed species stands (1, 2, 3, 5) Increase use of mixed age stands (1, 2, 3, 5) Use of low impact silvicultural systems (1, 2, 3, 4, 5) Modify thinning regimes (1, 2, 3) Underplanting of sensitive tree species (2, 3) Shorter or longer rotations (2, 3, 5) Cultivation methods to improve soil moisture availability (3)
Forest	Diversified ages and species across forests (1, 2, 3, 4, 5) Fire control measures (4)
Landscape	Larger contiguous blocks of forest in the landscape (2, 3, 4) Enhancing connectivity (Mention TOW research) (2)
National	Measures promoted in the UKFS and the UKWAS (1, 2, 3, 4, 5) Enhance control of introduction of damaging forest pests and diseases (1) Expansion of forest area (2, 3, 4)

ducted a survey of 481 researchers, policy makers and woodland owners and the third priority research question in the top ten was increasing knowledge of designing planting schemes to improve landscape connectivity, after pests and diseases and fostering better understanding between society and the forest sector.

In Britain a planning system for forest habitat networks has been designed by Forest Research, the Biological and Environmental Evaluation Tools for Landscape Ecology (BEETLE – Watts et al. 2005) and has been used to identify forest habitat networks, for example across Scotland (Forest Research 2021a). Furthermore, criteria for allocation of establishment grants considered the impact of new planting on forest connectivity and size (Scottish Government 2016, Forestry Commission England 2017). Non-governmental organisations have also been active. The Woodland Trust, through their Treescapes project seek to identify areas in GB where they can work with multiple partners to affect a large-scale increase in woodland and connectivity within landscapes (Borrill 2017). Furthermore, The National Forest Company has recently conducted a Geographical Information System (GIS) based exercise to identify habitat networks and areas where interventions would improve connectivity at a landscape level (Ordnance Survey 2017).

Forest

Risk of damage can be reduced across a forest by creating a mosaic of stands of different ages (O'Hara & Ramage 2013) and species (Natural Resources Wales 2017). Forest design guidelines for Great Britain encourage the diversification of ages of trees across forests (Bell 1998), while the UK Forestry Standard discourages felling of adjacent coupes until the neighbouring stand reaches a height of 2 m and recommends phased felling across an even-aged forest. Furthermore, it also encourages moderate diversification of tree species across a forest (Forestry Commission England 2017).

ACC is predicted to increase the frequency and severity of wildfires particularly in the southeast of England (Brown et al. 2012). An analysis of the current measures to counter wildfires identified a need by Fire Rescue Services to give wildfires a higher priority and to focus more on prevention measures (Moffat & Gazard 2019). Recently a specific guide on increasing resilience of woodlands to wildfire was published by the Forestry Commission (2014b), while a specific risk assessment template for wildfires has also been made available online (Forest Research 2019a). In 2022 four online vegetation fire training modules have been released aimed at developing skills and knowledge of land managers (LANTRA 2022).

Stand

As a forest stand develops there are interventions that improve resistance and resilience including altering rotation length, which influences not only financial returns but social and ecological values of forests (Roberge et al. 2016). Extending rotations has been shown to improve the value of provisioning, regulating, supporting and cultural ecosystem services and particularly for biodiversity conservation in Sweden (Roberge et al. 2016). However, a review of evidence (Barsoum et al. 2016) indicated that the link between rotation length and biodiversity was complicated. Kolström et al. (2011) note that there are two potential but contradictory strategies for adaptation to ACC; employing natural regeneration coupled with longer rotations or using highly selected genetic material on intensive, short rotations. Short rotations limit the temporal effect of climate change and allow rapid introduction of better adapted tree genotypes. However, there is currently limited experience of short rotation forestry in GB (McKay 2011) and the focus of research has been on biomass production rather than adaptation. In contrast longer rotations enable low intensity silviculture using natural regeneration which allows adaptation to take place in populations *in situ* and maintains the forest microclimate. Shortening rotations is likely to reduce the risk of damage from wind, at a landscape scale (Valinger & Fridman 2011) and from pests associated with older, larger trees, however it is also likely to reduce the value of many ecosystem services and increase the risk for pests linked to regeneration and early establishment (Roberge et al. 2016).

In terms of adaptation to climate change, extending rotations of even aged stands will generally increase the risk of wind damage but reduce that of fire damage. This is because across a forest there will be fewer sites recently clear felled and so less brash and other flammable harvesting residues. In GB, wind limits rotation length as it is a serious hazard to stands in the uplands. To aid decision making, a prototype model has been developed for GB that integrates carbon sequestration and substitution, financial return and wind risk (Saraev et al. 2017). Extending rotations will decrease the risk from pests and pathogens associated with forest regeneration and increase risk of damage from pests associated with later stages in stand development (Roberge et al. 2016), such as bark beetles (Keskitalo et al. 2016).

Mixed stands in Great Britain cover a very wide range of structure and composition, from single-aged mixed clone plantations of poplar (*Populus* spp.) to the diverse species and multi-aged structure found in some ancient semi natural woodlands. O'Hara & Ramage (2013) reviewed the role that multi aged forests could have in reducing the risks from damaging disturbances. They argued that such stands are as productive as monocultures, resist disturbance more effectively, are capable of better maintaining ecosystem services, and rebound more rapidly from disturbance. There is evidence for mixed species stands increasing resistance to pests and diseases (Guyot et al. 2016). However, to gain the greatest benefit, the mixes should be of unrelated species (Körner 2005, Scherer-Lorenzen et al. 2007, Tobner et al. 2014). For example, Wilson & Cameron (2015) recommend that, to increase resilience in upland Sitka spruce plantations, they should not be mixed with other spruce species. Sitka spruce is preferred by softwood processors in GB and a mixed stand would allow the manager to choose between a final crop of spruce, a final crop of the other conifer or a mixed final crop. This approach would lower the risk to growers of complete loss from a catastrophic pest or pathogen outbreak on Sitka spruce (Wilson & Cameron 2015); a recent study by Tuffen & Grogan (2019) identified 1,378 potential pest species of Sitka spruce. Such mixtures could also be useful in the lowlands when diversifying the tree species planted in Britain by ameliorating the microclimate for cold sensitive species, such as walnut (*Juglans regia* – Clark et al. 2008), allowing them to be established across a wider range of sites. Mixtures of trees that provide alternate hosts to a pathogen, such as larch (*Larix* spp.) and poplar (*Populus* spp.) for the rust *Melampsora larici-populina* should be avoided (Lorrain et al. 2018). However, gaps exist in our knowledge and understanding. There is a need to develop scientifically tested combinations of species for particular sites and objectives. For example, increases in productivity through mixing species tends to decline with site quality (Toïgo et al. 2015). Also, certain mixtures have been found to be less resilient to damaging climatic conditions, such as drought, than monocultures of the same species (Ovenden et al. 2022). There is also a lack of experience of establishing mixed species stands in the forestry profession, although a useful tool has been developed to improve decisions about species to combine in mixtures and planting patterns (Forest Research 2023).

Thinning is a useful tool for manipulating competition between trees and altering the microclimate within a stand. A meta-analysis undertaken by Sohn et al. (2016) showed that under drought stress there were beneficial effects on growth from moderate to heavy thinning in broadleaves and conifers. Thinning has also been applied to reduce damage by pathogens (Roberts et al. 2020); for example, in stands of pine (*Pinus* spp.) in GB infected by *Dothistroma septosporum*. The increased air flow and lowered humidity provides less suitable conditions for the pathogen (Brown & Webber 2008). The use of thinning and prescribed burning is also effective in reducing damage to stands by wildfires (Ritchie et al. 2007).

Close-to-nature forestry has a long history with it being applied to commercial forests in parts of Europe, on limited scale from the 19th century (Pommerening et al. 2021). Recently, there has been an increase in interest in close-to-nature forestry (Schneider et al. 2021). In Europe it is an element of the EU Forestry Strategy for 2030 (Larsen et al. 2022) with guidelines to its application being published in 2023 (EC 2023). Across Europe between 22% and 30% of forest is managed in this way (Mason et al. 2022). In GB also there has been growing interest in an aspect of close-to-nature forest management, the use of "continuous cover forestry" (CCF – Mason et al. 2022). This is defined (Mason et al. 1999) as "silvicultural systems whereby the forest canopy is maintained at one or more levels without clear felling" (clearfelling is defined as the felling of all trees on an area of more than 0.25 ha). There is a presumption in the UK Woodland Assurance Scheme (UKWAS) that forest managers will expand the use of CCF in windfirm areas (UKWAS 2018) and Malcolm et al. (2001) estimated as much as half of upland conifer forests in GB could be managed using CCF. Despite this, uptake remains low, with only 2-3% of forest stands in GB being managed in this manner (Wilson 2013), although 10% of the state forest area is CCF (Forest Research 2020a). Barriers to adoption of CCF have been identified, including perceived higher costs of management, lack of experience and variability of product outputs that reduce management efficiency (Helliwell & Wilson 2012, Wilson 2013, Vítková et al. 2014). Mason et al. (2022) describe further constraints to expanding adoption which include lack of knowledge and experience in the sector, high deer populations and a sawmilling sector focused on processing uniform material.

Brang et al. (2014) support the use of CCF in enhancing adaptation of stands to climate change as they exhibit increased tree species diversity, greater structural complexity, greater genetic diversity, increased resistance in individual trees to abiotic and biotic stress, substitute for high risk stands and maintain high levels of growing stock (Stokes & Kerr 2009). Furthermore, multi-aged stands provide more options, especially in a future environment where disturbances are likely to become more frequent and less predictable (O'Hara & Ramage 2013). Furthermore, CCF may be promoted by use of natural regeneration becoming more popular as a results of withdrawal of financial support for restocking in England and Scotland (Forest Research 2019b) and multi aged forests may better meet the needs of many woodland owners, who rank commercial value very low as an objective for management (Hemery et al. 2015).

There is considerable experience of cultivation treatments in the uplands (Paterson & Mason 1999) and lowlands (Willoughby & Moffat 1996) of Britain. However, there is limited experience of successfully establishing trees in dry conditions. For those areas in Britain where summer moisture deficits are predicted to increase there may be opportunities to improve soil water conditions through cultivation and other soil treatments. These include water harvesting structures, tillage to improve infiltration and planting in sunken pits or furrows. A description of a range of methods can be found in Critchley & Siegert (1991) that could be adapted to enable tree species to be planted in areas with what would normally be insufficient precipitation.

Tab. 4 - Recent initiatives to increase tree species diversification in Great Britain.

Trials	REINFFORCE: Resource Infrastructure for monitoring and adapting European Atlantic Forest under changing climate. International set of trials comparing performance of over 40 tree species and provenances across different soil and climatic conditions on sites with over 20 degrees latitude variation from Portugal to Scotland (Prieto-Recio et al. 2012). The early results from these trials and a set of additional trials established at the same time have been presented in Reynolds et al. (2020). In 2016 funding was made available for Forestry England and Forest and Land Scotland to establish eight trials using large scale plots of 20 tree species considered to have potential (Willoughby & Peace 2019).
Online databases and decision support systems	ESC provides recommended species for specific sites both under the current climatic conditions and under future predicted climates (Forest Research 2021c).
	Climate Matching Tool: Matches future or current climate of locations in the UK with those in Europe and the Pacific northwest America (Forest Research 2021b).
	SilviFuture: An online database has been developed to make accessible information on the location and performance of stands of novel tree species (Silvifuture 2019).
Sources of information on alternative species in print or online	Royal Forestry Society Species Profiles Project: Profiles of minor tree species with potential are published in the Quarterly Journal of Forestry and then made accessible online (Royal Forestry Society 2019)
	Forest Research tree species web pages: Brief profiles of over 60 tree species with future potential for planting in Britain (Forest Research 2019c).
	Minor conifers projects have produced useful publications; which are available online such as Wilson (2011), focused on Scotland and Ramsay & MacDonald (2013) which has a wider scope.

Underplanting offers a tool to regenerate stands and facilitate a change in species including the planting of tree species that would not thrive in the harsher conditions of a clear fell. Examples include the planting of a variety of shade tolerant species under Corsican pine, affected by *Dothiostroma septosorum* at Thetford and at Sherwood Forest (Kerr & Haufe 2016).

Species

ACC is likely to alter the range of tree species that can be established in Great Britain (Ennos et al. 2020), with areas in the southeast predicted to become Mediterranean (*i.e.*, prolonged summer droughts) by 2080 under a high emissions scenario (Ray et al. 2010). Much of the work in GB on future species suitability has used the Ecological Site Classification (ESC) which predicts suitability of a range of tree species based on climatic and soil variables (Ray 2008a, 2008b, Ray et al. 2010). ESC is described in detail in Pyatt et al. (2001) and has been adapted from predicting current tree species suitability to assessing future suitability under different climate change scenarios. An example of its application is an analysis by Broadmeadow et al. (2009) of tree species suitability in different parts of Great Britain. By 2080 of 28 tree species examined, the suitability of 20 was predicted to increase in central Scotland under a high emissions scenario. This contrasted with the situation in southeast England where there was a general decline in productivity and even the one remaining productive conifer species was categorised as being "unsuitable". However, ESC only considers physical attributes of a site and does not incorporate biotic factors. Changes in site conditions may increase the risk of pest and diseases becoming more damaging. For example, the suitable range for Corsican pine in GB was predicted to increase by ESC (Broadmeadow et al. 2002) but it is no longer planted due to damage from *D. septosporum* (Brown & Webber 2008). A more recent tool developed by Forest Research allows matching of future UK climates to current areas of Europe or northwest America and *vice versa* (Forest Research 2021b).

Changing climate will affect tree species to varying degrees (Park et al. 2014) and so adopting a diverse portfolio of species or provenances will reduce the risk of catastrophic damage from climate change or introduced pests and diseases (Hubert & Cottrell 2007). Santamour (1990) has proposed a general rule to reduce risk in urban forestry which states that no more than 10% of trees should be of one species, no more than 20% should be of one genus and no more than 30% should be of one family. Clearly the forests of Great Britain do not conform to these thresholds, nor might such thresholds be practical in forestry given site and silvicultural constraints.

Widening the portfolio of tree species, genera, and families available to forestry in GB will reduce the risk of catastrophic damage. One of the most informative sources on silviculture of minor forest species remains the Forestry Commission publication, Exotic Forest Trees in Great Britain (MacDonald 1957), as it was written before the selection of the current, narrow portfolio of commercial species. There has been a significant expansion on information and research on minor forest tree species in GB. These are described in Tab. 4. While these initiatives and others provide information and guidance on attributes of minor forest tree species, diversification has been slow, with particularly poor uptake in privately owned forests (Lawrence & Marzano 2014).

Native trees are favoured for planting for conservation and under ACC there needs to be pragmatism about what constitutes a native tree. Brown (1997) and Spencer (2015) suggest that "native" is best defined at a European level, while the Forestry Commission guidance for managing native woodlands also takes a broad view and includes the concepts of "advancing native" and "honorary native" tree species. Advancing native species are ones that were not locally native, but which were native to other parts of Britain and may be suited to areas outside their natural range due to climate change (Forestry Commission England 2010). An honorary native is a tree which is an exotic in Britain, but native to northwest Europe and which is likely to be well adapted to the future climate of Britain, for example sweet chestnut (*Castanea sativa* – Forestry Commission England 2010). Nonetheless, this approach may not be politically acceptable or meet with current conservation policies, such as those of the Woodland Trust which is focused on protecting and promoting native woodlands.

There are opportunities to develop better adapted trees through hybridisation. An example is *Picea* × *lutzei*, a hybrid of Sitka spruce and *Picea alba* which has shown some promise in trials (Stokes & Martin 2016, Stokes et al. 2018). The aim was to create a tree that is more drought tolerant than Sitka spruce but which retains its attractive properties.

Genetic

To maintain resilience within tree species, genetic diversity, particularly adaptive genetic diversity should be maintained as this provides potential for adaptation to new habitat conditions and a wider genetic base for tree improvement initiatives (Cavers & Cottrell 2015, Ivetic et al. 2016). Conserving genetic variation in tree species is best achieved through international cooperation across a tree species' natural range, such as through the European Forest Genetic Resources Programme (EUFORGEN) which aims to develop a pan European network for the conservation of genetic resources of native trees. Currently there are 34 countries involved (Kelleher et al. 2015) and while focused on 14 pilot tree species, 80% of the conservation units are concentrated on five economically important species (*Abies alba*, beech, Norway spruce, Scots pine and sessile oak – De Vries et al. 2015). To date 12 conservation units have been established in the UK across six native tree species (EUFORGEN 2021).

Climate change outpaces the ability of trees to migrate to suitable new habitats. Whittet et al. (2016) suggest three possible strategies: the currently adapted strategy, the predictive provenancing strategy and the species change strategy. The currently adapted strategy recommends using the current origins found on a site as forest trees are known to have high levels of genetic diversity and furthermore the seed zones used in GB, particularly in upland areas that cover a wide range of climatic conditions (Whittet et al. 2016). The predictive provenancing approach matches origins with the predicted warmer future climates. This is known more commonly as assisted migration and involved moving species or populations to new locations, better suited to their requirements (Hällfors et al. 2014). In Europe, this has been identified as a means of reducing but not preventing the impact of ACC on forests and the services they provide (Mauri et al. 2023). This approach has also been recommended in England and includes using origins from warmer locations, between 2° and 5° south, with the provisos that the further south they originate the greater the risk of poorly matching current climate (Forestry Commission England 2016) and that the origins should also be well adapted to edaphic and biotic conditions (Whittet et al. 2016).

An analysis of productivity of Sitka spruce provenances has shown that gains in yield can be made on warmer sites in GB by using material from more southern latitudes in Washington rather than Haida Gwaii (formerly called the Queen Charlotte Islands), the provenance currently used (Ray 2008a). The species change strategy is appropriate where the change in climate is too extreme to allow the productive use of the desired species or where an exotic pathogen threatens the extermination of a tree species. Under high emissions climate change scenarios most of the species currently climatically suited to areas such as southeast England are predicted no longer being suitable (Ray et al. 2010).

Genomics enables identification of and screening for genes in a species that confer desirable traits, and there is likely to be a trend towards it and away from phenotypic selection in tree improvement (Grattapaglia & Resende 2011). Genomics has been used recently in Europe to identify individuals of ash that are resistant to ash dieback (Boshier & Buggs 2015, Harper et al. 2016) which could form the basis for breeding resistant populations (McKinney et al. 2014) as resistance is highly heritable (Telford et al. 2015). The Living Ash Project, a UK initiative has used citizen science to identify potentially resistant ash trees and genomics to confirm the genetic basis of this resistance (Living Ash Project 2021). Another advance in genetic technology that could be used to create more resistant and resilient forests is genetic modification (GM). While normally associated with improving traits of intensively managed tree species, GM also has a role in conserving native tree species (Adams et al. 2002). GM has been used in Britain to develop English elms (*Ulmus procera*) that are resistant to Dutch Elm disease (*Ophiostoma novo-ulmi* – Gartland et al. 2005).

Discussion and Conclusion

This review describes many practices focused on developing resistance and resilience of forests in GB and these are supported by policy statements or initiatives. Foremost is the UKFS (Forestry Commission 2003) and the associated certification standard, the UKWAS (2018). Recently, in 2015 the Climate Change Accord: a Call for Resilient Forests, Woods and Trees was launched, describing a broad vision, endorsed by a wide range of organisations in the public, private and charity sectors. This document outlined a vision for adaptation supported by a series of action statements by different organisations focused on increasing resilience and resistance in UK Forests (Climate Change Accord 2015). Progress is monitored through regular meetings. More recently, the Tree Health Resilience Strategy for England was published in 2018 (DEFRA 2018). This presents a set of environmental goals involved at maintaining tree health at different scales and behavioural goals focused on changing behaviours and practices. As such there is a strong policy framework in GB to support increasing the resistance and resilience of forests to threats.

Despite the supportive policy, expanded research base, accessible tools and other support for adaptation, there remains slow change. A study by Hemery et al. (2015) assessed the awareness, action and aspirations of woodland owners in meeting the measures recommended in the UKFS for adaptation of forests to increase resilience and resistance to damaging agents. The study found low alignment between adaptation measures in the UKFS and the actions taken by woodland owners. The weakest areas related to forest planning with little contingency planning for the effects of damaging agents, a lack of projection of impacts of climate change on future suitability of tree species and also on forest infrastructure such as roads and culverts. A more detailed study of woodland owners (Ambrose-Oji et al. 2019), ranging from small woodland owners with an ecocentric view to management to large-scale commercial timber producers found quite different responses to forest resilience between these groups. While those with an ecocentric view were relying on natural processes and limited intervention to provide resilience, large scale commercial managers remained focused on planting large-scale monocultures of Sitka spruce despite the risk due to the superior returns and market acceptability provided by this species.

An update of Hemery et al. (2015) in 2020 showed that there had been an increase of awareness in woodland owners to environmental change and that observations of impacts in woodland had increased (Hemery et al. 2020). However, many forests in GB are not actively managed and for those that are, adherence to the UKFS and quality of long-term planning was low, with 69% not having a UKFS compliant management plan (Hemery et al. 2020). There is therefore a need to develop a framework of policy instruments that encourages woodland owners to improve their short- and long-term management of their woodlands. Young et al. (2018) identified a need in GB for a collaborative process to develop an overall vision and to create a toolbox aimed at enhancing forest resilience for a range of different ownership and forest situations. An aim of the recent England Trees Action Plan is to develop a Woodland Resilience Improvement Plan (DEFRA 2021) which will provide an overarching framework for promoting forest resilience in England.

Siedl et al. (2016) discuss the basis for long term resilience planning. They described the elements of this approach which included broadening objectives of management, using interventions that are likely to be successful across a range of potential outcomes and considering disturbance as an opportunity. Part of this multi-option approach to forest management involves adaptive forest management. Forest managers have traditionally operated in a predictable environment, with a limited number of objectives applied using hierarchical, science based and rational planning systems (Buizer & Lawrence 2014). Today, a wider range of management goals combined with an unpredictable future means approaches are required that incorporate assessment of risk and outcome, use of initiative, flexibility, innovation, and exchange of information (Millar et al. 2007, Lawrence 2017). One response to this uncertain future is provided by adaptive forest management which involves a dynamic approach to decision making where management actions are methodically designed as experiments. These are used to determine the effect of management on a system's response to a disturbance and thereby improve future management effectiveness in increasing resilience (Murray & Marmrek 2004). There are a variety of variations on adaptive forest management (Lawrence & Gillet 2011, Fuller & Quine 2016) but they all incorporate certain elements in common. Fuller & Quine (2016) describe six steps in their "Resilience Implementation Framework": (i) defining the components of the system; (ii) identifying threats to the system; (iii) deciding what changes to the system are acceptable; (iv) identifying the components of resistance; (v) selecting appropriate management interventions; and (vi) introducing monitoring and learning from experience. If the new intervention was unsuccessful then the process begins again. There are few examples of this type of approach being adopted in GB (Lawrence & Gillet 2011) and a case study from GB on the Bradford Hutt system is presented by Kerr et al. (2017).

In conclusion, many policies, initiatives, management tools and proposed changes to practice have been developed to increase the resistance and resilience of forests in GB to ACC and the damaging effects of exotic pests and diseases. However, there is a disconnect between this support and the behaviour of woodland managers towards improving resilience of their forests. Many woodlands in GB are undermanaged and where long-term management plans are in place, they are often not compliant with the UKFS, including the elements that are directed at adaptation. Potential solutions range from developing contextualised policy instruments to changing the way in which forest managers structure their decision making to test new approaches, increase flexibility and accept a wider range of outcomes.

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