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8. Risks for woodlands, forest management and forestry production in the UK from climate change

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Summary

- The frequency of extreme weather events, including heat waves, intense rainfall, and drought will increase over this century *(Likelihood: very likely / Confidence: high)*

- Trees, forests and woodlands in the UK will increasingly be vulnerable to the impacts of these extreme events. *(Likelihood: very likely / Confidence: high)*

- There is evidence of increasing storm frequency and intensity over the last century, but uncertainty in how climate change might influence future wind risk. (Likelihood: likely / Confidence: high)

- Wind damage to forests has increased across Europe over the last 50 years, and may double this century, but this is mostly attributed to increasing growing stock. *(Likelihood: very likely / Confidence: high)*

- A higher frequency of wildfires in the last decade has increased damage to forests and woodland. *(Likelihood: As likely as not / Confidence: low)*

- Wildfires are expected to have an increasing impact on forests and woodlands this century. *(Likelihood: likely / Confidence: medium)*

- Effects of climate change can be seen in tree phenological changes, especially earlier bud burst, making some species increasingly vulnerable to spring frost. *(Likelihood: likely / Confidence: high)*

- Increased rainfall and resulting soil inundation and flooding has resulted in increased forest damage, erosion and landslides. *(Likelihood: likely / Confidence: medium)*

- Management of the public forest estate is changing in an attempt to reduce the impacts of extreme events, pests and disease. Uptake of adaptation measures is however uneven across the sector as a whole. *(Confidence: high)*

- Climate change impacts need to be taken into account in managing all parts of the forest-wood chain. The extent to which this is happening is unclear from the literature, especially in forest nurseries and sawmills, and an assessment of the resilience of the whole UK forest industry is needed.

- Ongoing changes to forest management will have multiple benefits to society, including an improved resilience of urban areas and infrastructure to extreme events, such as protection from floods and landslides, and improved sustainability of the rural economy. *(Likelyhood: likely / Confidence: high)*

Introduction

Climate projections indicate an increasing frequency of extreme weather events this century. These are defined as events at the edges of the range of weather experienced in the past, and include heat waves, intense rainfall, and drought (UKCP09, Murphy *et al. 20*09). Extreme events experienced over recent years have had, and continue to have, large detrimental effects on forest health, ecosystem services and the economy. Examples include losses through windthrow in severe storms, wildfires in hot dry springs and summers, and prolonged rainfall leading to waterlogging, flood damage, erosion and landslides. The impacts on forests of extreme events are expected to increase substantially as the climate changes, but Lindner *et al.* (2014) warn that the potential impacts on forests have so far been underestimated in most studies. Extreme events have the potential for wide-scale, and increasing, disruption to forest operations, timber supply, carbon stocks, and the range of ecosystem services provided by forests and woodlands to society (Gardiner et al. 2013, Petr 2014). This paper reviews current observed impacts, trends and projected impacts, resulting from extreme events, and changes in abiotic risks to forests and woodland in the UK that are expected this century. The focus here is towards productive and urban forests, but impacts on woodlands providing other ecosystem services are included. Biotic threats to forests, other than from competition by weed species' are not explored here, except where they interact with abiotic threats, as these are covered in the companion LWEC evidence papers on "Effects of insect pests and pathogens on UK forestry with climate change" (Webber, Denman and Green 2016; and Wainhouse and Inward 2016). Nor does this paper examine the direct impacts of the changing climate on tree growth and woodland ecosystem services, or on the natural adaptation of species – these are addressed in the companion LWEC evidence papers on impacts of climate change on tree and stand growth and productivity (Lukac 2016), and on forest ecosystem services and climate change (Ray *et al.* 2016).

Method

The literature reviewed in compiling this paper was sourced based on searches using the Scopus Abstract and Citation database (Elsevier 2015), Google Scholar, and other literature sources available to the author, including the Forestry Commission Library Service. The literature searches were designed to identify published literature that would help answer the following questions:

- What are the impacts of extreme events on forests and woodlands?;
- What are the impacts of climate change on land capability and availability for forestry?;
- What are the risks from climate change related changes in performance of competing vegetation and invasive plant species?;
- What are the impacts of climate change related risks on operational aspects of forestry, nursery production, whole-chain processes, and on urban forestry and woodland?

Search strings constructed to support these research questions included *forest* OR *woodland* OR *tree* AND *"climate change"* with the following terms and phrases: *"abiotic risk"*; *threat* ; *impact*; *"extreme event"*; *"land capability"*; *"invasive plant"* OR *weed* OR *vegetation*; *"forest operation"*; "*nursery production"*; *"wood chain"*; *urban*; and *arboriculture*. Sifting of search results by the author focussed on literature relevant to British Isles, UK, GB, England, Scotland and Wales published between 2000 and 2015. Relevant literature was included from earlier years, and from elsewhere if relevant and where there was insufficient literature focussed on the UK. In addition, 'grey' unpublished literature was included when it was known to, or could be located by, the author.

Impacts of Extreme Events

Drought

Current climate projections (UKCP09) indicate a high probability of more frequent hot and dry summers in much of the UK (Murphy *et al.* 2008), especially towards the south and east. Summer drought events cause serious and wide-spread damage to UK forests and woodlands. Severe soil water deficit can lead to reduced tree growth and sometimes death. As an example, a study by Green and Ray (2009) identified 288 medium or high drought risk forest sites in eastern Scotland, 125 of which include Sitka spruce as a major component. A drought event in 2003 caused severe damage to Sitka spruce in northeastern Scotland, leading to 14–20 % mortality at some sites (Green *et al.* 2008).

Drought causes xylem collapse in trees, leading to stem lesions and cracks in the cambium (Green and Ray 2009). Drought-induced stem cracking is a common problem in spruce (Cameron 2015) fir, and oak and considerably reduces the value of timber, as the defects make it unsuitable for structural use in its raw form (Price 2015). Drought also increases the vulnerability of trees to damage by pests and diseases (Green *et al.* 2008; Anderegg *et al.* 2015). For example, Netherer *et al.* (2015) demonstrated that the defence capability of droughted Norway spruce decreased as twig water potentials became increasingly negative and resin exudation decreased. Drought stressed trees also become more susceptible to common tree root diseases including *Armillaria* spp. and *Heterobasidion annosum* (Lindberg and Johansson 1992, Sangüesa-Barreda 2015; see also the companion LWEC technical paper “Insect pests and pathogens of trees”, Section A on insect pests (Wainhouse and Inward 2016), and Section B on pathogens (Webber, Denman and Green 2016)). Forests may be expected to show increasing mortality in response to changes in drought severity and frequency this century, even in locations not previously considered to be vulnerable to drought. This risks the maintained provision of a range of ecosystem services from these forests, including a potential reduction of forest carbon sequestration (Allen *et al.* 2010).

Increasing drought frequency is expected to lead to increased physical damage to trees, reduced growth and productivity, and susceptibility to more frequent and widespread disease in forests and woodlands (Read *et al.* 2009). The decision support tool ‘Ecological Site Classification’ (ESC) developed for forest managers in the UK (Pyatt *et al.* 2001) can be used to show where tree growth will be limited by soil moisture deficit (the monthly maximum accumulated excess of evapotranspiration over rainfall in the summer months) in future climate scenarios, and where drought-susceptible species would no longer be expected to be suitable. Increasingly, ESC is capable of assisting with selection of suitable species for establishment, taking into account the current and projected future site and climate conditions (Ray *et al.* 2014). An ESC analysis of drought risk to three major tree species grown across the UK (Petr *et al.* 2014) found that drought would result in reduced tree growth over the next 80 years using B1, A1B, and A1FI IPCC emissions scenarios. Potential production across the public forest estate for these species was estimated to decrease due to drought by the 2080’s by 42% in the lowlands and by 32% in the uplands, in comparison with the baseline climate (Petr *et al.* 2014). However, despite their applicability, decision support tools including ESC have not been taken up uniformly across the forestry and related sectors. Improved interactions at the science–policy–practice interface may be needed to further increase the uptake of these tools by both public and private sector forest management (Stewart *et al.* 2014).

Extreme rainfall and flooding

Increasing impacts of flood events have been observed across Europe (Jongman *et al.* 2014), and climate projections considered along with expected socio-economic development, indicate that financial losses may be expected to double by 2050. In the UK, projected increases in winter rainfall, will lead to increased risk of flooding of infrastructure, including roads and rail, and urban areas (Kay *et al.* 2009). The economic and social impacts of increased flooding have been highlighted by severe flood events in recent years, especially those in England between 2012 and 2014 (Met Office/CEH 2014).

Forests are vulnerable to extreme rainfall events through an increased risk of landslides, erosion and rock falls, and an increased risk of windthrow to trees with waterlogged root systems (Norris *et al.* 2008). Wetter winters in the UK are expected to increase the frequency and scale of landslides and debris flows from vulnerable slopes, with associated increased disruption to transport infrastructure and society (Winter *et al.* 2009). However, forests and woodlands play a vital role in maintaining soil stability on vulnerable slopes during extreme rainfall events (Pimentel and Kounang 1998). Without the soil binding benefits of tree roots combined with the ground sheltering and rain interception functions of tree crowns, soil loss would be considerably greater (Norris *et al.* 2008). Aforestation of slopes is increasingly seen as an important part of a mix of actions to effectively reduce the risk of erosion and landslides on the most vulnerable slopes (Norris *et al.* 2008, Stokes 2010, Rayner and Nicoll 2012).

There are signs that forest management in parts of the UK is changing to help reduce the impact of flood events. Trees in riparian areas are increasingly being used to slow the flow of flood water, and reduce peak floods as they reach urban areas downstream (Nisbet *et al.* 2011). The impact of woodland on flood flows, depends on the interaction of several factors, including attenuation through the greater water use by trees, the ‘sponge effect’ of improved infiltration of down-slope woodland buffers, and the greater hydraulic roughness associated with riparian and floodplain woodland slowing the passage of flood waters (Nisbet and Thomas 2006).

Measures to improve natural flood management with expansion and management of riparian woodlands and adjustment of forest drainage schemes to reduce peak flows (Nisbet *et al.* 2011, Iacob 2012), have been developed. Such methods have been implemented in recent years in flood alleviation projects including ‘Slowing the flow at Pickering’ in England (Nisbet *et al.* 2015, and http://www.forestry.gov.uk/fr/slowingtheflow), and the Eddleston Water project in the Scottish Borders (http://www.gov.scot/Resource/0038/00387105.pdf). As most natural flood management schemes are relatively new, there is only limited direct evidence of their effectiveness in reducing peak flows (Iacob *et al.* 2012), however, detailed modelling exercises indicate that they will provide large downstream flood mitigation benefits and offer a means of tacking increased flood risk with climate change (Thomas and Nisbet 2007).

The increasing risk of windthrow of trees on inundated soils has potentially large economic and risk implications (Mason and Perks 2011) but these are difficult to quantify or model due to large variations in waterlogging extent and water table depths across forest stands (Quine *et al.* 1995, Mason and Valinger 2013).

Frost

Frost can result in shoot loss and reduction of tree growth (Hufkens *et al.* 2012), and repeated frost damage may lead to a considerable reduction in productivity (Redfern and Hendry 2002). Loss of leader shoots is detrimental to tree form and has an economic cost in terms of reduced timber quality (Macdonald and Hubert 2002). Young trees are particularly vulnerable to frost and may be killed (Broadmeadow *et al.* 2009).

Spring air temperatures are projected to rise across the UK this century (UKCP09, Murphy *et al.* 2009), and have already been shown to have had a strong effect on tree budburst dates. The link between air temperature and tree phenology has been demonstrated (see Sparks and Gill 2002, Broadmeadow *et al.* 2009, and Read *et al.* 2009 Figure 4.1), and, for example, leafing was reported to occur three weeks earlier in 2010 than 1950 in an oak trial at Ashstead, Surrey, corresponding with an approximate 1°C increase in mean air temperature over that period (Broadmeadow *et al.* 2009). Earlier budburst will make trees more vulnerable to damage from spring frosts, as the timing of the latest frosts have not changed in recent decades (Read *et al.* 2009).

Tree species vary in their response to temperature. Tree leafing on most temperate tree species respond to thermal forcing, so elevated spring temperatures result in earlier flushing (Fitter *et al.* 1995; Polgar and Primack 2011). But, some species are also sensitive to autumn and winter temperatures, with lower temperatures also associated with advanced bud burst (Murray *et al.* 1989; Polgar and Primack 2011). Therefore interspecific variation in the sensitivity of phenology to temperature means that the temperature increases projected this century would be expected to lead to advances in leafing in some species and delays in others; see the companion technical paper “Impact of climate change on UK tree growth”). In general, with reduced chilling, pioneer species (such as *Betula pedula*) are observed to advance in order of budburst, while climax species (such as *Fagus sylvatica*) show a relative delay (Laube *et al.* 2014).

Roberts *et al.* (2015) modelled future phenology of 13 tree species in the Marsham phenology time series of first leafing dates, on the basis of projected temperatures under the A1F1 scenario for 2010–2039 and 2040–2069. They found that the median first dates of all species are expected to shift relative to historic values, and several species with late spring phenology, including sweet chestnut, oak, beech, and ash, are predicted to advance their phenology considerably. By 2010–2039 the predicted median oak first leafing date will be 14 days earlier than historic records and by 2040–2069 it will be a further 10 days earlier. In contrast, species with early spring leafing that are most sensitive to chilling, including hawthorn and birch, are predicted to be delayed or advance less. This variation in phenology would be expected to make some tree species increasingly sensitive to spring frost while others may be expected so show little change.

Wind

There remains a high degree of uncertainty around wind climate projections and changes in storminess related to climate change (Lindner and Rummukainen 2013). Storm frequency and occurrence of extreme wind speeds do not show such clear signals as other aspects of the climate in model projections used in the UK. UKCP09 assumes that the average wind climate will not change significantly in the UK over this century. However, some modelling studies report a potential increase in frequency of damaging winds, expressed as reducing return periods, around the British Isles over the century, (Leckebusch et al. 2008; Della-Marta and Pinto 2009).

There is also now evidence that the wind climate is already changing in the UK. In a report on recent weather extremes in the UK, the Met Office stated:
“*A comprehensive study of trends in storminess, for the period 1871-2010 from an ensemble of reanalyses by Wang et al. (2013) provides some important insights. They show a robust signal of increasing numbers of strong winter cyclones and with increasing intensity for the high latitude North Atlantic, covering the region to the north of the UK and including Iceland.*

This is associated with a reduction in storminess further south and supports a wide body of evidence for a poleward shift of the Atlantic storm track. However, their analysis of changes in storminess further south over the mid-latitude North Atlantic – the path of the recent storms – suggests a more complex signal. Although the number of strong winter cyclones has not changed since 1871, the mean intensity has increased. Notably, for very strong cyclones, the mean intensity has increased significantly. A more comprehensive study of storms affecting the UK is needed to explore these findings in more detail, but the current evidence does suggest an increase in storminess" (Met Office 2014).

Wind damage to forests is a major problem across much of the UK and Europe (Table 1), and storms cause approximately half of all damage to forests (European Union 2010). Wind damage to forests and woodland occurs as uprooting or snapping of tree stems. Windthrow of trees is a natural disturbance to forests and woodlands, and in natural or close-to-natural woodlands it provides the benefits of maintaining structural dynamics, regeneration and diversity (Pontailler *et al.* 1997). However, in commercial plantations managed for timber production, windthrow reduces productivity of stands that are harvested following storm damage, and leads to loss of, or damage to, timber (see Table 1). In addition, windthrow disrupts forest operations, increases risks to operators especially on steep ground, and, following severe storms, oversupply can depress timber prices. Timber (Gardiner *et al.* 2013) and soil losses (Nicoll *et al.* 2005) following windthrow can be considerable, and windblown trees can be more dangerous to harvest (Quine *et al.* 1995), and pose a risk to infrastructure. Risks of wind damage to forests varies across the UK, with forests in the north and west, and at higher elevations being at most risk. There is some damage from storms during most winters in UK forests that are exposed to the highest wind speeds. Wind speeds that cause wider scale damage are of course less common and have longer return periods between occurrence, and the most extreme, catastrophic storms that cause extensive damage (such as the 1987 storm) typically have return periods of 100 years or more.

Date	**location**	**Damage (Million m^3)**
Oct 1987	S. England and N. France	11.5 (3.8 in UK)
Jan-Mar 1990	England, N. and Central Europe	110.0 (1.2 in UK)
Dec 1999	Central Europe and Scandinavia (Lothar/Martin)	193.0
Jan 2005	N. Europe (Gudren)	86.5
Jan 2007	Central Europe and Scandinavia (Kyrill)	54
Jan 2009	S.W. France (Klaus)	45

Table 1: Recent damage from major storms in Europe. More information on these and other damaging storms is provided by Gardiner *et al.* (2013).

Gardiner *et al.* (2013) reported that wind damage to European forests has increased considerably over the last 50 years and is expected to continue to increase, possibly more than doubling, this century. This projection is largely based on an increase in growing stock with increasingly large areas vulnerable to damage, but changing climate, especially increased winter rainfall and growing season temperature, is expected to further increase the severity and extent of damage (Gardiner *et al.* 2010, Schuck and Schelhaas 2013).

Many UK foresters do already take wind risk into account in planning harvesting age, thinning, and forest road building. Tools have been available for several decades to help with this. These include 'DAMS' windiness scores that can be used to inform decisions on suitability of stands for thinning or conversion to CCF, and ForestGALES (Gardiner *et al.* 2004; Nicoll *et al*. 2015), a decision support tool that replaced the older Windthrow Hazard Classification (Miller 1985) to aid decisions on timing of harvesting and thinning to reduce losses from windthrow (Hale and Nicoll 2015). ForestGALES is used by managers of commercial conifer plantations across both private and public sector forests (Stewart, *et al.* 2014), but uptake is not yet uniform and is greatest in the most wind exposed parts of the country, especially the north, and west, and where there are higher elevation forests. A limitation of this tool is that the current version can not provide estimates of wind risk to broadleaf species. A potential concern is that while foresters focus management to minimise damage from storms with <20 year return times, the growing forest estate is increasingly vulnerable to less frequent, but higher intensity, storms such as the 1987 storm that caused extensive damage in South England (Grayson 1989). Cameron (2015) proposes reducing this risk by normalising the age distribution of UK forests to create an approximately balanced distribution, from newly established stands to those with mature trees.

Wildfire

The UK Climate Change Risk Assessment (CCRA1) indicates that more frequent wildfires are expected over future decades due to warmer and drier conditions (DEFRA 2012). A projection of wildfire incidence in the UK over this century using the McArthur Forest Fire Danger Index suggests a 30-50% increase by the 2080s with the highest risk in the south of England (Moffat et al. 2012). Increased pest and disease problems increasing leaf/needle litter and deadwood amounts may also exacerbate the problem (Jactel *et al.* 2009).

Evidence from across mainland Europe (Schelhaas, *et al.* 2003) indicates that damage from wildfires is increasing. There is some, but limited, evidence in the UK of increasing numbers of wildfires over recent decades (CLG 2006) especially in drought years (McMorrow 2011). The impact of wildfires on forests is substantial and an analysis of Incident Recording System (IRS) statistics for Great Britain by Forestry Commission England shows that in the four financial years 2009/10 to 2012/13, over 211,000 fires burned an estimated 71,000 ha and required over 181,000 person hours to suppress (equivalent to 14 years 7 months). The proximity of many woodlands to urban areas and infrastructure means that forest wildfires pose a real threat to society, and following a particularly severe fire season in 2011 with 65,000 fires (Gazzard 2014), wildfire was added to the National Risk Register of Civil Emergencies (Cabinet Office 2013).

Wildfire can have profound effects, both positive and negative, on forest ecosystems (Johnstone and Chapin 2006) and the wildlife habitats and species where they occur (Moffat *et al.* 2012), however, the impact of fire on forests in the UK is almost always negative. Ray *et al.* (2010) states that increased frequency of forest fires would change the composition, structure and age profile of woodlands and will require new approaches to woodland management.

The Forestry Commission England Climate Change Risk Assessment (Forestry Commission 2012) describes the role of the Climate Change Strategy Group and the Climate Change Action Plan for the Public Forest Estate (PFE). This Plan uses PFE Forest Design Plans (FDPs) as the main instrument to improve habitat resilience, involving greater use of continuous cover management, planting for stands of mixed species and mixed age, and planning for forest fire and other risks (Forestry Commission 2012). However, despite this, Moffat and Pearce (2013) highlighted a relative unpreparedness for wildfires in the UK compared to other countries, especially in relation to risk reduction. A recent scoping study on risk assessment for forest fire at the rural-urban interface (Kazmierczak *et al.* 2014) included a wildfire threat analysis in a case study of South England. This demonstrated the potential to produce maps of ignition risk, and values at risk, across an area that have potential for use in forest and land management decisions.

The Forestry Commission has recently responded to increasing fire risk by releasing a practice guide for the forest industry (Forestry Commission 2014), aimed at building wildfire resilience, that uses a range of toolkits based on Forest Management Plan principles as described in the UK Forestry Standard (Forestry Commission 2011a), including wildfire risk assessment process and templates. Factors considered include: site location and climate; site topography; land use and vegetation type; weather; and forest and tree health. Wildfire resilience can be achieved through a number of forest management techniques, which should be considered during the forest management planning process. These are: managing vegetation and fuels; creating fire breaks and fire belts; improving forest design; building silvicultural resilience; planning for people, and planning for an incident response. Adoption of these good practice recommendations are expected to help reduce fire risks and improve forest resilience.

Impact on land capability and availability for forestry

There appears to be no current evidence in the UK of loss of area suitable for growing tree species due to the changing climate. However, projected changes in temperature and rainfall have major implications for the suitability and growth of tree species grown commercially across the UK (Hulme *et al*. 2002). The Forestry Commission Ecological Site Classification tool (Pyatt *et al*. 2001) can be used to examine the potential change in land area expected to be suitable for growth of tree species (Ray *et al*. 2002). Responses of trees to projected climate change, are expected to vary across the UK (Moffat *et al.* 2010). In east and west England, the area currently assessed as being ‘very suitable’ for commercially grown species will decline by 2050. Conversely in west and east Scotland, some commercial tree species show an increase in the area expected to be very suitable. The area ‘suitable’ for some tree species are expected to decline on a range of site types in the south of England and parts of east Scotland, largely due to increased drought stress (Moffat *et al.* 2010). Recommendations of how to adapt to this change have been developed, for example, Cameron (2015) recommends replacing drought stressed Sitka spruce in eastern Scotland with a range of more drought tolerant species. Increased flooding may be also be expected to lead to loss of tree species (Kramer *et al.* 2008) and a reduction of woodland cover in affected areas, unless measures are taken to introduce or encourage replacement with flood tolerant species (Vreugdenhil *et al.* 2006).

There is also little evidence of a change in the area of land available for forestry due to altered priorities for land use related to climate change. One current issue is the removal of trees to restore peatland and heathland habitats (Anderson *et al.* 2014) that is occurring in parts of the UK. This has largely been for conservation purposes (for priority species and habitats) as well as for GHG balance reasons in the case of deep peat areas (Moffat *et al.* 2012, Morison et al. 2012). Another indirect impact of climate change, the installation of wind turbines in upland forests, may also lead to loss of forested area. However, in Scotland where many turbines have been installed on upland forested land, the Scottish Government has developed a policy to minimise the net loss of forest area (Moffat *et al.* 2012). Conversely, recommendations related to the management of riparian areas for biodiversity, flood protection and other related ecosystem services, is expected to lead to a continued increase in land required for new native woodlands (Parrott and Holbrook 2006).

Risks from competing vegetation and invasive species

Projected temperature and precipitation changes this century are expected to lead to increased problems with weed species in UK forests. Vegetation that competes increasingly successfully with young forest and woodland trees will result in greater mortality (Aitken *et al.* 2008). However, weed species are already routinely controlled or managed as part of forest and woodland management (Ray 2008), so dealing with an increase would be expected to be within the capability of forest management. The risks of invasive plant species spreading more easily due to increased temperatures and humidity and precipitation levels, and out-competing young woodland or forest trees, remain a concern (Manchester and Bullock 2000, Moffat et al. 2014). In addition to the direct threat of competition, introduced, invasive species may potentially act as a reservoir for pathogens; a recent example being the transmission of *Phytophthora ramorum* from *Rhododenron ponticum* to *Larix* species in UK forests (Purse *et al.* 2013).

Impacts on operational aspects of forestry

Forest management

Forest management practice is changing in response to, or in anticipation of, climate change or climate change related risks and impacts. Such changes include:

- Altered stocking densities in response to tree health concerns such as *Dothistroma* needle blight on pines (Bulman et al. 2013), or in response to likely reduced rainfall,
- Changes in stand structure, such as transformation to continuous cover to improve resilience to a range of threats (Mason 2007),
- Reductions in rotation lengths due to increased growth rates or due to increased biotic and abiotic risks in some parts of the UK (Ray *et al.* 2010).

Impacts on forest operations may also be expected through increased winter rainfall restricting the ability to use machinery over more extreme winters (Broadmeadow and Ray 2005). Machine use on wet or saturated soils, as well as being considerably slower than on dry firmer soil, can lead to unacceptable damage (see “Forest and water guidelines” (Forestry Commission 2011b)). Good forestry practice on poorly-draining soils includes soil protection to prevent rutting, soil erosion and compaction damage, thereby preventing soil entering watercourses as a result of forest operations. The frequency and intensity of winter rainfall in the uplands of the UK under current climatic conditions already makes soil particularly vulnerable, but this is addressed by protecting soil using brash roads for forest harvesting machinery as specified in the Forest and Water Guidelines. Increased rainfall may lead to a reduced ability to harvest, thin, extract timber and cultivate for restocking (Ray *et al.* 2008) in the UK. However, the impacts of climate change are expected to be greater in countries where harvesting is commonly conducted on frozen winter soils, and where unfrozen winter soils will therefore limit the ‘window’ for harvesting operations (Venalainen *et al.* 2001).

Infrastructure

Management of the forest infrastructure appears to be changing in UK forests, both in response to extreme events, and with the aim of reducing green-house gas emissions (Mason *et al*. 2009, Dickerson *et al*. 2013). An example is an increase the size and number of drainage culverts under forest roads (Nisbet 2001, Forestry Commission 2011c) to reduce problems with forest road washouts and slope erosion that can lead to debris flows from forests onto neighbouring public roads and infrastructure. Recommendations for forest road construction and use now aim to minimise damage from vehicle trafficking and extreme weather and thereby minimise the need for repair and rebuilding (Dickerson *et al.* 2013).

Nursery production

Increasing tree species diversity to spread or reduce risks, and to introduce a component of species or provenances that are better suited for the projected future climate, are an increasing challenge for the UK forest nursery sector. This is on top of potential climate related problems of a shortened window for lifting stock, wetter winter conditions, drier growing seasons, and reduced opportunities for ‘back-end’ planting of bare-root stock (Ray 2008). However, nursery issues are often overlooked in forestry literature related to climate impacts and adaptation, and unfortunately many of the nursery issues raised by nursery managers and foresters appear not to be adequately documented.

Tree nurseries are now increasing production of a wide range of ‘alternative’ conifer and broadleaf species to supply expected demand, but constraints to commercial production include; lack of market certainty following a production process that may take 2 to 3 years (Ogilvie 2009), lack or shortage of seed supply from known or desired provenances (Hommel 2014), and insufficient knowledge in the trade of how to produce planting stock of these species. At the same time, nurseries are increasingly constrained by tree health issues and resulting restrictions (Ioras 2013). A striking example is ash seedling production in UK tree nurseries. Ash production had been increasing in recent years due to an emphasis on expansion and better management of productive native broadleaf woodlands (Forestry Commission 1994), but halted abruptly in 2012 due to the outbreak of *Chalara* in the UK (Defra 2013a). Constraints were placed on ash seedling movement (Plant Health (Forestry) (Amendment) Order 2012.), infected plants in nurseries were destroyed (Defra 2013a), and a revised policy to no longer support planting of ash was implemented (Forestry Commission 2013). Recommendations for replacing of ash with alternative species (Defra 2013a) put further pressure on tree nurseries to increase production of a range of other species, but again without the certainty of market demand in the future.

Successful establishment of nursery grown bare-root stock trees requires lifting and planting when trees are dormant (Morgan 1999). Whilst warming winters might be expected to limit the lifting and planting window, tree nurseries routinely store planting stock in cold stores to allow successful planting regardless of winter temperatures. However it is still necessary for plants to be lifted when dormant, so mild winters will tend to limit this (McKay 1997). Cell-grown planting stock can be lifted and planted outside the periods recommended for bare-root plants, and may have better survival rates (Leugner et al. 2009), potentially making them more suitable as planting stock as the climate changes.

Whole chain aspects

Decisions on forest and woodland management and operations, made by owners, managers and planners, ultimately affect operations in sawmills and the profitability of the timber industry. For example, moves to expand continuous cover forestry, to improve forest resilience and reduced risks, have an impact on log sizes that sawmills will be required to process, and will require replacement of equipment (Macdonald *et al.* 2010. Concerns over the risks to the limited range of commercial conifer species currently used in the UK is leading to diversification to a range of ‘alternative species’. Planting has increased of a number of species that were previously only present in small stands, or as specimen trees, but for many of these there is limited knowledge of the wood properties and product performance of their timber (Ramsay and Macdonald 2013). However, planting of these species is taking place in the absence of reliable information about their silviculture and the timber that will be produced when they are grown in UK conditions. As a result, recent reviews of suitability of these species for productive forestry (Wilson 2011) and their timber properties (Ramsay and Macdonald 2013) have been conducted, but all aspects require more detailed research. Trials have been established in England, Scotland and Wales, linked to similar mainland Europe trials to monitor the performance of a wide range of tree species from planting (see http://www.forestry.gov.uk/fr/infd-7ytc93). This will eventually provide information on the impacts of climate and biotic and abiotic risks on ‘alternative species’, but current evidence is limited. Clearly more trials of ‘alternative’ species will be needed (Willoughby *et al.* 2007), although the applicability of results from such trials are constrained by the time it takes to establish trees and assess their growth being on a similar time-scale to the climate change impacts themselves.

Impacts on urban tree species choice and woodland

Trees in urban areas will experience similar pressures and risks from climate change to those experienced in rural forests and woodlands, but they will sometime be exposed to greater extremes (Moffat 2015). In particular the urban heat island effect (Arnfield 2003) exposes urban trees to higher average and extreme summer temperatures than trees in non-urban woodland (Wilby 2003; Emmanuel and Krüger 2012). Kolokotroni and Giridharan (2008) reported up to 9 degree temperature differences between London inner city and rural reference sites. Also, water availability to trees is commonly limited in urban areas – especially to street trees - both where soils are poor or shallow with limited water capacity (Moffat 2015), and where rainwater is prevented from penetrating due to hard surface coverings and drainage systems (Randrup *et al.* 2001). These abiotic stresses will interact with biotic agents to have an impact on tree health and survival. Tubby and Webber (2010) reviewed potential climate change impacts on urban tree pests and pathogens and concluded that "*climate change is likely to lead to increased physiological stress in trees growing within urban areas that, in turn, will predispose trees to attack from a range of pests and pathogens. Climate change will also present a more favourable environment for many native and non-native organisms with the potential to cause harm*". This may already be having an impact on the health of urban trees, which in many towns and cities are characterised by an aging population of a limited number of species (Moffat 2015). For example, a case study in Edinburgh estimated that 15% (nearly 100,000) of the city's trees were in a critical condition, dying or dead (Hutchings *et al.* 2012). Responses to these impacts are typically replacement of trees showing signs of decline, rather than any proactive removal, and appropriate replacement or diversification. However when replacing urban trees, city planners and arboriculturalists do appear to aim to maintain or increase tree cover (Hall *et al.* 2012, Armson *et al.* 2013) while diversifying with species that are perceived to be both less vulnerable to pests and diseases and better suited to future climates (Moffat 2015).

Conclusions

The frequency of extreme weather events, including heat waves, intense rainfall, and drought is projected to increase over this century. There is evidence of increasing storm frequency and intensity, but uncertainty remains in how climate change might impact future wind risk to forests and woodland. Trees, forests and woodlands in the UK, with a predominantly ageing growing stock, at least in conifer forests, will increasingly be vulnerable to the impacts of wind. There is however some evidence of increasing impacts of aspects of the changing climate on trees. Effects of climate change can be clearly seen in earlier bud break, making some tree species increasingly vulnerable to spring frost damage. Increased rainfall and resulting soil inundation and flooding may be linked increased forest damage, erosion and landslides. A higher frequency of wildfires in the last decade may have resulted in increased damage to forests. However, the evidence is not strong for increased impacts to forests of increased rainfall or fire, and further analysis is needed. Although it is possible to describe likely effects of climate change on forestry, considerably more evidence will be needed before potential impacts of 2°C and 4°C warming can be compared. Clearly, a 4°C change would be likely to radically change the nature of forest growth and the forest industry in the UK.

Forest management is evidently starting to change in an attempt to reduce the impacts of extreme events, partly in anticipation of climate change. Changes include managing forests for fire and wind risk, by upgrading forest roads for resilience to extreme rainfall events, and by managing riparian areas to reduce downstream flood levels. Ongoing changes to forest management will have multiple benefits to society, including improved resilience of urban areas and infrastructure to extreme events, such as protection from floods and landslides, and by improving sustainability of the forest industry. Some forest and woodland managers are following adaptation guidelines provided in the UK Forestry Standard (Table 3). The emphasis is on implementation of measures to improve structural and species diversity, thereby reducing or spreading the risks.

Risk	**Climate factors involved**	**Observed / expected impact**	**Sector Response**
Drought damage	Reduced summer rainfall Higher summer temperature	Drought cracks / ‘shake’ Poor stem form/ timber quality Reduced timber quality – Reduced economic return	Species change e.g. less use of drought intolerant species in drier East Conversion to CCF and mixed species
Flooding and waterlogging	Increased rainfall	Woodlands increasingly used as part of natural flood management	Develop and implement natural flood management guidelines. Replacement with flood tolerant species.
Soil erosion / landslides	Increased storm frequency Increased rainfall Increased wind	Damage to infrastructure and urban areas	Develop protection forestry guidelines Risk assessment, removal of vulnerable trees, protect infrastructure with rock fall netting, tree topping, Encourage native woodland restoration on slopes to protect soil and protect infrastructure from landslides
Frost damage	Warmer winter temperature Warmer early spring temperature Maintained frost frequency	Frost damage to buds / shoots Poor stem form/ timber quality	Species change / avoid vulnerable species
Windthrow	Increased winter rainfall Increased storm frequency Increased windiness Increased air temperature	Faster growing trees reach vulnerable height sooner. Increased wind losses Damaged timber – reduced returns Increased operator risk	Species diversification, restricted thinning in exposed areas. Conversion to CCF Encourage understory development Implement wind risk DSS Implement contingency plans

Wildfire damage	Increased spring/ summer air temperature Reduced rainfall Increased fuel from insect / disease.	Reduced forest area Reduced production Risk to infrastructure and urban areas	Develop guidelines and implement contingency plans

Table 2. Summary of risks, impacts and expected sector responses

There are, however, many barriers to such changes, including a lack of confidence in climate projections and in the viability of options for adaptation (Lawrence and Marzano 2014, Lawrence 2015). Therefore, although climate change impacts will need to be addressed in all parts of the forest-wood chain, the implementation of adaptation measures appears to be uneven. (Hemery et al. 2015). Climate change impacts and adaptation may not always (or often) be reported as such, and the extent to which they remain hidden from the literature is not clear. There are, in particular, notable gaps in the literature on the impacts of climate change on forest nurseries and sawmills, as well as on rural employment. It is therefore important that the resilience of the UK forest industry, from seed to product, should be assessed, to identify current and future vulnerabilities and to prioritise adaptation actions. The British woodland survey 2015 (www.sylva.org.uk/bws) has provided a welcome start in addressing this knowledge gap. The survey aimed to capture present actions and opinions across the sector, and to understand progress in awareness and actions in adapting to environmental change among woodland owners and managers, tree nursery businesses, and forestry professionals (Hemery *et al.* 2015). Results of this, and other recent studies, indicate considerable inconsistency in climate change awareness, and in implementation of adaptation activities, and indicates that action so far has not moved the sector towards a state where it could be described as resilient. More detailed analysis of the sector is needed to understand motivations and differences in attitude and response to climate change (Lawrence and Marzano 2014) so that adaptation can be accelerated.

Table 3. UK Forestry Standard Guidelines – Climate Change Adaptation (Forestry Commission 2011a):

- Plan for forest resilience using a variety of ages, species and stand structure; consider the risks to the forest from wind, fire, and pest and disease outbreaks.
- Consider alternatives to clearfell systems, such as continuous cover forestry, where suitable sites and species combinations allow and management objectives are compatible.
- Have appropriate contingency plans in place to deal with risks to the forest, including spillages, pest and disease outbreaks, extreme weather events and fire.
- Consider projections of changes to rainfall patterns when specifying designs for culverts, drainage systems and roads.
- Review forest rotation lengths in response to changing productivity and wind risks, and review planting seasons in response to changing conditions and establishment success.
- Review species suitability and diversity over time as forest management plans are renewed.
- Consider the susceptibility of forests to pests and diseases and develop appropriate strategies for protection; review practice as further evidence becomes available.
- Diversify forest composition so that no more than 75% of the forest management unit is allocated to a single species and a minimum of the following are incorporated:
  10% open space;
  10% of other species or ground managed for environmental objectives;
  5% native broadleaved trees or shrubs.
- When managing or creating native woodland, encourage a representative range of the native species associated with the woodland type.
- When selecting trees and shrubs for new woodlands, consider the risks and opportunities of climate change for particular species and regions to decide if alternative species or increased species diversity are merited.
- Where timber production is an important objective, consider a wider range of tree species than has been typical of past planting, and consider the use of planting material from more southerly origins.
- Choose trees or shrubs which are well adapted to the site and are drawn from a sufficiently wide genetic base of parent trees to promote future adaptation.
- Encourage natural regeneration of native tree and shrub species to promote natural selection and climate change adaptation, and conserve distinctive genetic patterns – especially in and around semi-natural woodlands.
- Improve the ecological connectivity of the landscape for woodland and other species by extending and linking habitat features; consider the juxtaposition of wooded and non-wooded habitats and aim for the best overall result for biodiversity.
- When siting new woodland, consider the potential benefits in relation to flood alleviation, improvement of water quality and other ecosystem services.
- On steep slopes where there is a risk of slope failure or serious erosion, consider alternatives to clearfelling.
- In urban situations, consider the potential benefits of woodland and trees in reducing the impacts of climate change.
- Be vigilant for pests and diseases in forests and woodlands, particularly in urban areas where the risks of new problems are high.

Adaptation measures designed to spread or reduce particular risks, for example transforming forest stands to continuous cover forestry to reduce risks from pests and diseases and potentially from drought and soil erosion, may sometimes initially increase other risks, such as the risk of wind damage (Mason 2002). Such contradictions, would however be expected to have relatively minor impact overall, and a lack of progress on implementation of adaptation measures would leave forests and woodlands across the UK at much greater risk, especially to abiotic factors such as drought, fire and wind.

Climate change impacts need to be addressed by appropriate adaptation and adaptive forest management of forests and woodlands across the UK (Lawrence and Nicoll 2016).

Implementation of adaptation measures is most urgent in forest stands and woodlands that have the highest vulnerability to climate change related impacts (Mason *et al.* 2009), usually those with the lowest structural and species diversity. However only a relatively slow rate of change is operationally practical, as adaptation actions are usually constrained to being applied during scheduled forest interventions, especially restocking and thinning, and these operations are usually limited to less than 1% of forest area annually (Defra 2013b, Ray *et al.* 2014). The limitations of this slow potential rate of implementation, further reinforces the urgency of early adaptation decisions and action across the sector.

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Glossary

From *UK Forestry Standard* glossary (Forestry Commission 2011) where indicated*

Bare-root planting stock	Plants that leave the nursery without any rooting substrate. These can be raised from seedlings or cuttings. (See: www.forestry.gov.uk/pdf/ODW1002a.pdf/$FILE/ODW1002a.pdf)
Brash	The residue of branches, leaves and tops of trees, sometimes called 'lop and top', usually left on site after harvesting. *
Cambium	Layer of living cells just under bark and at growing tips of shoots and roots, from which new growth develops.
Cell-grown planting stock	Seedlings that are usually less than one year old and have been produced under controlled conditions in polythene tunnels or glasshouses and are delivered in containers. Managing Native Broadleaved Woodland.
Clear felling	Cutting down of an area of woodland (if it is within a larger area of woodland it is typically a felling greater than 0.25 ha). Sometimes a scatter or small clumps of trees may be left standing within the felled area. *
Continuous cover forestry	A silvicultural system whereby the forest canopy is maintained at one or more levels without clear felling.*
Culvert	A structure, usually a large pipe, that allows water to flow under a road.
DAMS	Detailed Aspect Method of Scoring – a system for scoring windiness derived from tatter flags and using representation of location and terrain to calculate a score; see Nicoll *et al.* (2015) ForestGALES manual.

Connectivity	The degree to which the landscape facilitates or impedes movement among resource patches.
Ecosystem services	The benefits people obtain from ecosystems. *
ESC	Ecolocical Site Classification (ESC) is a computer-based system to help guide forest managers and planners to select ecologically suited species to sites (see http://www.forestry.gov.uk/esc).
ForestGALES	A wind risk decision support tool for forest management in Britain (see www.forestry.gov.uk/forestgales).
Flushing	The bursting of buds in Spring.
Invasive species	Animal or plant species which spread rapidly to the exclusion of other species. Many invasive species are not native or locally native. *
Natural regeneration	Plants growing on a site as a result of natural seed fall or suckering. *
Phenology	The study of natural phenomena in biological systems that recur periodically (e.g. development stages, migration) and their relation to climate and seasonal changes. *
Resilience	The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change. *
Restocking	Replacing felled areas by sowing seed, planting, or allowing or facilitating natural regeneration. *
Riparian	Relating to or situated adjacent to a watercourse or water body.*
Rotation	The period required to establish and grow trees to a specified size, product, or condition of maturity. The period varies widely according to species and end use, but for conifers in the UK this is usually about 35 years and for broadleaves at least 60 years.*
Thinning	The removal of a proportion of trees in a forest after canopy closure, usually to promote growth and greater value in the remaining trees. *
Tree topping	The practice of removing whole tops of trees.
Understory	The vegetative layer and especially the trees and shrubs between the forest canopy and the ground cover.
Wildfire	A large, destructive fire that spreads quickly over woodland or brush.

WHC	Windthrow hazard classification. A method to zone forest areas of 500 ha or more by adding classification scores for windiness and soil together to estimate a hazard class. Each class was associated with a 'critical height' when windthrow would be expected to start, and a 'terminal height' when 40% of trees would be expected to be windthrown. See Millar (1985).

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