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National Forest in Wales Evidence Review Annex-3

ERAMMP Report-35
Annex-3: Future-proofing our Woodland

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Abbreviations Used in this Annex

ALC	Agricultural Land Classification
AOD	Acute Oak Decline
APHA	Animal and Plant Health Agency
ASC	Adaptation sub-committee
ASNW	Ancient Semi Natural Woodland
CCF	Continuous Cover Forest
CCRA	Climate Change Risk Assessment
COD	Chronic Oak Decline
DAMS	Detailed aspect method of scoring
DEFRA	Department for Environment, Food and Rural Affairs
ERAMMP	Environment and Rural Affairs Monitoring & Modelling Programme
ESC	Ecological Site Classification
FC	Forestry Commission
FSC	Forest Stewardship Council
INNS	Invasive Non-Native Species
IPCC	Intergovernmental Panel on Climate Change
ISPM	International Standards For Phytosanitary Measures
NRW	Natural Resources Wales
UKCCRA	UK Climate Change Risk Assessment
UKCCRA NAP	UK Climate Change Risk Assessment National Adaptation Plan
UKCEH	UK Centre for Ecology & Hydrology
UKCP	UK Climate Projections
UKFS	UK Forestry Standard

Abbreviations and some of the technical terms used in this report are expanded on in the programme glossaries: https://erammp.wales/en/glossary (English) and https://erammp.cymru/geirfa (Welsh)

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1. Introduction to Annex-3

Forests in Wales deliver a wide range of ecosystem services (explored in Annex-5/ERAMMP Report-37: *Ecosystem Services*, however, trees and forests are facing a challenging combination of pressures including climate change, pollution, fragmentation, invasive species, and pests and diseases, which threaten the ability to deliver these benefits.

In this Annex we consider the impacts of climate change and the increasing threat from pests and diseases on forests in Wales, with a focus on woodland expansion and the management of un- or under-managed woodland. We explore potential adaptation measures to increase the resilience of forests and the forestry sector in Wales and ensure the continued delivery of benefits for future generations.

This Annex begins with an overview of climate change risk, resilience and policy (Section 2) followed by a summary of the likely impacts of climate change on forestry in Wales (Section 3). Specific risks and resilience measures, including changes in species suitability and productivity, wind, fire, and drought risk are explored in Sections 4-7. Tree health and forestry pests and pathogens are considered in Section 8. The impacts of climate change on ecosystem service provision is considered in Section 9 alongside the beneficial role of forests in resilience to other sectors, the wider risk of climate change on the forestry sector in Section 10. Before concluding with an exploration of resilience building and adaptation measures in Section 11.

2. SUSTAINABILITY, RISK AND RESILIENCE

Sustainable forest management is a fundamental theme of both the Woodland for Wales Strategy (2018) and the UK Forestry Standard (UKFS 2017) where it is defined as 'the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems.' An integral component is the continued delivery of benefits into the future.

UK forests face a wide range of pressures and stresses which threaten their core ecosystem functions and ability to deliver a range of benefits, goods and services, including pollution, fragmentation, invasive species, climate change and pests and pathogens. The resilience of forests is therefore a central theme in sustainable forest management. Resilience, according to the Intergovernmental Panel on Climate Change (IPCC 2012) is defined as "the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions". An important distinction for resilience in the forestry sector, where management objectives can incorporate both ecological and financial elements, is the difference between ecological resilience, operational resilience and financial resilience. Resistance refers to the ability of a system to avoid harm from an external risk. A key component of resilience is understanding the potential risks to a system, for which we need to better understand risk.

The IPCC (2014) states that "risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure, and hazard." This incorporates two definitions of risk, the first is a combination of the impacts (consequences) of a risk and the likelihood (probability) of that risk occurring. The second, for a risk event that may cause negative impacts, the interaction between vulnerability (susceptibility to harm and lack of capacity to recover), exposure (presence in a location which could be adversely affected), and hazard (the potential occurrence of the risk event). Based on these definitions, to understand and model current and future risk to forests in Wales we need to understand the range of potential risks and their impacts, the probability of the risk occurring, the susceptibility of the system to harm, the ability of a system to recover, and the likelihood the location could be affected. Instead of complicating our understanding, these components can be viewed as range of potential routes to reducing risk and increasing resilience.

Whilst the definitions of resilience and risk apply to both climate change and tree health, the key aim of adaptation, as defined in the UKFS (2018) is to reduce the current and future risk and impacts of the changing climate and increase the resilience of the forest, including its ability to recover. Therefore, adaptation measures refer specifically to risk management and increasing resilience in relation to climate change. As there are interactions between climate change and tree health, adaptation measures can be used to describe certain elements of increasing resilience to pests and pathogens. The concept of risk management is fundamental to adaptation, and the different components of risk present a range of approaches to adaptation.

2.1 Climate Change Risk Management

National and Regional Climate Change Policy and sector guidelines follow a strategic and iterative climate change risk assessment framework (e.g. UK Climate Change Risk Assessment National Adaptation Programme (UKCCRA NAP)) to offer a route to resilience, which involve the stages of:

1) identify potential risks
2) assess risks and impacts
3) identify and select risk reduction (adaptation) strategies
4) monitoring, evaluation and revision

This Annex follows this approach in its structure (Figure 2-1).

Figure 2-1 Risk management process

2.2 Climate Change and Forestry Policy

The Climate Change Act (2008) sets UK targets for reducing greenhouse gas emissions and defines adaptation-related requirements, which include five-yearly climate change risk assessments and national adaptation programmes to address these risks.

In Wales, Part 2 of the Environment (Wales) Act (2016) complements the UK Climate Change Act (2008). The UK Climate Change Risk Assessment (UKCCRA) was carried out in 2012 and 2017 (UK GOV 2012, 2017) and includes a summary of risks for Wales as well as risks for UK forestry. Underpinning each CCRA is an Evidence Report carried out by the adaptation sub-committee (ASC). The latest UKCCRA evidence report includes a 'Summary for Wales' (ASC 2016).

The Second Climate Change Adaptation Plan for Wales, *Prosperity for All: A Climate Conscious Wales* (Welsh Government 2019) is the Welsh Government's strategy to address identified risks in the UKCCRA. Specific guidance for the forestry sector is also included in 'Woodlands for Wales' (Welsh Government 2018) which sets out the strategic direction for Welsh forestry. All documents outline the importance of resilience to climate change and forest pests and pathogens.

3. Climate Change Risk and Impacts for Forestry in Wales

3.1 Current Climatic Conditions in Wales

As described in the UK Climate Change Risk Assessment Evidence Report (2017) Summary for Wales (ASC 2016), Wales has a maritime climate with the predominant winds being from the west and southwest from the Atlantic Ocean. The weather is mild, cloudy, wet and windy, with regional variations in the amount of sunshine, rainfall and temperature due to the country's wide geographic variations. The highest average annual rainfall is in Snowdonia and the Brecon Beacons, with the lowest in coastal regions and in the east. Rainfall is higher in winter months than summer months.

3.2 Climate Data

The second and current Climate Change Risk Assessment (CCRA; UK GOV 2017) and CCRA Evidence Report (CCC 2016; ASC 2016) are based on the UK Climate Projections[1] 2009 dataset (UKCP09; Met Office 2009). Our main evidence base for understanding the impacts of climate change on forestry (as for other sectors) are also currently derived from UKCP09 projections. These are currently our best-available sources of evidence and are widely accepted by academics and policy makers. The maps of ecological species suitability provided in Figure 4-1 (on p.9) also incorporate this dataset.

The UK Climate Projections 2018 (UKCP18, Met Office 2018) are the latest authoritative set of climate change data available in the UK. A summary of projections and impacts for Wales are available in 'UKCP18 headline findings' (UKCP 2019) and are included in the Second Climate Change Adaptation Plan for Wales (Welsh Government 2019). The general trends and key findings from this latest dataset are consistent with UKCP09 (Met Office 2009), with higher resolution data anticipated to allow better regional projections, although accuracy will be constrained by the accuracy of other spatial data, e.g. soil survey results. It is intended that key evidence for forestry will be updated ahead of, and in, the planned third Climate Change Risk Assessment Evidence Report due in 2022, as UKCP18 data become available for forestry modelling and results are published.

3.3 Future Climate Change Projections & Impacts for Wales

The climate change projections in the Committee on Climate Change Evidence Report Summary for Wales (ASC 2016) are summarised here and in Table 3-1. Under a UKCP09 medium emissions (A1B) scenario, regional summer mean temperatures are projected to increase by between 0.9 – 4.5 ºC by the 2050s compared to a 1961-1990 baseline, and summer rainfall is likely to reduce. This is likely to result in an increase in the frequency and severity of heat waves, summer

[1] https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/index

drought, and increased risk of wildfires. Winter precipitation is most likely to increase, with projections varying between -2 - to +31%, resulting in an increase in regional & seasonal flooding, landslides, and greater storm damage.

3.4 Impacts of Climate Change on Forestry in Wales

The projected impacts of climate change on forestry in the UK are summarised in Morison and Matthews (2016) and Nicoll (2016), and for Wales in Forestry Commission Research Note 301 (Ray 2008) and the second Climate Change Risk Assessment Evidence Report Summary for Wales (ASC 2016). The major impacts can be divided into gradual changes, such as changes in tree species suitability, and extreme events, including increased risk from wind, wildfire and drought. Tree species suitability refers to the compatibility of a tree species to site conditions, including both soil and climate properties as described in Section 4 and ranges from un-suitable to marginal, suitable and very suitable. Understanding suitability is essential for all forest types, as it underpins tree and stand health as well as growth and productivity. Climate change impacts on forestry in Wales are summarised in Table 3-2 and explored in detail in Sections 4 to 7.

Table 3-1 Projected Climate Change & impacts in Wales

Climate Variable	Change so far	What is projected in the future?	Certainty	Linked to climate change?	Impacts	Regional Differences
Summer Temperatures	Warmer	Warmer	High	Yes	Change to species distribution. Heat wave impacts on infrastructure health & environment	Warmer in south wales
Winter Temperatures	Warmer	Warmer	High	Yes	Change to species distribution. Increased pest and disease risk	Warmer in south wales
Winter Rainfall	Wetter	Wetter	High	Inconclusive	Regional & seasonal flooding, landslides	
Summer Rainfall	No trend detected	Drier	High	Inconclusive	Increased drought & wildfire risk,	Drier in South wales
Windstorms	No trend detected	Inconclusive, increase in extreme winds	Medium	Inconclusive	Storm damage to property, business, environment	Higher risk in upland areas

Source: Met Office www.metoffice.gov.uk/weather/climate-change/effects-of-climate-change

Risks specific for woodland expansion are related to the increased vulnerability of young, newly planted trees to stress and extreme events compared to established stands. They are more vulnerable to scorch damage, late frosts and have higher mortality rates during heat waves and drought than established stands with deeper root systems. These risks are considered in more detail in upcoming sections.

Risks to undermanaged forests potentially include a greater risk from drought (see Section 7), and higher risk from wildfires due to higher levels of deadwood which act as a fuel load, and limited access routes and firebreaks (see 6). Undermanaged woodland may be accessed less frequently by owners, managers and recreational users, therefore risks such as fires, wind throw, pests or pathogens are less likely to be detected, although they may be at lower risk from accidental fires. Damage to stands, such as from wind throw, can lead to subsequent pest or pathogen damage if it is not cleared (see 8). Undermanaged woodlands with lower biodiversity are likely to be less resilient to change than well-managed woodland (reviewed in Bellamy et al. 2018). See also Annex-2/ERAMMP Report-34: *Managing Undermanaged Woodland.*

Table 3-2 Projected Climate Change Impacts on forestry in Wales

Climate Variable	**Forestry vulnerability**	**Woodland creation vulnerability**	**Undermanaged woodland vulnerability**	**Adaptation options**	**Forestry benefits**
Increase in Summer Temperatures	Species suitability. Scorch & mortality in young trees. Increased fire risk. Higher risk in Southern Wales.	Establishment risk, scorch and mortality	Drought risk, scorch damage, fire risk	Species, provenance & site selection. Thinning. Fire risk management. Monitoring	Potential increase in productivity from higher growth rate & longer growing season on some sites
Warmer Winter Temperatures	Increased risk from pest and pathogen outbreaks	Increased risk from pest and pathogen outbreaks	Increased risk from pest and pathogen outbreaks	Increase species diversity, monitoring and contingency planning	Increased growing season, reduced winter mortality, increased species choice
Increase in Winter Rainfall	Fine root damage and reduced growth on sites prone to waterlogging. Soil damage. Access constraints	Establishment risk from flooding, waterlogging, soil erosion	Flooding, soil erosion, landslides.	Site selection, drainage & engineering. Active management	-
Decrease in Summer Rainfall	Species suitability, drought damage & mortality, esp. dry soils and southern Wales. Increased fire risk	Establishment risk from drought damage & mortality	Drought risk, fire risk	Species, provenance & site selection. Management plan (thinning, mixtures). Fire risk management. Monitoring.	-
Increase in storms & extreme wind events	Moderate winds on exposed sites and wet soils. Vulnerability to extreme winds	-	Wind damage, subsequent pest and disease risk	Site and species selection, management choice (thin/no thin with age, location & condition). Contingency planning	-

4. Climate Change Impacts on Tree Species Suitability & Selection in Wales

4.1 Forest Tree Species Composition

The current climatic and geographic conditions in Wales support a wide range of forest types, including native upland oakwood, ashwood and mixed broadleaved woodlands, as well as productive conifer forest. The species composition of the forest area in Wales, both broadleaved and coniferous species, is presented in Figure 4-1. Wales has a relatively rich species diversity compared to the UK as a whole. Sitka spruce is the dominant productive coniferous species across UK forests, and in Wales it occupies nearly 30% of the stocked forest area which creates a potential vulnerability to pathogen or pest damage such as spruce bark beetles (*Dendroctonus micans* and *Ips typographus)*. However, Sitka spruce is the most valuable commercial species in the UK forestry industry and is in high demand, it is robust, fast growing and has well established markets. In the next Sections we review impacts on species suitability and explore species selection for resilience in 4.10.

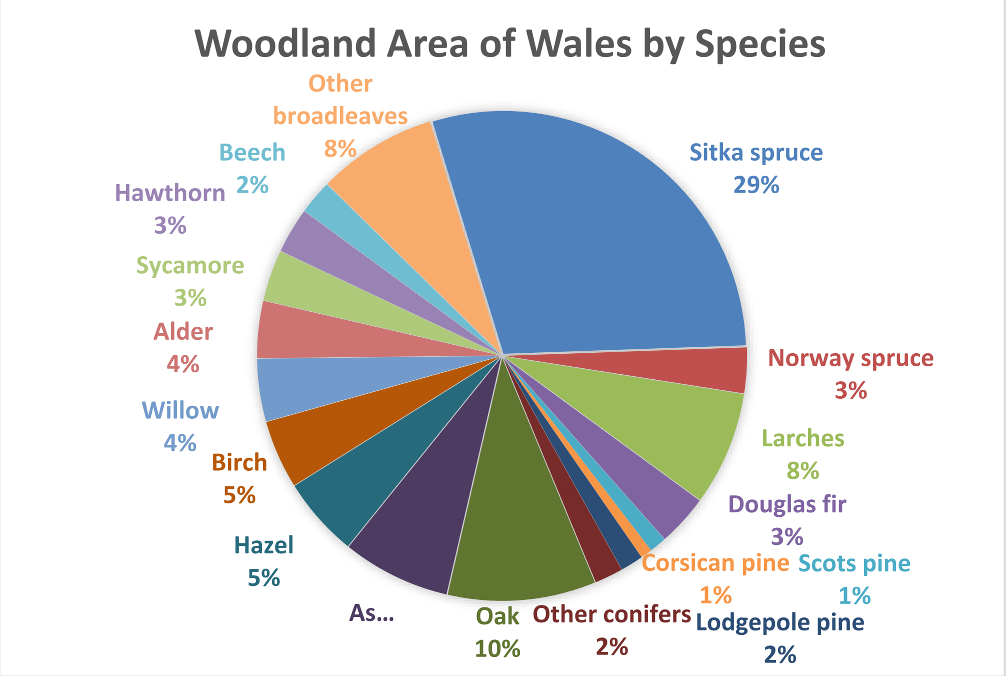

Figure 4-1 Woodland Area of Wales by species, data from Forestry Statistics (2019) and National Forest Inventory (2014a, b)

The risks to native woodland and conifer forest from a changing climate are inherently different, due to their different biodiversity, ecosystem service provision and management objectives. Native forests and ancient woodlands support high levels of biodiversity and provide valuable habitats for associated communities, including plants, fungi, micro-organisms and insects. They comprise and depend on key species, each of which may be affected by a changing climate and are therefore more vulnerable to both gradual change and extreme events. Non-productive broadleaved species can continue to grow slowly on sites where suitability becomes lower, but they are likely to be less robust, support less biodiversity and may be more vulnerable to pest or pathogen damage (see Annex-1/ERAMMP Report-33: *Biodiversity*).

The management objectives of commercial forests are financial as well as ecological and social, therefore productive forests are also vulnerable to financial risk, and more so from extreme events and pest or pathogen damage, especially in the next 50 years, as the species suitability, especially of key conifer species remains high. Increasing forest tree species diversity on productive sites is considered a key adaptation strategy to reduce risk, particularly against pest or pathogen damage. Species choice in plantation forest is typically constrained by market demand as well as suitability and growth rates. As described, the current demand for Sitka spruce whitewood creates inherent vulnerability through a lack of species diversity. Conversely, the recent statutory felling of *Phythopthora* infected larch stands resulted in a change to both processing and consumer behaviour due to the high volume of material coming to market. It is this critical mass which has driven change.

4.2 Climate change impacts on tree species suitability

Tree species suitability for a site ranges from un-suitable to very suitable and underpins tree and stand health as well as growth and productivity. It is therefore to understand how suitability varies spatially and temporally for all forest types and management objectives. As summarised in Table 3-2 climate change will impact tree species suitability and productivity, with more extreme changes in south Wales. The projected warmer climate will result in opportunities for an increase in suitability on sites where nutrient and water availability does not become limiting in the short-term future. However, reduced summer rainfall will cause more frequent droughts and will constrain species choice on sites with free draining soils to more drought tolerant species. Changes in the seasonal distribution of rainfall will result in more frequent winter flooding and will constrain species choice on sites prone to waterlogging.

Species suitability can be modelled spatially for current and future time horizons using ecological and biophysical data and climate change projections. In the next sections, we describe and compare the application of two tree species suitability models to Wales and suggest further work to support policy and practitioner decision making. Implications for species selection are summarised in Section 4.10.

4.3 Ecological Site Classification methodology & approach

The ecological site classification (ESC) decision support tool allows the assessment of ecological suitability for a wide range of tree species for a given site. The ESC method assesses four climate and two soil factors to ascertain ecological suitability; accumulated temperature, moisture deficit (rainfall), exposure (windiness) and continentality, and soil moisture regime and soil nutrient regime. Ecological suitability varies on a scale of 0-1, with the minimum value of all the factors constraining suitability. The value of suitability translates to categories as follows, 0- 0.29 unsuitable, 0.3 – 0.49 marginal, 0.5 – 0.74 suitable, 0.75 – 1 very suitable. Potential productivity (yield class, m3 per year) is calculated as the suitability score multiplied by the maximum potential yield class for each species. A species may still survive and grow slowly at lower suitability scores, forming a valuable part of an ecosystem, such as at natural treelines. Full details of the ecological site classification method can be found in Pyatt et al. (2001).

Forest Research have carried out modelling of species suitability, productivity and ecosystem services delivery using the Ecological Site Classification (ESC) model using current and future climate data (Beauchamp et al. 2016; Ray et al. 2014; 2019). Projected changes in temperature and rainfall over the rotation of forest stands are used in ESC to model projected changes in suitability and productivity of key forest species. Only temperature and rainfall variables change under future climate scenarios.

Models have been developed using scientific evidence and expert opinion, however they are at the edge or outside the scope of their tested range under high scenario climate projections. The ESC decision support tool requires an accurate site assessment and detailed soil information alongside expert knowledge of local climate conditions in order to be applied to individual forest stands with the highest accuracy. Large-scale modelling which is based on soil maps are therefore only as accurate as the underlying data. The model is considered the best currently available for modelling the impacts of climate change on forests in the UK and is widely used by the forestry sector, researchers and policy makers. It is noted that individual species models are less robust under extreme modelled change. The confidence is therefore medium and acceptance high. An online version of the ESC decision support tool is available.[2]

4.4 ESC species suitability under future climate projections in Wales

The data presented in Figure 4-2 were calculated using the ESC model for ERAMMP. Baseline climate data are a 20-year average for 1981-2000, with projected data for 2020 and 2080 using the UKCP09 11-RCM, which follow a medium emissions scenario; the change in ecological suitability is also presented.

Projections for Sitka spruce show ecological suitability decreasing from predominately suitable and very suitable in baseline and 2020 to suitable and marginal in central, west and northern wales by 2080; there is a larger decrease in suitability in southern Wales, where it becomes unsuitable by 2080. Suitability increases at higher elevations. Overall, the modelled data show Sitka spruce will remain a suitable species choice in Wales, except for in South Wales. However, Sitka spruce is the dominant species in Wales, and in the UK, and many strategies to increase resilience to climate change support species diversification.

Under baseline conditions beech is suitable and very suitable in areas at lower elevation, with suitability decreasing to marginal and unsuitable at higher elevations. Suitability is projected to decline by 2080 to unsuitable in southern and western areas and marginal in eastern areas. Suitability increases slightly in some areas of higher elevation but remains unsuitable in others.

[2] www.forestdss.org.uk/geoforestdss/

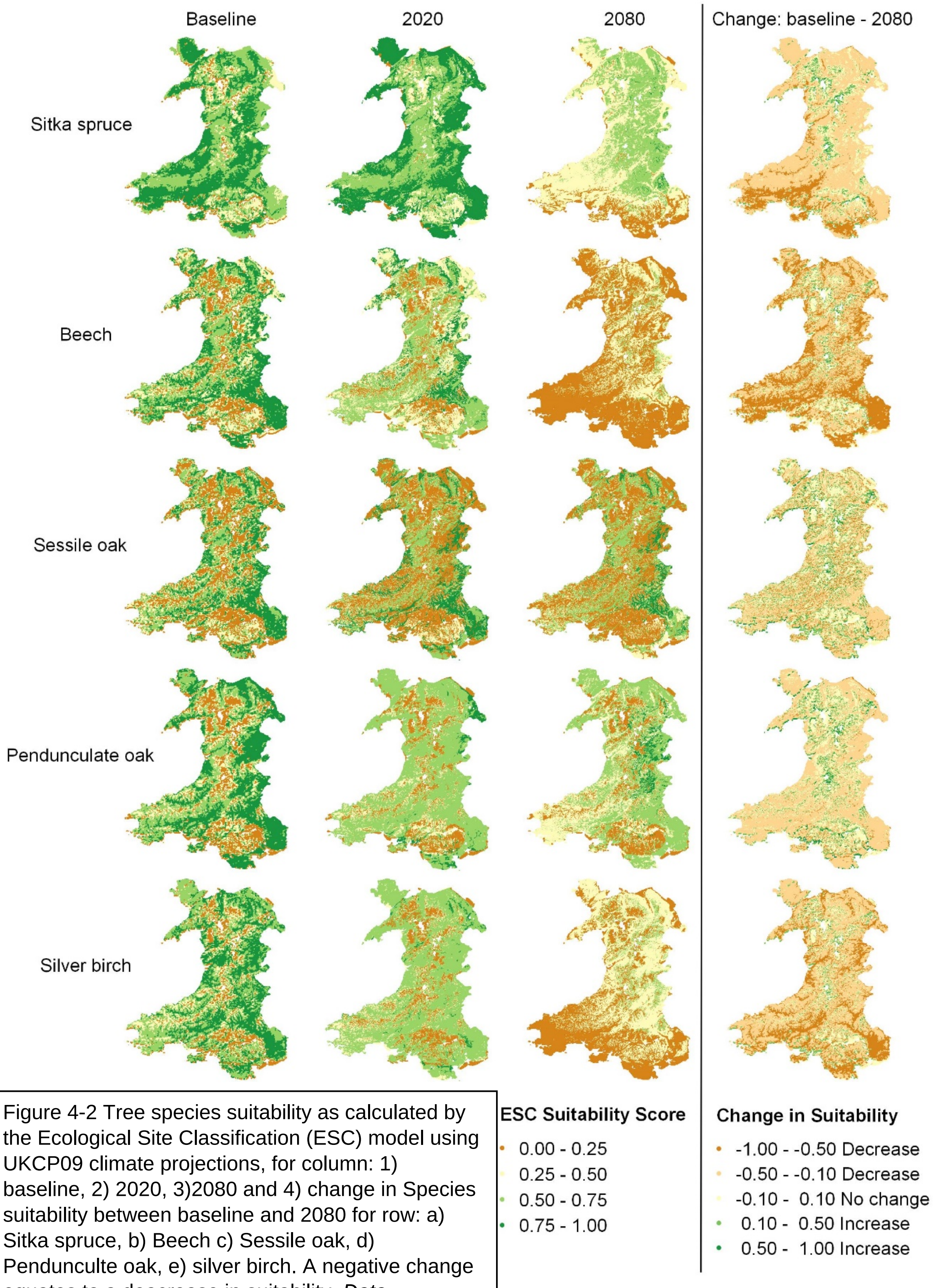

Figure 4-2 Tree species suitability as calculated by the Ecological Site Classification (ESC) model using UKCP09 climate projections, for column: 1) baseline, 2) 2020, 3)2080 and 4) change in Species suitability between baseline and 2080 for row: a) Sitka spruce, b) Beech c) Sessile oak, d) Pendunculte oak, e) silver birch. A negative change equates to a deacrease in suitability. *Data calculated for ERAMMP by Forest Research.*

Sessile oak shows a varied pattern of suitability in all time periods. Suitability remains very suitable in eastern areas, and suitable in scattered western areas to 2080. It is unsuitable at higher elevations. Pendunculate oak is the most common oak species in Wales. Suitability varies from very suitable to unsuitable at higher elevations during the baseline period, with suitability decreasing to suitable and marginal by 2080, remaining unsuitable in many areas and very suitable in eastern-central areas.

Modelled suitability for silver birch decreases from very suitable during the baseline period to suitable in 2020 and further to unsuitable in southern Wales and marginal in central and northern Wales by 2080. Suitability increases in some areas at higher elevations from unsuitable to suitable and marginal. By 2080, silver birch remains mostly marginal with pockets of suitable across central and northern Wales.

Overall, projected species suitability declines for these modelled species, but all species remain suitable or very suitable in small areas of Wales. Suitability decreases are higher in southern Wales, where many species are likely to become unsuitable due to decreased summer rainfall and increased summer temperatures. Suitability remains higher in northern, central and eastern areas and there is a modelled increase in suitability at higher altitudes, although this must also be considered alongside wind risk.

4.5 Biophysical Suitability & Agricultural Land Classification

A recent report by Environment Systems (2020) for the Committee on Climate Change modelled the biophysical suitability of Sitka spruce and sessile oak, with some analysis provided for beech, using UKCP18 climate data for the present day, 2050 and 2080, for medium and high emissions scenarios. The models incorporate Agricultural Land Classification (ALC) data for soil properties, which grades soil for wetness, droughtiness, depth, gradient, rock, and stone content. The climate data are based on annual average rainfall, accumulated temperature, and local factors. In addition, frost, wind, salt spray and flood risk data are overlaid, and combined to give a suitability category of suitable, limited suitability or unsuitable. A constraint and sensitivity layer is overlaid to exclude areas unsuitable for planting according to current environmental and policy guidelines, to give an estimate of the area of land suitable for woodland expansion under present day conditions and projected climate change. The work is a development of the Welsh Government ‘Capability, Suitability and Climate’ project to model tree species suitability.

The model results show that beech is unsuitable or has limited suitability across most of Wales and was therefore replaced by sessile oak for further modelling. Sessile oak is modelled as suitable under current conditions across Wales except for in upland areas. Suitability declines under the medium emissions scenario and further under the high emissions scenario, in particular in south Wales. Models project that sessile oak will remain suitable in parts of west Wales.

Sitka spruce is widely suitable across Wales, with limited suitability in central Wales at higher elevations. Suitability decreases slightly by 2050 and further by 2080 but remains suitable over large areas of Wales. Suitability declines further under the high emissions scenario, becoming less suitable at lower elevations and more suitable at high elevations.

Environment Systems conclude that the amount of land predicted to remain suitable for sessile oak and Sitka spruce by 2080 is set to decline significantly, and that to meet the planting Welsh Government's planting ambitions, planting will need to be carried out in areas subject to certain biophysical limitations where suitability and growth may not remain optimal.

4.6 Comparison of ESC & Biophysical Suitability Model Results

Both methods agree that the basis for assessing species suitability includes an assessment of both climate and soil properties. A full, direct comparison between the results of the ESC model and the ALC biophysical models is complicated by the different climate data, soil data, spatial resolutions, thresholds for suitability, and different suitability categories. Some broad trends are similar in both approaches, species suitability is lower at higher elevations under baseline conditions and improves at higher elevations under future climate scenarios as drought stress is reduced. This lends confidence to the trend of suitability improving at higher elevations in future, with independent sources of evidence reaching the same conclusions.

A comparison of modelled results for Sitka spruce show similar suitability distributions under the ESC baseline and Environment Systems current conditions, with Sitka spruce widely suitable across Wales with reduced suitability at higher elevations. Projections for 2080 under the medium emissions scenario also show similar distributions of suitability, with the exception that ESC projections show Sitka spruce remains suitable in eastern areas of Wales, where Environment Systems show suitability as limited. Suitability increases at some high elevations under both models.

A comparison of suitability maps for sessile oak under ESC baseline conditions and Environment Systems current conditions shows a similar distribution of ESC suitable and very suitable and Environment Systems suitable site conditions. Both show Sessile oak is unsuitable in upland areas. Comparing the ESC 2080 and Environment Systems medium emissions scenario for 2080, both show a reduction in suitability for Sessile oak, which remains unsuitable at higher elevations. The projections differ in that ESC models a higher suitability in eastern Wales, but Environment Systems predict greater suitability in Western Wales.

ESC shows that beech would have been suitable under the baseline climate data, whereas the Environment Systems report shows that beech is unsuitable. Both projections show it is unlikely to be suitable due in 2080 due to drought. It is worth exploring further how beech is performing under current conditions and why the models differ in this conclusion.

4.7 Differences in the modelling approach

One main difference with the modelling approaches is that ESC encapsulates soil properties into two variables, which is a robust simplification, and the Environment System report uses more detailed soil categories but at a lower resolution. ESC is typically run at 50-250m resolution, here modelled at 250m resolution, with climate data downscaled as necessary so that outputs are relevant for operational applications. This is a fundamental divergence in that ESC is a tool that can be applied at all scales, whereas the ALC modelling in the report is a broad strategic analysis and is therefore missing some detail.

The ESC model potentially underestimates suitability under future climate projections, as it undervalues soil water holding capacity; a modification to the model is being tested at Forest Research. The method for calculating soil water holding capacity and moisture deficit is likely to be less pessimistic in the Environment Systems models.

4.8 Application of the Ecological Site Classification to Agricultural Land Classification

A recent study by Forest Research examined the potential for Agricultural Land Classification (ALC) 'moderate quality agricultural land' (subgrade 3b) to act as a proxy for forest establishment, on behalf of Bangor University (Bathgate et al. 2020). This study used Ecological Site Classification (ESC) models and data at 250m resolution for the baseline climate period (1961-1990) and also considered constraints/opportunities related to accessibility, riparian zones and existing woodland. Alongside ESC outputs estimates of carbon sequestration were derived for 7 coniferous species and 7 broadleaved species.

ESC modelling highlighted that approximately 95% of ALC 3b class land in Wales would be suitable for Sitka spruce, birch and oak. This area reduced to approximately 50% for species less tolerant of wetter soils, such as Douglas fir. The analysis indicated that ALC grade 3b land offered higher productivity than in presently afforested sites in Wales and on ALC 'poor quality agricultural land' (grade 4). Douglas fir and western hemlock were found to be competitive with Sitka spruce on many sites and, in some cases, Douglas fir outperformed Sitka spruce in terms of carbon sequestration despite having similar or lower yield class.

While substantial areas of ALC grade 3b land were not within 2000m of existing road infrastructure there were very few sites that had steep slopes that might impact upon forest machinery operating limits. However around 5-10% of the ALC grade 3b land would be considered as riparian in terms of Forest Stewardship Council (FSC) Forest and Water guidelines, and this would favour afforestation with predominately alder and birch.

A formal analysis of future climate implications was not undertaken, but UKCP09 data were included for reference to facilitate subsequent analysis should this be required.

4.9 Future work on species suitability and land availability

The Environment Systems (2020) report provides a valuable extension to species suitability modelling by excluding constrained and sensitive areas and providing estimates of land area suitable and potentially available for woodland expansion.

This step is beneficial to informing woodland expansion policy. The ERAMMP Quickstart model overlaid similar sensitivities and constraints and could also be used to calculate suitable land area for woodland expansion using a wider range of species using the ESC model.

The conclusion made by Environment Systems, that it will be a challenge to meet planting targets, is valid, but the limited range of species modelled may mean this assumption is overly pessimistic. Two species were modelled in the Environment systems report, however species with different climatic and ecophysiological properties are likely to be suitable in different areas. To understand the full impacts of climate change on forest tree species suitability in Wales and understand the impacts on woodland expansion, further modelling is required using a broader range of species.

The ESC model incorporates species suitability information for over 50 forest tree species, however the ESC decision support tool doesn't host the same detail of soil data as in these described studies, or incorporate existing land use. For the ERAMMP modelling work 11 species were modelled, of which 5 are presented in this review. Bathgate et al. (2020) consider 14 species under a baseline climate period of 1961-1990. Therefore each study contributes valuable information to decision making. Combining the detailed spatial classifications of existing forest area and land use, as in Bathgate et al*.* (2020) as well as areas to exclude from planting, as in Environment Systems (2020), will further improve our understanding of potential climate change impacts on woodland creation. This work is underway in the development of the ERAMMP Integrated Modelling Platform.

4.10 Species selection for resilience

Research is ongoing to explore potential species for future climates and to understand their properties, including the growth, form, timber properties, suitability and biodiversity impacts of minor (already grown in the UK at small scales) and novel (not widely grown in the UK) species (e.g. Bladon & Evans 2015; Gill-Moreno et al*.* 2016; Mason et al. 2018a, b; Savill et al*.* 2015, 2016; Wilson et al. 2018). Evidence also shows that growing stands of species in mixtures are more resilient to projected future climates, with some combinations showing increased drought tolerance, faster growth rates, as well as the innate resilience from increased species diversity (e.g. Coll et al. 2018; Drossler et al. 2018) (see 2.11). Mason et al. (2018b) provide a review of potential species for Western areas of the UK based on research from the Kilmun forest garden in western Scotland. Long term experiments, monitoring sites and arboreta are providing valuable sources of information (Mason et al*.* 2018c).

Species suitability will change over the next 60 years and beyond, and species choice is likely to change gradually over the next century, with a broader range of species being encouraged, including more southerly provenances where appropriate, and more drought tolerant species, such as pines. The Royal Forestry Society (2018) found that more land managers are already considering a wide range of alternative species. Details of the range of potential alternative species and species mixtures are outside the scope of this report due to the breadth of species and evidence, and rapidly growing literature. Details of a wide range of alternative species can be found on the Forest Research[3], Royal Forestry Society[4], and SilviFuture[5] websites.

When considering changes to future species selection and forest composition, consideration must be given to the tree health implications of introducing new hosts, the risk of introducing new pests or pathogens, and new host and pest/pathogen interactions to the UK. There is concern that the increase in non-native species could increase risks, especially to tree health (Ennos et al. 2018), see Section 9. Strategic, gradual change, with the use of decision support tools such as ESC at both operational and policy scales, and ongoing research into management, species and provenance choice, is preferred in order to prevent maladaptation. An adaptive response at policy and operation scales, with monitoring and regular reviews of risk, evidence and strategy, as in the risk management framework in Section 2.1 is required to identify when a step change in policy and practice may be necessary.

For native woodland, species change may also be encouraged through natural or assisted regeneration. There is limited evidence this can also support resilience where species regenerate under e.g. drought conditions. Change in species choice may not be appropriate on native woodlands due to dependent specialist taxa and species. See Section 11.

[3] https://www.forestresearch.gov.uk/tools-and-resources/tree-species-database/
[4] https://www.rfs.org.uk/learning/forestry-knowledge-hub/forest-resilience/alternative-tree-species/
[5] https://www.silvifuture.org.uk/

5. Climate Change, Forestry and Wind

Wind is a major constraint to forest management in the UK (Quine et al. 1995). Wind exposure can reduce establishment options, constrain rotation lengths, and reduce options for thinning, and transformation to continuous cover. Damage to woodlands by wind events leads directly to increased costs of harvesting and reduced timber value, but there are also indirect costs, including reduced amenity value, safety concerns for forest workers, and damage to wildlife habitats (Gardiner et al. 2013).

Wind damage is expected to increase as the climate changes as a result of more frequent or intense storms and changing rainfall patterns leading to increased waterlogging (Nicoll 2016). The wind climate in Wales is dominated by frequent extra-tropical cyclones (low pressure systems) that form in the Atlantic and pass west to east across or close to the British Isles. Around 160 of these weather systems affect Britain each year, with the strongest winds experienced in the winter months (Quine et al. 1995), especially in the west. The frequency and intensity of storm events in winter months is projected to increase as the climate changes (Fung et al. 2019), resulting in a likely increase in storm damage to forests. The forest area of Wales has changed considerably over the last century, with considerable expansion in relatively exposed upland areas.

Large-scale forest wind damage across the UK in the 20th century provided the impetus for research into the interactions between wind and trees (Gardiner et al. 2019), and the development of tools to reduce vulnerability to wind across the industry. Firstly, a simple “Windthrow Hazard Classification” was introduced to provide a “terminal height”, i.e. a maximum height at which stands should be harvested to reduce the likelihood of wind damage (Miller 1985). This system was found to be limited in its effectiveness, being based on absolute values rather than risk (Nicoll and Gardiner 2019), so was later replaced by the risk based “ForestGALES” decision support tool (Gardiner et al. 2000).

ForestGALES takes into account species, edge effects, spacing, thinning, soils, and local wind climate based on the DAMS (“Detailed aspect method of scoring”) system, to provide spatially specific information on current wind risk, and how wind risk will change over time as stands grow (Gardiner and Quine 2000). Essentially risk varies with a number of factors including species and soil types, but increases considerably immediately following stand thinning, when stand edges are removed, and in particular as trees grow in height. ForestGALES can be run using standard stand (or sub-compartment) data and provides the critical wind speed that will damage a stand, and the expected frequency (or return-time) for that wind speed at that location. Validation of the ForestGALES model has shown it to be considerably less pessimistic than the Windthrow Hazard Classification system (Hale et al. 2015), and therefore allows for stands to be grown longer before harvesting. Prediction of how risk will change over time as stands grow, assists with decisions on appropriate management and timing of stand thinning and harvesting.

Factoring wind into forest management decisions is essential, especially in more wind exposed areas. The higher the windiness, the more limited managers will be in conducting thinning operations and transformation to continuous cover forest (CCF) without loss of the stand to windthrow. On sheltered sites (DAMS <13) wind damage is not expected to be a problem in thinned stands except in extreme storms, on moderately exposed sites (DAMS 13-16), more care is needed in decisions on where and when thinning will be appropriate and careful assessment based of ForestGALES is needed to explore how risk changes with thinning and as stands grow in height. On more exposed sites (DAMS 17 or above) current guidance is that opportunities for thinning are limited and a no-thin option may be most appropriate. Where thinning is considered in more exposed sites, ForestGALES will again help understand the change in risk, and the higher the wind risk, the earlier the thinning should be started (Forestry Commission 2010). This is because trees are effective in acclimating to their wind regime as they grow, so early thinning allows trees to allocate more growth below ground and to the stem base, thereby improving their stability (Nicoll et al. 2019). Other strategies to reduce the risk of wind damage include the use of shorter rotations or undertaking precautionary felling, but these potentially decrease income from timber sales so should not be applied without first analysing the risks.

The application of wind risk management tools is most effective as a measure against damaging wind speeds experienced in relatively common storms. For the extreme wind speeds experienced in less common, catastrophic, storms, effective measures may be limited to ensuring that forest areas have a relatively even distribution of stand heights so that risks are spread (and not all stands are damaged in a single event), and having contingency plans in place to prepare for wide-scale windthrow (Forestry Commission 2015; Gardiner et al. 2013).

6. Climate Change, Forestry and Wildfire Risk

6.1 Forest fires

Wildfires[6] in the UK are usually small and are more likely to affect open habitats like moorland, heath and grassland, not woodlands or forests. They do not usually start in woodland, although they can spread from open habitats into woodland. Forest fires are a subset of all wildfires, but it is necessary to consider wildfire risk in general as the risk depends on the location of the woodland in the mosaic of habitats within the landscape, whether rural, urban or in the rural-urban interface, and in the latter in particular social factors can have a large influence.

While wildfires in the UK are not on the scale of some other countries, they can cause major impacts for ecosystems, society, and human health and wellbeing. For example, smoke can induce acute reductions in air quality and an increase in associated health issues, road closures, and evacuations (e.g. 50 homes were evacuated near Saddleworth Moor, Yorkshire, in 2018). Severe fires which burn into dry peat also result in substantial carbon losses to the atmosphere, impacts on scenic sites, and reduced water quality through eroded peat entering upland reservoirs and polluting water supplies.

Major wildfire events in the UK over recent years have highlighted the risk they pose and has led to recognition of wildfire as a new environmental hazard in the UK National Risk Register (Cabinet Office 2013). This risk is likely to grow in a changing climate (Moffatt et al. 2012; Brown et al. 2016), and will be affected by changes in land use, including afforestation. Wildfire incidents are surprisingly common in the UK. As an example, analysis by the Forestry Commission (FC) showed that in the eight financial years between April 2009 and March 2017 over 250,000 wildfire incidents were dealt with by the Fire and Rescue Services in England alone although woodland fires accounted for only 11 to 15% of the number of incidents, and only between 1% and 5% of land area burnt (similar analysis has not yet been carried out for Wales). While some wildfires start naturally, for example by lightning strikes, the large majority are started by people, either accidentally or deliberately.

Most of the wildfires that affect forests and woodlands in the UK are 'surface fires', which are fuelled by leaves and needles in the litter layer, scrub and other low-level vegetation. Some are 'ground fires' that burn into peat. Only a small minority of wildfires will result in a 'crown fire', an extreme and highly hazardous fire event. Site topography is a key factor in determining the spread of a fire after ignition - fires spread faster on sloping ground than on the flat.

There are two main periods for wildfires, in late spring (March -April) when the previous season’s ground vegetation growth has dried off and in summer (July-September) in hot or prolonged dry conditions, (also coinciding with the holiday season). There is substantial inter-annual variation caused by weather conditions, and significant fire seasons occurred in 1976, 2003, 2006, 2011 and 2018, because of prolonged dry, warm conditions in those years. In particular, in 2018 there were

[6] Defined as ‘uncontrolled vegetation fires’

large fires across the UK (Sibley 2019), with satellite monitoring recording areas burnt totalling over 180 km^2, including major fires in several parts of Wales in June and July.

The risk and vulnerability of forests to wildfire varies with species, stand age, and adjacent land use. In general, broadleaved species have a lower vulnerability than conifers like pine, firs, spruce and cypress, due in part to the lower litter accumulation rates and the stand and canopy structural properties. However, eucalyptus species are at high risk due the flammability of the leaves and bark. Young stands at the thicket stage of development are at particular risk due to the higher probability of ignition due to fuel loads from shaded out ground vegetation, the higher probability of spread into the lower canopy, and vulnerability to damage to the small trees. Disease can increase the risk if dead material increases the fuel-load, and some diseases such as needle blight can lead to accumulation of material held in the canopy that creates ‘ladder fuels’ resulting in fire spread into the canopy, leading to much more damaging fires.

6.2 Human aspects of wildfire risk

As noted above, wildfires are frequently started by people, and could potentially impact on woodlands across Wales (de Jong et al. 2016). Wildfires started deliberately have been a persistent, widespread, costly and potentially dangerous issue in South Wales. Analysis by Forest Research a decade ago showed that between 2000 and 2008 there were nearly 550 forest fires in that region (Jollands et al. 2011). The problem continues: in spring 2015, there were 513 deliberate fires in Rhondda Cynon Taff and 244 of these were in the Rhondda (NRW 2017d). The local geography (dense linear urban populations adjacent to rural open access land), the flammable vegetation cover (Molinia grass, bracken, and gorse), the steep slopes and the relatively young conifer plantations in that area all combine to increase the risk of fire spread. Deliberate fire setting is the prime cause, and Jollands et al. (2011) showed that the majority of fires appeared to start near roads and public rights of way. That analysis also showed that areas of relative socio-economic deprivation (as measured by the Welsh Index of Multiple Deprivation) are more prone to experiencing wildfires, and the peak fire season is generally between March and May, with over 60% of wildfires occur between 4pm and midnight. While some risk reduction measures can be carried out - for example, choice of species for planting and reducing fuels near public access points, the main risk mitigation strategies are presently still broadly social and education, but can be both. For example, the current ‘Healthy Hillsides’ project in the Rhondda valleys)[7] (NRW 2017d) aims to minimise the impact and severity of wildfires with pro-active land management. This includes making firebreaks, reducing fuel, (by controlled grazing, bracken control, and controlled burns) and encouraging natural woodland regeneration, as well as working with landowners and communities. This and other similar projects, show that integrated land use management can help increase resilience to wildfire.

[7] https://www.welshwildlife.org/uncategorized/healthy-hillsides-project/)

6.3 Climate change impacts

There is as yet no clear evidence that climate change has changed wildfire frequency or areas affected in the UK, because of its episodic nature, the annual variability in occurrence and in the short record of data collection (since 2009 only). However, as the UKCP18 projection headline statement is that there is “a greater chance of warmer, wetter winters and hotter, drier summers”, this is likely to increase wildfire and forest fire risk (see Table 3-1 above). For example, Met Office analysis has shown that the chance of summers as hot as that of 2018 was <10% in a baseline climate period, but by mid-century the chance will be around 50%. Beyond 2050 the chance of a warmer summer than 2018 depends more strongly on emissions scenario. A detailed analysis of future wildfire risk will be provided in the CCRA3 through Met Office research using UKCP18 regional projections. The provisional computed fire weather indices for England and Wales suggests the probability of ‘very high fire danger days’ increases substantially after 2050, particularly in the summer with the RCP8.5 high emissions scenario. However, there are strong regional differences and the cooler, wetter climate of Wales is likely to reduce the risk compared to SE England.

Fire risk can be increased by inappropriate management, and Fire and Rescue Services have reported that brash from harvesting has added to fire spread and intensity on several occasions in Wales and in Scotland. However, wildfire resilience can be reduced by good forest management planning. The UKFS Climate Change Guidelines highlight the three key areas for wildfire adaptation for high risk forests and woodlands: selecting less fire susceptible species, undertaking adaptive management and more resilient management (Gazzard 2015). The Forestry Commission has produced a Practice Guide to assist forest managers reduce fire risk (Forestry Commission 2014) which highlights reducing the likelihood of wildfires occurring, reducing the severity of damage and impacts on people and the environment if they do occur, and assisting with fire suppression activities.

While the above risk reduction and resilience-building activities rely on forest managers, actions also need to be taken at the wider landscape scale. The UK presently has no fire danger rating system to aid in managing the risk (for example, identifying when and where the risk is greatest), although there are new research projects underway which should inform the development of any UK system in the future, which is under discussion (e.g. POST 2019). Active land management to reduce risk is supported by the wildfire community, and if wildfire risks do increase as the climate changes, it will be necessary to put in place an integrated land-use risk management approach to increase resilience to wildfire, as the 2017 CCRA identified.

7. Climate Change, Forestry and Drought Risk

Forests support critically important ecosystem processes that underpin atmospheric, hydrological and edaphic regulation (Trumbore et al. 2015). The frequency of extreme weather events, including heat waves, intense rainfall, and drought will increase over this century in the UK (well accepted; Nicoll 2016). 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 (well accepted; Read et al. 2009).

International research to date on drought has formed part of broader studies of climate change and disturbance impacts on forests (Seidl et al. 2017), including the United Kingdom (Brown et al. 2016). Studies have focused on the mechanisms driving drought-induced reductions in productivity and mortality (Adams et al. 2017). Such studies provide insights into impacts but do not provide management strategies to minimise the risk to commercial forestry.

Changing climate patterns, including increasing variation in rainfall, will likely impact forest productivity (Thurm et al. 2016; Davies 2019) and ecosystem function (Keenan et al. 2015; Trumbore et al. 2015) by exacerbating drought stress and potentially elevating plant mortality (Greenwood 2017), especially at the establishment phase (well accepted). This will likely lead to a restriction in planting dates in spring due to drought concerns on eastern and southern sites (limited evidence; Ray 2008).

Some UK studies have investigated how timber growth rates might change in future decades as the climate suitability alters at a catchment scale (Mason et al. 2012) or if the return interval of drought events changes (Petr et al. 2014). For strategic regional risk mapping and adaptation planning where safeguarding sustainable commercial volume return is major objective, the longevity of the forest cycle may result in species with higher yields but lower drought tolerance still providing higher volume and carbon sequestration returns, over the next rotation (limited evidence), if a significant increase in drought duration and impact is decades away (Davies 2019). Climate change and drought impacts will likely increase over time, and further insight is needed into whether such change will occur at a rate that warrants immediate change to planting regimes (Mason et al. 2012). This is especially significant for Britain where over the next few decades, substantial hectarage in both the national and private forest estates will be ready for harvest and restocking.

Increasing temperatures and decreasing precipitation, combined with increasing frequency and severity of forest disturbances are likely to alter the composition, structure and function of forests (Allen et al. 2009). Particularly significant will be the effects of changing climate on tree growth, as this will determine the rate of carbon uptake and storage in forest ecosystems. Reductions in tree growth during and following drought episodes are of significance, as they may limit the ability of many ecosystems to act as carbon sinks (Adams et al. 2009; Buras et al. 2018).

At a UK and Welsh level, based on extrapolation from research for productive conifers in Scotland (Green and Ray 2009; Davies 2019), drought impacts will likely result in lower yields in drought years and some increased mortality of well-established commercial conifer stands is considered a likely but localised threat (limited evidence) when extreme droughts events occur. Reductions in net carbon gain (and growth) in commercial stands exposed to drought are already evident (Xenakis 2019). Ability to access water from reliable sources, such as stored groundwater (McLaughlin et al*.* 2017), is one strategy some trees may use to survive in a warmer world with intense droughts. Species rooting patterns are potentially a source of screening for soil moisture tolerance (limited evidence). An improved knowledge of soil-climate-species interactions with a focus on soil properties is required.

Adaptation of silvicultural practice through species diversification has been identified as a means of reducing drought risk (Anderegg et al. 2018) and reduce the risks from other biotic and abiotic sources (Kolstrom et al. 2011). This can be done through planting mixed stands with components of more drought tolerant species or provenances (Mason et al. 2012), but to do this requires specific information on species' tolerance and site suitability (limited evidence), in order to manage for ecosystem stability and forest productivity (Bauhus et al. 2017). Some of the most drought tolerant species are pines (well accepted): however, common commercial pine species are unable to match spruce and larch timber yields, even when factoring for drought growth reductions in more drought prone conifers (Davies 2019). However, pines should be planted in the most drought prone areas especially where increased diversification and increasing landscape scale resilience are required (Lawrence and Nicoll 2016). The potential for Douglas fir-spruce and western hemlock-spruce mixtures on lower water holding capacity soils in regions predicted to increasing drought impacts warrants further investigation (Cameron and Mason 2013; Cameron 2015).

The potential for significant detrimental interaction between drought stress and the damage caused by forest pests and pathogens has been addressed in a recent meta-analysis (Jactel et al. 2012), and the connection between the physiological status of the tree and disease development is key. An overreliance on one species could lead to widespread loss in future if a pest or disease threatening that species arrives (Davies et al. 2017), Different types of natural disturbance risk also interact, and drought stress can weaken the tree resilience susceptibility to pest and disease attack or windthrow (Seidl et al. 2014; Csillery et al. 2017).

To improve drought resilience in forested landscapes matching species to site, as underpinned by UK forestry standards, is vital. The matching of species response and site constraints to variation in future probabilistic drought risk scenarios is a priority research need. Improved knowledge of rotational length impacts under future climate requires new data on historic species response, forest modelling which interacts with climate, and integration with national probabilistic weather projections to assess the risk and exposure of different forest types at stand, local and regional scales (Van Oijen & Zavala 2020).

8. Tree Health

Plant Health, including tree health, is a devolved matter. Tree health policy in Wales (as a subset of plant health) is the responsibility of Welsh Ministers, whilst regulatory activities are carried-out on behalf of Welsh Ministers by Natural Resources Wales, supported by Forest Research (FR) and the Animal and Plant Health Agency (APHA). Some tree health activities, including plant passporting for timber movement within Great Britain, are coordinated by the Forestry Commission (FC).

It is well accepted that the magnitude of expression of the effect of a tree pest or disease is the result of an interaction between the tree (the host), the pest organism, and the environment; the disease triangle (Stevens 1960, Franci 2001), Figure 8-1.

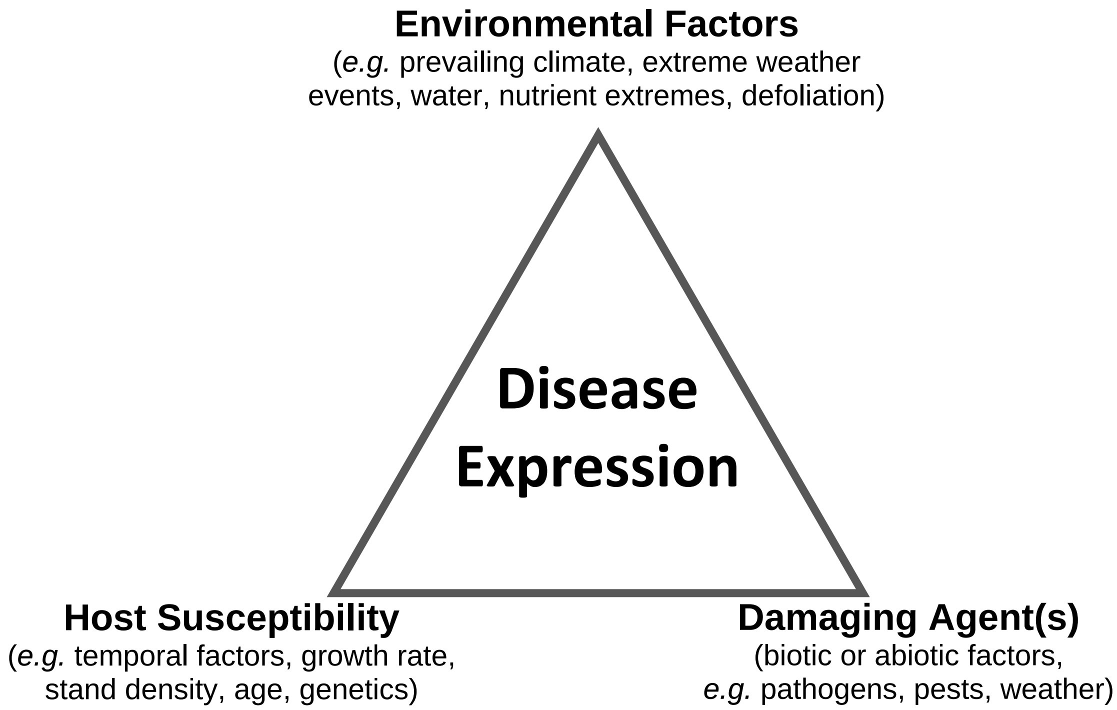

Figure 8-1 The disease triangle illustrating that the degree of disease expression is the product of a complex interaction between physical environment, host condition, and damaging agent(s).

Threats to tree health can be broken down as:

Abiotic – including adverse local soil conditions (edaphic factors), climatic factors (*e.g.* temperature, wind, rainfall), and mechanical damage (*e.g.* from horticultural or forestry machinery).

Biotic – including viruses, bacteria, fungi, plants, invertebrates (primarily insect species), birds and mammals (including man).

It is well accepted that a tree weakened by adverse environmental conditions (*e.g.* drought and shallow soils) or already affected by the presence of another biological organism (such as a root rot fungus) is likely to succumb more quickly to a new threat; the decline spiral, proposed by Manion (1981) is illustrated in Figure 8-2

Manion recognised three classes of factor which contribute to tree decline. The first are long-term, generally static (*i.e.* non- or slowly-changing) "*predisposing factors*" that weaken a tree being grown in the wrong location by putting it under permanent stress and thereby increasing its susceptibility to other factors. *Predisposing factors* include climate, soil type, aspect and elevation, genetic potential and tree age. The effect of *predisposing factors* can be minimised [within the national Forest Programme] by appropriate species selection; the right tree in the right place.

The second group of factors, which are short in duration and of biological or physical nature, were described by Manion as *inciting factors*. *Inciting factors* generally cause significant injury to the tree from which recovery *may* be possible, in the absence of long-term predisposing factors. Examples of inciting factors include defoliation, herbicide damage, mechanical injury, frost, drought, air pollution and salt. Some inciting factors are human-mediated and may consequently be mitigated against by good silviculture and tree care.

The final group are *contributing factors*; long-term (persistent) and biological in nature. These include bark beetles, canker fungi, root and sap rot fungi, wilt organisms, bacteria, mycoplasmas and viruses. Whilst often blamed for the condition of the host, these contributing factors may be considered as indicators of weakened hosts. Limiting both *predisposing* and *inciting* factors across the National Forest Programme will maximise resilience by reducing the impact of contributing factors.

It is increasingly accepted that both acute and chronic oak decline (AOD and COD) are symptoms of the interaction of factors within the disease decline spiral.

The effect of forest management options on forest resilience to pests and pathogens is well accepted. A useful review of recent evidence is provided in Roberts et al. (2020).

There is currently conflicting evidence around the effect of structural connectivity of woodlands and the risk of pest/disease transmission (including evidence for ash dieback and other fungal wind-borne diseases), and the importance of facilitating species range shifts in response to climate change to support biodiversity (whether of tree species in natural woodlands, or of woodland habitat specialist biodiveristy).

There is also conflicting evidence around the resilience building measure of increasing forest tree species diversity and the increase or introduction of non-native species having negative impacts on tree health. This risk can be mitigated by diversifying with site-native, naturalised and well-established species, until further evidence is available.

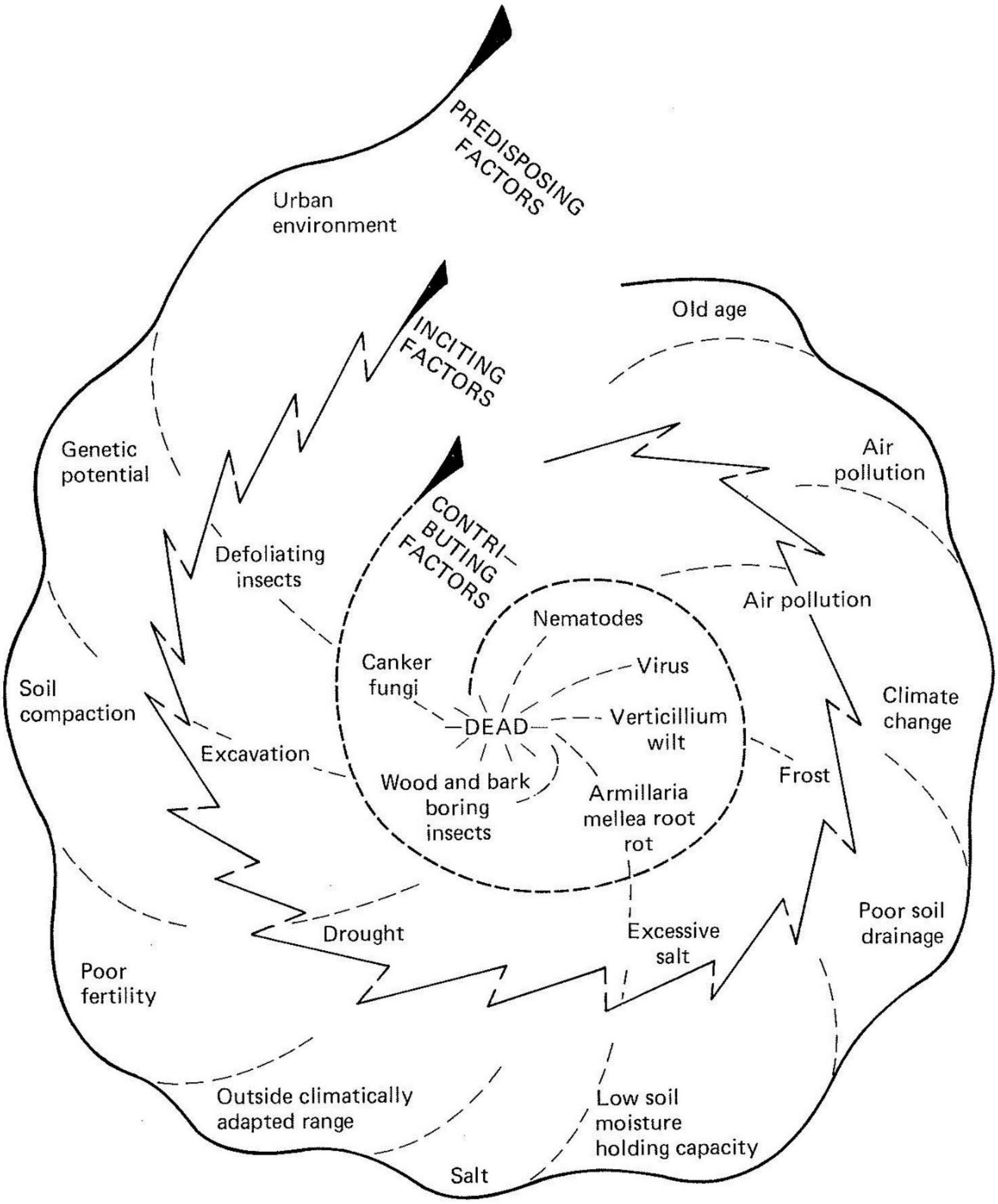

Figure 8-2 The Manion Decline Spiral, showing three classes of factors that may play a role in tree decline (Manion 1991, p328).

The majority of recent biotic threats to trees can be categorised either as: Invasive Non-Native Species (INNS) affecting native or naturalised tree species; or native species (not previously recognised as potential tree pests or pathogens) affecting introduced (non-native) tree species. In these cases, the impact of the pest species (disease expression) is exacerbated because the pest and host have not co-evolved; it does not usually make biological sense for an organism to kill its host. A recent example of a non-native pathogen impacting a native tree species is [Chalara] ash dieback, caused by the introduced fungus *Hymenoscyphus fraxineus*. In its native range, *H. fraxineus* is a leaf pathogen of native ash species – the ash trees simply shed their leaves when they detect the presence of the leaf fungus. Common ash (*Fraxineus excelsior*) has only recently been exposed to *H. fraxeneus* and has consequently not had the opportunity to evolve this leaf-shedding defence mechanism; the fungus is consequently able to grow down the leaflet midrib (petiole), and compound leaf stalk (rachis) to enter and kill the living inner bark (cambium) of the tree. Where death of the cambium occurs around the entire circumference of a twig, branch or tree stem, all tree tissue beyond that point dies causing the visible symptoms of ash dieback.

In rarer situations, adverse growing conditions, including those exacerbated by unusual or extreme climatic conditions (such as drought), can potentially allow a previously benign [native or naturalised] organism to negatively impact on the health of native [and/or introduced] trees.

Unlike in many agricultural or horticultural environments where the growing plants are regularly examined (sometimes many times in a single year), the location and accessibility of many forests and woodlands means that [new] pest and disease problems may not become apparent for several years. There is strong evidence that some recently introduced pests and diseases may have been present in GB for more than 10 years before discovery. This can have significant implications on our ability to manage the pest or disease, as it will be further from the lag phase and closer to the exponential-type phase of expression.

If we take as an example Chalara ash dieback in Britain, the arrow in Figure 8-3 at A is the initial point of discovery (2012), here assumed to be within 2 years of the date of introduction. This being the case, the arrow at B is where we would be 8 years later (2020), still with relatively low numbers of affected trees across Britain. However, there is now strong evidence that the disease has been present in the UK since at least 2004, eight or more years longer than previously assumed (*i.e.* at point B). Rather than still being at the end of the lag phase, the rate of spread of the disease has now progressed to point C (the exponential-type growth phase) explaining the rapid apparent spread of the disease to the point where control is impossible.

In the case ash dieback, this has been exacerbated by the presence of numerous loci of infection across Britain from infected planting stock imported from European tree nurseries.

It is generally accepted that, having a deadwood resource (standing and fallen) is beneficial for the woodland biodiversity (Annex-1/ERAMMP Report-33: *Biodiversity*), but that the risk to the public (mainly from standing deadwood) must be managed, as must the contribution to wildfire risk on vulnerable sites. Useful guidance is provided in the publication "*Common sense risk management of trees: Guidance on trees and public safety in the UK for owners, managers and advisers*" (National Tree Safety Group 2011).

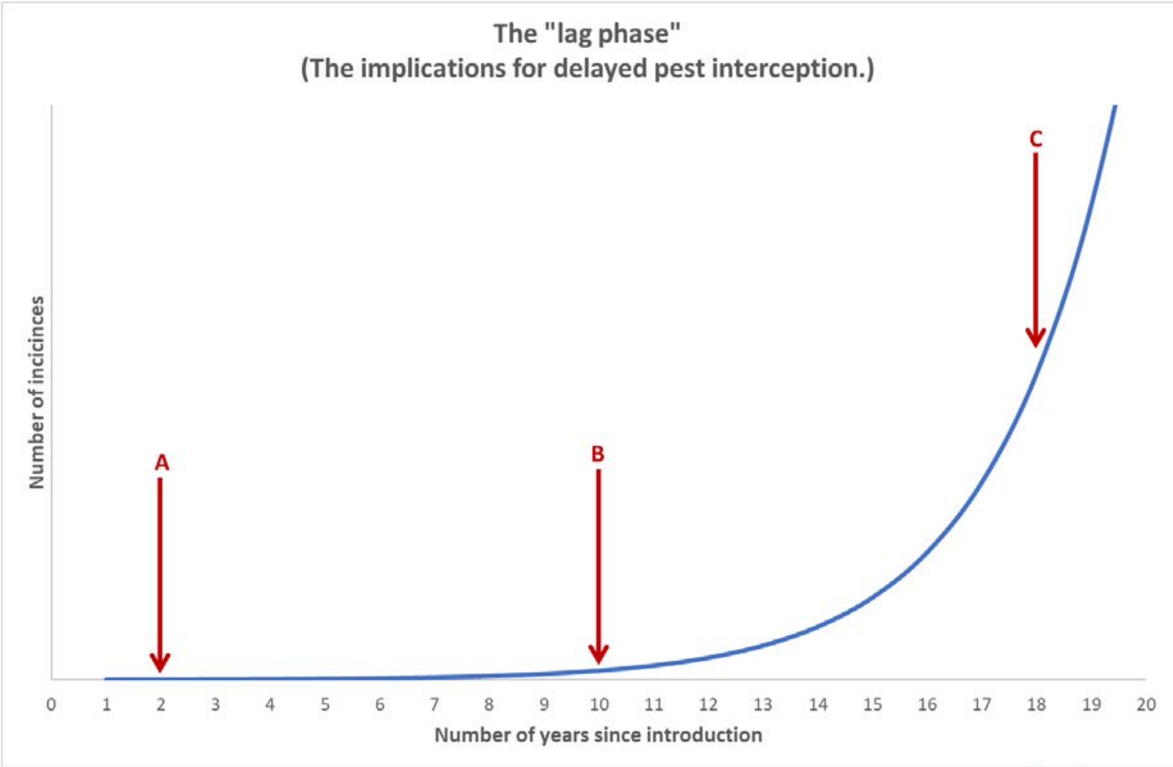

Figure 8-3 Illustration of the effect of delayed pest interception on the numbers of incidences, and rate of expansion of pest population.

It is well accepted that the key to managing the introduction of pest and disease organisms is to understand, and limit, the potential pathways for entry.

The key here is to manage once, remove many. There is good evidence that using locally-grown (GB-origin) plants is safest. Otherwise, imports should be considered only where the "place of production has freedom pests" (*i.e.* has protected zone status), and a period of quarantine should be considered. Plant passports unfortunately don't guarantee freedom from pests, as evidenced by the recent widespread introduction of ash dieback before 2012 and interceptions of oak processionary moth on passported imported trees in the summer of 2019.

Live plant imports in declining order of risk: large specimen trees, complete with root balls; trees and shrubs (bare-rooted or with growing medium); bonsai and penjing; rootless cuttings; seeds and other germplasm.

Pests transported in untreated wood also pose significant risk. Previous examples of pests introduced to the UK in untreated wood include the great spruce bark beetle (*Dendroctonus micans*) and the Asian longhorn beetle. The declining risk profile (*i.e.* highest to lowest risk) for untreated wood is: firewood; rough wood packaging, including dunnage; sawn wood with bark; manufactured wood packaging; sawn wood without bark; manufactured and processed wood. A good rule-of-thumb is "the more bark is present, the higher the risk". Treatments (*e.g.* heat, fumigation, high temperature kiln drying; microwaves) remove most of the risk. The ISPM15[8] standard for wood packaging is an excellent example of a process-based solution to

[8] https://www.gov.uk/wood-packaging-import-export

a previously highly dangerous pathway. A greater use of home-grown timber rather than imported could also reduce this risk.

Quarantine (Notifiable[9]) pest and diseases – these are pests and diseases that have the potential to cause significant socio-economic damage to the agriculture, horticulture and/or forestry sectors. A downloadable matrix listing notifiable tree pests and diseases for Great Britain[10] is published by Forestry Commission England, the current version of which is accessible from the GOV.UK website[11]. In February 2020, the matrix listed 27 notifiable organisms and their pathways for spread. Factsheets for a sub-set of these organisms is maintained on the DEFRA website[12], however the focus of these factsheets is currently the agriculture and horticulture sectors. Additional up-to-date information on all notifiable and other significant tree pests and diseases is available on the pest and disease resources area of the Forest Research website[13].

A further invaluable source of current information is the on-line UK Plant Health Risk Register maintained by Defra[14]. As at 22nd January 2020, this listed 1,050 pests and diseases which threaten agricultural crops, trees, gardens and countryside. Thirteen of the top 20 listed organisms ranked by mitigated risk rating have trees as hosts.

However, not all recently introduced pests and diseases appear on lists. To illustrate this, successful establishment of major pests not on lists before arrival in receiving country include:

- Asian longhorn beetle (*Anoplophora glabripennis*), introduced from Asia into the USA and several EU countries, including UK;
- Emerald ash borer (*Agrilus planipennis*) introduced from Asia into the USA and Russia;
  - Oriental chestnut gall wasp (*Dryocosmus kuriphilus*) introduced from Asia into the USA and parts of EU (including GB);
  - *Phytophthora ramorum* (origin unknown) introduced into the USA and EU (including the UK);
  - *Phytophthora kernoviae* (origin unknown) introduced into the EU (including the UK) and New Zealand;
  - Chalara ash dieback (*Hymenoscyphus fraxineus*) introduced from Asia into the EU (and from the EU into the UK); and
  - there are very many other examples worldwide

[9] https://planthealthportal.defra.gov.uk/pests-and-diseases/pest-and-disease-factsheets/notifiable-pests/
[10] Although the matrix makes specific reference to England, the published information is also directly applicable to Scotland and Wales.
[11] https://www.gov.uk/guidance/report-a-tree-pest-or-disease-overview
[12] https://planthealthportal.defra.gov.uk/pests-and-diseases/pest-and-disease-factsheets/notifiable-pests/
[13] https://www.forestresearch.gov.uk/tools-and-resources/pest-and-disease-resources/
[14] https://secure.fera.defra.gov.uk/phiw/riskRegister/

Value at risk

A useful and widely accepted concept, when prioritising the resources that should be directed towards the protection of trees and woodlands, is “value at risk” (Davies et al*.* 2017). This common-sense approach dictates that the greater the objective value at risk, the higher the priority for protection. It is important to note that the calculation of woodland “value” should include an assessment of all appropriate anticipated socioeconomic outputs (see also Annex-1/ERAMMP Report-33: *Biodiversity*).

Multi-agency tree health contingency plans have been developed by the Forestry Commission, in conjunction with the relevant stakeholders in the devolved administrations. A number of these plans have been successfully applied to recent interceptions and outbreaks including *Ips typographus* (the larger eight-toothed spruce bark beetle, December 2018 in Kent) and the oak processionary moth (July 2019, various locations, including in Wales).

9. Climate Change Impacts on Forest Ecosystem Service Provision

Forest ecosystem service provision is explored in Annex-5/ERAMMP Report-37: *Ecosystem Services* impacts of climate change on a number of ecosystem services.

9.1 Impacts on cultural ecosystem services Recreation, health, aesthetics, employment

Recreation

Visits to forests have risen steadily over the last 20 years from 303 million visits in 1994 to approximately to 575 million visits in 2015 (Forestry Commission 2019). While climate change is perhaps not a recognised direct reason for increased numbers of visits, warmer and drier summers in recent years are likely to have contributed to people choosing to visit forests (Ray et al. 2016). Forests are thus considered as an important resource for increasing visitor numbers in a warmer climate (Snowdon 2009).

Human health

Climate change is very likely to have severe consequences on human health. For example, the 2003 European heatwave produced very high maximum temperatures, 20-30% higher than the seasonal average (Ray et al. 2016). Urban heat islands form in towns and cities, in which temperatures are several degrees higher than rural areas, exacerbating the effect of heatwaves (Doick et al. 2014). There is substantial evidence showing the heat reduction benefit which urban greenspace, and urban trees and woodland parks in particular, provide (Doick et al. 2014; Gill et al. 2007; Handley and Gill 2009; Klemm et al. 2015). Increasing urban woodland and greenspace is considered a very effective adaptation strategy for climate change and will provide an important regulating service in urban areas (Lindley et al. 2006).

There is also recent evidence of a human health benefit from the exposure to weak concentrations of volatile organic chemicals and other compounds released by trees that stimulate the body and its immune system (Moore 2015). However, for these benefits to be resilient to climate impacts such as extreme weather, species which exhibit greater plasticity and genetic diversity to drought should be favoured, particularly in urban woodland, and as street trees in cities (Ray et al. 2016).

Landscape Aesthetics

The direct impacts of climate change on trees and forests will alter the visual aesthetics of our landscapes, with potentially negative impacts such as from increased forest clearance of damaged or diseased stands. However, the proposed adaptation strategies of increasing species diversity and changing species selection and management may benefit visual aesthetics, as people tend to enjoy some species diversity, with open spaces to allow views of the landscape (Edwards et al. 2012) and heterogeneous woodlands managed using low impact silvicultural systems (Ray et al. 2016) over single-aged stands of monocultures. Woodland expansion is a key aim of Welsh climate change policies to increase carbon sequestration and will also impact landscape aesthetics; the impact of woodland type and location on landscape aesthetics are considered in Annex-5/ERAMMP Report-37: *Ecosystem Services*.

Employment

Climate change is likely to affect site conditions, forest management operations, workload and employment. Increased winter rainfall will restrict access on sites prone to water logging, as requirements prevent access to prevent soil erosion. Planting times may also be restricted or delayed during periods of drought or heavy rainfall due to increased plant mortality. Site access is already restricted during certain times of the year to protect priority species such as ground nesting birds and climate change may alter the timing of these restrictions. The increased vulnerability and mortality of newly planted and establishing stands to extreme events will lead to additional work and increased plant supply at beating-up, if stands fail to establish due to drought, fire or storms. This can also reduce workforce and plant availability for woodland creation. The impacts of climate change on the forestry sector are considered in Section 10.

Adaptation measures such as changing species and closer to nature forestry will result in an increase in management intensity and require increased fencing, which could increase employment opportunities. Upskilling of the sector may be necessary to support these adaptation measures, as additional knowledge is required to establish and grow novel species and to manage irregular stands. Increased numbers of recreation users in woodland and forests during hotter summers and heat waves could increase employment opportunities in recreation and tourism enterprises.

9.2 Impacts on regulating and maintenance services Climate change mitigation, water quality and quantity, slope stability & landslides

Climate change mitigation

Climate change has the potential to affect the amount of carbon sequestered by trees and woodlands in the UK, through both gradual changes and disturbance from extreme events. See Annex-4/ERAMMP Report-36: *Climate Change Mitigation* for further details. Potential adaptation measures such as replacing commercial conifer stands with slower growing species, in order to increase species and structural diversity, will also affect carbon accounting. However, ‘there is no mitigation without adaptation’. ‘Climate-smart forestry’ aims to address the cross-cutting considerations of climate change mitigation and adaptation.

Water quality & quantity

Climate projections indicate that more frequent, and more extreme, storm events will lead to increased flooding and negative impacts on water quality. Woodland creation and management in riparian zones are increasingly being used to slow peak flood flows with the aim of protecting downstream property and infrastructure (Nisbet et al.

2011), however the evidence for the benefits to flood mitigation in extreme flood events, as projected to increase under climate change, is conflicted (see Annex-5/ERAMMP Report-37: *Ecosystem Services*). Compared to intensive agriculture and pasture, agroforestry systems promote improved regulation of soil water and infiltration (Pramova et al. 2012) thereby moderating some of the detrimental impacts of extreme events (Stokes and Kerr 2009). Wood-pasture systems and well-placed shelter belts in upland catchments have been shown to be highly effective in reducing overland flow, by improving soil structure and infiltration (Marshall et al. 2009) thus helping to attenuate peak flows and downstream flooding, as well as soil erosion, following intense rainfall events. Nisbet et al. (2011) reviewed modelling work that predicted a reduction in peak flows by between 13 and 48% by planting shelterbelts across the lower parts of sloping pasture (Jackson et al. 2008), figures supported by field observations. Further details of this regulating service can be found in Annex-5/ERAMMP Report-37: *Ecosystem Services*.

Forests, trees and hedgerows can also provide shade for animals and other taxa and riparian woodland can reduce water temperature during heatwaves. Forests, hedgerows and shelterbelts can provide protection and shelter during storms with financial and environmental benefit.

Slope stability and landslides

Both slow and rapid movements of soil, rock, and associated vegetation are triggered directly by climate factors, including snowmelt and intense rainfall, and indirectly by climate-influenced processed (e.g. stream-bank erosion) (Dale et al. 2001). Climate change is expected to increase storminess, soil saturation, and therefore landslide occurrence (Daleet al. 2001). Landslides occur less in forested areas than non-forested areas (Pramova et al. 2012). However, uncertainties remain about the role of forests in landslide prevention. Some studies conclude that landslides occur independent of vegetation cover and that rainfall intensity can overwhelm the role of roots in stabilizing soils. Thus, forests can reduce the effects of increased rainfall intensity on soil erosion, but may have a lesser role to play for disaster risk reduction (Pramova et al. 2012). See Annex-5/ERAMMP Report-37: *Ecosystem Services*.

Protective Forestry

Forestry can serve a protective role and contribute to resilience measures in other sectors and land uses. The protective role of forests are summarised in Table 9-1.

Table 9--1 Climate Change Projections and Protective Forestry in Wales

Climate Variable	Impacts across Wales	Benefits of Protective Forestry	Potential Risk to other sectors
Increase in Summer Temperatures	Species distribution. Heat wave damage to health, infrastructure & environment	Urban Cooling, Riparian cooling. Shelter for animals, & insects	Increased wildfire risk
Warmer Winter Temperatures	Species distribution & biodiversity. Increased pests & pathogen risk	None	None

Increase in Winter Rainfall	Regional & seasonal flooding, landslides	Natural flood management, Slope stability	Landslide risk
Decrease in Summer Rainfall	Increased drought & wildfire risk	Urban cooling, animal shelter	Increased wildfire risk
Increase in frequency & severity of storms (wind risk)	Storm damage to property, business, environment	Shelterbelts, animal & property protection	Damage to property, transport and infrastructure

Forests, trees and woodlands can also pose a risk to other sectors and land users, which may increase under climate change, and these effects can and must be mitigated, for example through cross-sector risk assessment and the appropriate management of trees and woodland adjacent to roads, railways and buildings, and the appropriate location and management of new woodlands. The possibility of increased pollen production and Volatile Organic Compounds can aggravate certain medical conditions and should be considered when selecting species in urban areas, as there are reports of short-term variation in pollen concentration being associated with allergy medication purchases, asthma symptoms, and asthma-related emergency department visits.

9.3 Impacts on provisioning services: biodiversity and forest products

Biodiversity

Climate change impacts on biodiversity are considered in Annex-1/ERAMMP Report-33: *Biodiversity* and Annex-5/ERAMMP Report-37: *Ecosystem Services*.

Forest products

Climate change impacts on productivity are discussed through this Annex; disruption from extreme events will also disrupt timber availability, e.g. drought will reduce growth rates, and windthrow and wildfire may lead to loss in volume and revenue. Productivity is correlated with suitability for any given tree species, i.e. a higher suitability score equates to a higher growth rate, however species can have very different maximum yield classes. Species with similar suitability scores may have different growth rates and productivity, therefore changes to species selection will also impact production and markets (see Annex-6/ERAMMP Report-38: *Economics and Natural Capital Accounting*). The impacts of climate change on the forestry sector are considered in Section 10 in this Annex.

10. Climate Change Risk to the Forestry Sector

As well as impacts on forests and woodlands projected climate change will impact directly on forestry sector businesses (Surminski et al. 2016) potentially affecting economics and employment. There is an increased risk of damage to buildings, and disruption to transport, infrastructure and IT services during heat waves, storms, flooding or fire, as well as impacts on working conditions and productivity (Dawson et al. 2016). Business continuity and contingency planning incorporating climate risks should be encouraged in order to allow the forestry sector to continue delivering the widest range of ecosystem services (Beauchamp 2018a).

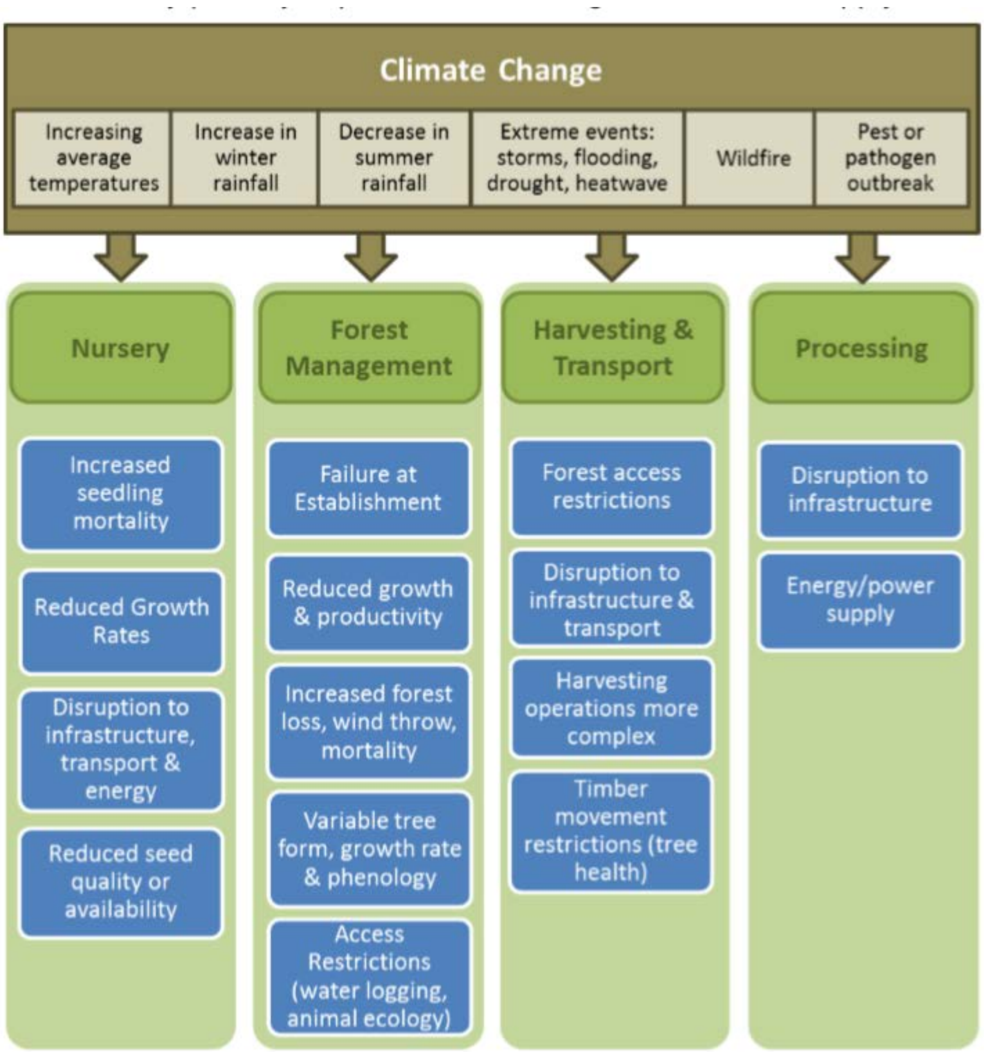

Figure 10--1 Primary impacts of climate change at each stage of the forestry supply chain, reproduced from Beauchamp (2018b).

Climate change will impact local, national global supply chains, including those in the forestry sector. Potential impacts for the forestry sector in Scotland are considered in Beauchamp (2018b), with the principles and considerations applying to Wales, see Figure 10-1. Note that not all forestry businesses are included and the impacts on interdependent supply chains for recreation and tourism also need to be considered, as do the impacts on workload and employment.

For the aims of the National Forest in Wales, including woodland expansion and management, the risks to nurseries and forest management need to be considered, however climate change impacts at any stage in the supply chain will have secondary impacts further up and down the chain. To illustrate this, the potential secondary impacts of disruption to forest management elsewhere in the supply chain are presented in Figure 10-2 with the wider range of primary and secondary climate change impacts considered in Beauchamp (2018b). It will be important to consider the interdependent supply chains for recreation and tourism; for example widespread felling of Larch stands as a result of infection with *Phtyopthora ramorum* lead to the closure of walking and mountain biking routes to allow forest operations. The extended period of disruption lead to severe financial strain on surrounding businesses, including cafes, hotels and bike shops, and many were forced to close.

Resilience building measures are needed at each stage of the forestry supply chain and across the supply chain to address these risks, including greater research, communication, investment, education and training, as well as continuity and contingency planning.

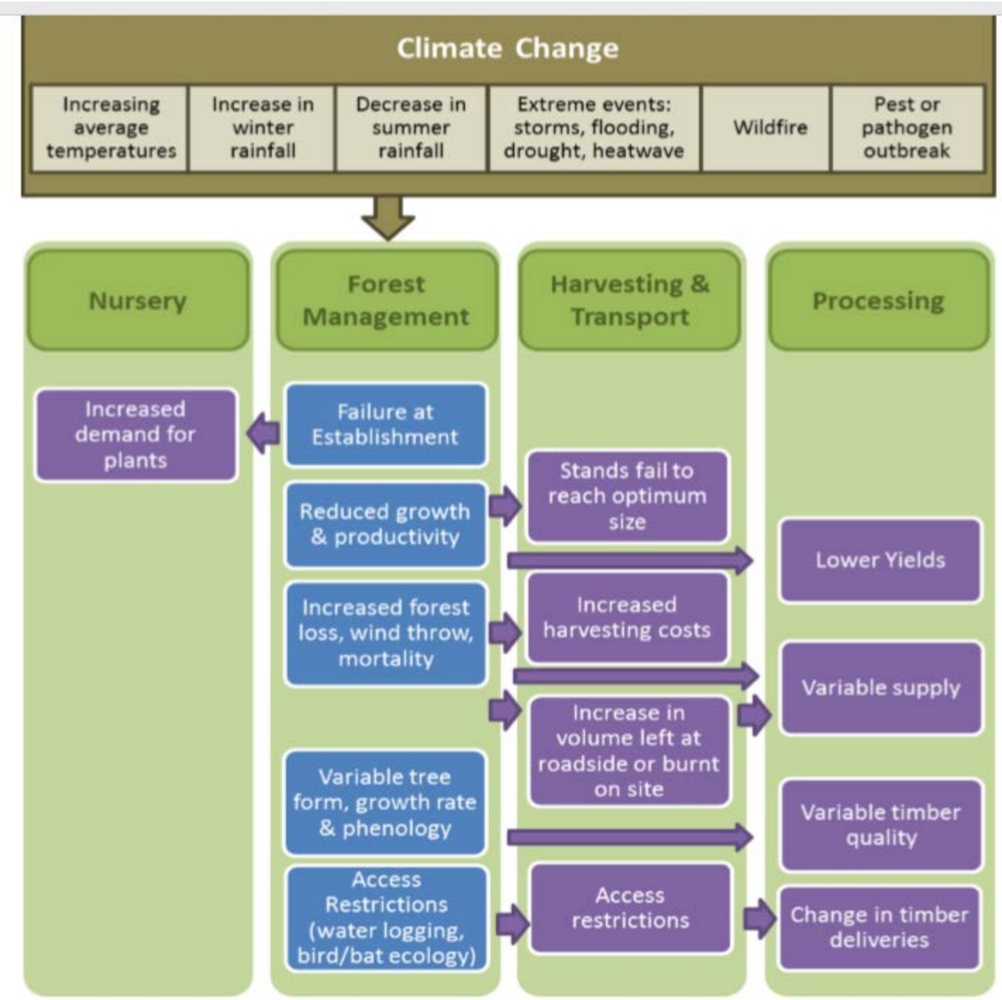

Figure 10-2 Secondary impacts of climate change from forest management across the forestry supply chain, reproduced from Beauchamp (2018b).

11. SUMMARY FOR FUTURE-PROOFING

11.1 Resilience Building & Adaptation

There are a range of approaches to resilience and adaptation; primarily routes in the forestry sector aim to decrease vulnerability to risks, by either reducing the impacts of a climate risk or increasing the rate or capacity for recovery. Measures to reduce vulnerability may include selecting an appropriate forest type for the location; species selection for current and future site and climate conditions; selecting an appropriate management strategy and management plan; increasing species, genetic and structural diversity; site engineering; and optimising woodland condition and biodiversity. Resistance building measures aim to prevent impacts from a risk occurring, e.g. by selecting species resistant to a forest pest or pathogen (Fuller and Quine 2016).

Social and political actions can also reduce vulnerability and support resilience, such as raising awareness of risk, identification of risks and appropriate adaptation measures, and supporting capacity building for resilience and adaptation across the sector.

Adaptation by reducing exposure is rarely possible for existing woodland but is an essential adaptation consideration for new woodland creation, through avoiding high risk sites, such as high wind risk or areas prone to wildfire/arson. We can reduce the exposure of new and existing forest to some tree pests and pathogens by containing spread through statutory felling and monitoring imports of timber, wood products, pallets, plants and seeds through border and nursery checks. Reducing the hazard is not an option for climate risk as we cannot influence our climate, except through climate change mitigation.

Where anticipatory adaptation actions are not possible then increased monitoring can minimise vulnerability and exposure risk, by leading to rapid action e.g. monitoring for wildfire, pests and pathogens both on the ground and through aerial surveys. Contingency planning can assist in increasing resilience by reducing the severity of impacts and increasing the rate of recovery (Beauchamp 2018a). Further details of adaptation actions are contained in Forest Research adaptation manual (Forest Research 2020).

Forest management objective is crucial in determining the definition of resilience and selecting appropriate adaptation actions; whether conservation, timber production, wood fuel production, protective forestry, amenity. Accepting the level of risk and potential consequences alongside felling and replanting may be an option on some sites, however where conservation is critical then different resilience building measures must be implemented.

For Native, Ancient and ASNW Woodlands improving woodland condition, increasing woodland size and connectivity can increase resilience (Annex-1/ERAMMP Report-33: *Biodiversity*). Woodland condition can be improved through appropriate species selection, a diverse age-size structure, presence of open space, diverse species composition, appropriate level of grazing activity and limiting Invasive Non-Native

Species. Increasing the biodiversity of the forest and landscape can support ecosystem processes and increase resilience (reviewed in Bellamy et al. 2018, see Annex-1/ERAMMP Report-33: *Biodiversity*). There is currently conflicting evidence around the effect of structural connectivity of woodlands and the risk of pest/disease transmission (including some work on ash dieback and other fungal wind-borne diseases), and the importance of facilitating species range shifts in response to climate change (whether of tree species in natural woodlands, or of woodland habitat specialist biodiversity)

Acceptance of natural colonisation of some non-native but naturalised tree species (e.g. beech and sycamore) in woodlands may be a valid adaptation strategy, but this must be reviewed where conservation is a major objective. Guidelines for sustainable forest management and increasing the species, genetic, and structural diversity in Wales are available in Natural Resources Wales Forest Resilience Guides (NRW 2017, a, b, c). In some cases this will be achieved across the landscape or wider scale.

11.2 Achieving Resilience

Increasing the diversity of tree species in the forest landscape is considered a key strategy for reducing risk from the dominance of a single species and supporting resilience to future change. There is concern that the increase in non-native species could increase risks, especially to tree health (Ennos et al. 2018). Barriers to diversification within forestry and associated sectors have been identified and need to be considered to support adaptation (Atkinson & Ambrose-Oji 2017; Barsoum & Henderson 2016; Lawrence & Marzano 2014; RFS 2018).

Commonly discussed barriers to the diversification of productive forests include the lack of markets for minor species and insufficient timber volume to create markets, slower growth rates, higher establishment and management costs, increased vulnerability to browsing, limited seed and seedling availability, and limited knowledge in establishing and managing novel tree species. Support to develop markets for future timber may be beneficial, in addition to support for local hardwood, wood-fuel and non–timber forest products. Clear national strategies for managing, moving and processing infected timber and material may be needed, and consistent guidance and stance on funding sources and support for clearing and replanting infected or damaged woodland could support with managing tree health risks.

Barriers to the restoration and active management of native woodland are partly financial, where the cost of intervention is greater than potential revenue and also due to confidence, risk, knowledge and experience (Lawrence & Dandy 2014; Lawrence & Marzano 2014). Likewise, the conversion of stands to more resilient closer to nature management also comes with higher costs, increased perception of risk, and requires a different skill set (Barsoum & Henderson 2016; Lawrence & Marzano 2014).

Sufficient funding for landowners to plant diverse, well adapted woodland, appreciating that more diverse species and resilient management options may require additional effort and cost to establish and manage has been identified as part of the solution to support adaptation, along with reducing bureaucracy, personal contact with advisors, and greater understanding of the cultural and emotional connection of landowners to their land (Lawrence & Dandy 2014; WEAG 2012). Advanced planning is needed support forest nurseries and to allow seed and seedling availability for novel species and this delay needs to be accommodated within local planning and grant schemes which can often constrain planting to short term scales.

Current policy, such as in the Woodland for Wales strategy (Welsh Government 2018) and guidelines in the UK Forestry Standard (2017) supports sustainable forest management, and the evidence suggests there is scope for further policy support, grants and incentives to support the forest sector to establish diverse and resilient woodlands and meet planting targets.

12. References for Annex-3

Adams HD, Guardiola-Claramonte M, Barron-Gafford GA, Villegas JC, Breshears DD, Zou CB, Troch PA, and Huxman TE. (2009) Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought. PNAS, 106, 7063–7066.

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D. D., Hogg, E. H., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S. W., Semerci, A. and Cobb, N. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests, Forest Ecology and Management, 259, 660–684.

Anderegg, W.R.L., Konings, A.G., Trugman, A.T., Yu, K.L., Bowling, D.R., Gabbitas, R., Karp, D.S., Pacala, S., Sperry, J.S., Sulman, B.N., Zenes, N., (2018). Hydraulic diversity of forests regulates ecosystem resilience during drought. Nature, 561, 538-541.

ASC (2016) UK Climate Change Risk Assessment 2017 Evidence Report – Summary for Wales. Adaptation Sub-Committee of the Committee on Climate Change, London. Available at: https://www.theccc.org.uk/wp-content/uploads/2016/07/UK-CCRA-2017-Wales-National-Summary.pdf

Atkinson, G. and Ambrose-Oji, B. (2017) What do Forest Managers want to know about adaptation? Forest Research. Available at: https://www.forestresearch.gov.uk/research/what-do-forest-managers-want-to-know-about-adaptation/

Barsoum, N. & Henderson, L. (2016) Converting planted non-native conifer to native woodlands: a review of the benefits, drawbacks and experience in Britain Forestry Commission Research Note 24 (FCRN024) Available at: https://www.forestresearch.gov.uk/documents/6977/FCRN024.pdf

Barton, J. and Pretty, J. (2010). What is the best dose of nature and green exercise for improving mental health? A multi-study analysis. Environmental Science & Technology, 44.10: 3947-3955.

Bathgate, S., McKay, H.M. and Jenkins, T.A.R. (2020) Climate-Smart Woodlands: The potential for woodland creation on ALC grade 3b land in Wales. Forest Research Project Report. In preparation.

Bauhus, J., Forrester, D. I. & Pretzsch, H. (2017). Mixed-Species Forests: The Development Of A Forest Management Paradigm in Pretzsch, H., Forrester, D. I. & Bauhus, J. eds. Mixed-Species Forests - Ecology and Management. Springer, 1–25.

Beauchamp, K. (2018a) Climate change impacts on Scotland's forestry supply chain. ClimateXChange Available at: www.climatexchange.org.uk/media/3055/climate-change-impacts-on-scotlands-forestry-supply-chain.pdf

Beauchamp, K. (2018b) The Role of Contingency Planning in Climate Change Adaptation for the Forestry Sector in Scotland. ClimateXChange. Available at: www.climatexchange.org.uk/media/3050/the-role-of-contingency-planning-in-climate-change-adaptation-for-the-forestry-sector-in-scotland.pdf

Beauchamp, K., Bathgate, S. & Ray, D. Nicoll, B. (2016). Forest ecosystem service delivery under future climate scenarios and adaptation management options: a case study in central Scotland. Scottish Forestry, 70. 30-41.

Bellamy, C. Barsoum, N. Cotteell, J. Watts, K. (2018) Encouraging biodiversity at multiple scales in support of resilient woodlands. Forestry Commission Research Note 33

Bladon, F., and Evans, J. (2015). Alternative species in situ. Quarterly Journal of Forestry, 109 (2) 117-121.

Brown, I., Thompson, D., Bardgett, R., Berry, P., Crute, I., Morison, J., Morecroft, M., Pinnegar, J., Reeder, T., and Topp, K., (2016). UK Climate Change Risk Assessment Evidence Report: Chapter 3, Natural Environment and Natural Assets. Report prepared for the Adaptation Sub-Committee of the Committee on Climate Change, London.

Buras, A., Schunk, C., Zeiträg, C., Herrmann, C., Kaiser, L., Lemme, H., Straub, C., Taeger, S., Gößwein, S., Klemmt, H.-J. and Menzel, A. (2018). Are Scots pine forest edges particularly prone to drought-induced mortality? Environmental Research Letters, 13, 025001.

Cabinet Office (2013) National Risk Register of Civil Emergencies. Cabinet Office, London.

Cameron, A.D. (2015). Building Resilience into Sitka Spruce (Picea sitchensis (Bong.) Carr.) Forests in Scotland in Response to the Threat of Climate Change. Forests 6, 398-415.

Cameron, A.D., Mason, B. (2013). Western hemlock (Tsuga heterophylla (Raf.) Sarg.): are we ignoring one of our most useful tree species? Scottish Forestry 67, 10-14.

Choat, B., Jansen, S., Brodribb, T.J., Cochard, H., Delzon, S., Bhaskar, R. Bucci, S.J., Field, T.S., Gleason, S.M, Hacke, U.G., Jacobsen, A.L., Lens, F., Maherali, H., MartínezVilalta, J., Mayr, S., Mencuccini, M., Mitchell, P.J., Nardini, A., Pittermann, J., Pratt, R.B., Sperry, J.S., Westoby, M., Wright, I.J., Zanne, A.E. (2012). Global convergence in the vulnerability of forests to drought. Nature, 491(7426):p752

Coll, L., Ameztegui, A., Collet, C., Löf, M., Mason, B., Pach, M., Verheyen, K., Abrudan, I., Barbati, A., Barreiro, S., Bielak, K., Bravo-Oviedo, A., Ferrari, B., Govedar, Z., Kulhavy, J., Lazdina, D., Metslaid, M., Mohren, ., Pereira, M., Peric, S., et al. (2018) Knowledge gaps about mixed forests: What do European forest managers want to know and what answers can science provide? Forest Ecology and Management, 407, 106-115.

Committee on Climate Change (2016) UK Climate Change Risk Assessment 2017 Evidence Report Available at: www.theccc.org.uk/UK-climate-change-risk-assessment-2017

Csillery, K., Kunstler, G., Courbaud, B., Allard, D., Lassegues, P., Haslinger, K., and Gardiner, B., (2017). Coupled effects of wind-storms and drought on tree mortality across forest stands from the Western Alps and the Jura mountains. Global Change Biology 23, 5092-5107.

Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J. and Simberloff, D. (2001). Climate change and forest disturbances: climate change can affect forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides. BioScience, 51(9), pp.723-734.

Davies S. (2019). Applying financial risk approaches to the challenge of assessing natural disturbance risks to forests, PhD Thesis, University of Edinburgh, p.185.

Davies S., Patenaude, G. and Snowdon, P. (2017) A new approach to assessing the risk to woodland from pest and diseases. Forestry 90, 319-331.

Dawson, R.J., Thompson, D., Johns, D., Gosling, S., Chapman, L., Darch, G., Watson, G., Powrie, W., Bell, S., Paulson, K., Hughes, P., and Wood, R. (2016) UK Climate Change Risk Assessment Evidence Report: Chapter 4, Infrastructure. Report prepared for the Adaptation Sub-Committee of the Committee on Climate Change, London.

de Jong, M.C., Wooster, M.J., Kitchen, K., Manley, C., Gazzard, R. and McCall, F.F. (2016). Calibration and evaluation of the Canadian Forest Fire Weather Index (FWI) System for improved wildland fire danger rating in the United Kingdom. Natural Hazards in Earth System Sciences, 16, pp.1217-1237.

Doick, K.J., Peace, A. and Hutchings, T.R. (2014). The role of one large greenspace in mitigating London's nocturnal urban heat island. Science of the Total Environment, 493:662–671

Drossler, L., Agestam, E., Bielak, K., Dudzinska, M., Koricheva, J., Liziniewicz, M., Lof, M., Mason, B., Pretzsch, H., Valkonen, S., and Wellhausen, K. (2018) Over- and underyielding in time and space in experiments with mixed stands of Scots Pine and Norway Spruce. Forests, 9, 495; doi:10.3390/f9080495

Edwards, D., Jay, M., Jensen, F., Lucas, B., Marzano, M., Montagne, C., Peace, A. and Weiss, G., (2012). Public preferences across Europe for different forest stand types as sites for recreation. Ecology and Society, 17(1):p27

Ennos, R., Cottrell, J. Hall, J., O'Brien, D. (2018). Is the introduction of novel exotic forest tree species a rational response to rapid environmental change? A British perspective. Forest Ecology and Management. 432. 718-728.

Environment Systems (2020) Tree Suitability Modelling – Planting Opportunities for Sessile Oak and Sitka Spruce in Wales in a Changing Climate, Final report. Report prepared by Bell, G., Naumann, E.K., Medcalf, K. for the Committee on Climate Change

Forest Research (2020) Forestry Adaptation Manual in press

Forestry Commission (2014). Building resilience into forest management planning, Practice Guide 22.

Forestry Commission (2019). Forestry Facts and Figures 2019: a summary of statistics about woodland and forestry in the UK. Forestry Commission, Edinburgh. Available at: www.forestry.gov.uk/statistics

Forestry Commission England (2019). Wildfire Statistics for England 2009-10 to 2016-17. Available at: https://www.gov.uk/government/publications/forestry-commission-england-wildfire-statistics-for-england-2009-10-to-2016-17

Forestry Commission, (2010). Thinning. Operational Guidance Booklet 9. Forestry Commission, Edinburgh 53 pp.

Francl, L.J. (2001). The disease triangle: a plant pathological paradigm revisited. The Plant Health Instructor, 10.

Fuller, L. and Quine, C.P. (2016). Resilience and tree health: a basis for implementation in sustainable forest management. Forestry, 89: 7–19.

Fung F, Bett P, Maisey P, Lowe J, McSweeney C, Mitchell JFB Murphy J, Rostron J, Sexton D and Yamazaki K. (2019). UKCP18 Factsheet: Wind. Met Office Hadley Centre, Exeter. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-fact-sheet-wind.pdf

Gardiner B, Peltola H, Kellomäki S. (2000). Comparison of two models for predicting the critical wind speeds required to damage coniferous trees. Ecological Modelling, 129, 1-23.

Gardiner, B., Achim, A., Nicoll, B., and Ruel, J-C. (2019). Understanding the interactions between wind and trees: an introduction to the IUFRO 8th Wind and Trees Conference. Forestry 92, 375-380.

Gazzard, R. (2015). Wildfire Resilience. Chartered Forester, April 2015, pp. 20-22.

Gardiner, B., Schuck, A. R. T., Schelhaas, M. J., Orazio, C., Blennow, K., & Nicoll, B. (Eds.). (2013). Living with storm damage to forests. European Forest Institute, Joensuu pp. 132

Gill, S.E., Handley, J.F., Ennos, A.R. and Pauleit, S. (2007). Adapting cities for climate change: the role of green infrastructure. Built Environment, 33 (1), 115-133.

Gil-Moreno, D., Ridley-Ellis, D., and McLean, P. (2016). Timber properties of noble fir, Norway spruce, western red cedar and western hemlock grown in Great Britain. Forestry Commission Research Note 26, Forestry Commission, Edinburgh, 6p.

Green, S. and Ray, D. (2009). Climate change: risks to forestry in Scotland due to drought and fungal disease. Forestry Commission Research Note 8. Forestry Commission, Edinburgh.

Greenwood (2017) Tree mortality across biomes is promoted by drought intensity, lower wood density and higher specific leaf area. Ecology Letters, 20, 539-533.

Hale, S. E., Gardiner, B., Peace, A., Nicoll, B., Taylor, P., and Pizzirani, S. (2015). Comparison and validation of three versions of a forest wind risk model. Environmental Modelling & Software, 68, 27-41.

Handley, N. and Gill, S. (2009). Woodlands helping society to adapt in F.-S.P. Read DJ, Morison JIL, Hanley N, West CC, Snowdon P (eds.) Combating climate change - a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change. National Assessment of UK Forestry and Climate Change Steering Group. The Stationery Office, Edinburgh.

IPCC (2012) Glossary of terms in Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.) Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 555-564. Available at: https://archive.ipcc.ch/pdf/special-reports/srex/SREX-Annex_Glossary.pdf

IPCC (2014) Impacts, adaptation, and vulnerability Climate Change 2014: contribution of Working Group II to the IPCC's Fifth Assessment Report (WGII AR5) Annex II Glossary Available at: https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-AnnexII_FINAL.pdf

Jackson, B.M., Wheater, H.S., Mcintyre, N.R., Chell, J., Francis, O.J., Frogbrook, Z., Marshall, M., Reynolds, B. and Solloway, I. (2008). The impact of upland land management on flooding: insights from a multiscale expaerimental and modeling programme, Journal of Flood Risk Management, 1(2):71-80.

Jactel, H., Bauhus, J., Boberg, J., Bonal, D., Castagneyrol, B., Gardiner, B., Gonzalez-Olabarria, J.R., Koricheva, J., Meurisse, N., and Brockerhoff, E.G., (2017). Tree diversity drives forest stand resistance to natural disturbances. Current Forestry Reports 3, 223-243.

Jollands, M., Morris, J. and Moffat, A.J. (2011). Wildfires in Wales. Report to Forestry Commission Wales. Forest Research, Farnham. Available at: http://www.forestry.gov.uk/fr/wildfiresinwales#finalreport

Keenan R.J., Reams G.A., Achard F., de Freitas J.V., Grainger A., and Lindquist E. (2015). Dynamics of global forest area: Results from the FAO Global Forest Resources Assessment, Forest Ecology and Management, 352, 9-20.

Klemm, W., Heuinkveld, B.G., Lenzholzer, S. and van-Hove, B. (2015). Street greenery and its physical and psychological impact on thermal comfort. Landscape and Urban Planning, 138, 87-98.

Kolstrom, M., Lindner, M., Vilen, T., Maroschek, M., Seidl, R., Lexer, M.J., Netherer, S., Kremer, A., Delzon, S., Barbati, A., Marchetti, M., Corona, P. (2011). Reviewing the Science and Implementation of Climate Change Adaptation Measures in European Forestry. Forests 2, 961-982.

Lawrence A. and N. Dandy (2014) Private landowners' approaches to planting and managing forests in the UK: what's the evidence? Land Use Policy 36: 351-360.

Lawrence, A & Marzano, M (2014) Is the private forest sector adapting to climate change? A study of forest managers in north Wales Annals of Forest Science, 71, 291–300

Lawrence, A., Nicoll, B., (2016). Chapter 33 - Climate Impacts and Adaptations in Forest Management in Letcher, T.M. (ed.), Climate Change: Observed Impacts on Planet Earth. (2nd Edition), Elsevier, pp. 585 - 594.

Lee, J., Park, B-J., Tsunetsugu, Y., Ohira, T., Kagawa, T. and Miyazaki, Y. (2011). Effect of forest bathing on physiological and psychological responses in young Japanese male subjects. Public Health, 125:93–100.

Lindley, S.J., Handley, J.F., Theuray, N., Peet E. and McEvoy, D. (2006). Adaptation Strategies for Climate Change in the Urban Environment: Assessing Climate Change Related Risk in UK Urban Areas. Journal of Risk Research, 9:543–568.

Manion, P.D. (1981) Tree Disease Concepts. Prentice-Hall Inc., Englewood Cliffs, NJ.

Marshall, M.R., Francis, O.J., Frogbrook, Z.L., Jackson, B.M., Mcintyre, N., Reynolds, B., Solloway, I., Wheater, H.S. and Chell, J. (2009). The impact of upland land management on flooding: results from an improved pasture hillslope. Hydrological Processes, 23, 464–475

Mason, W.L. (2018c) Forest Gardens find a renewed role in British forestry. CFA Newsletter, 85, 10-12.

Mason, W.L. Jinks, R., Savill, P., and Wilson, S.McG. (2018a) Southern beeches (Nothofagus species). Quarterly Journal of Forestry, 112, 30-43.

Mason, W.L., Petr, M., and Bathgate, S. (2012). Silvicultural strategies for adapting planted forests to climate change: from theory to practice. Journal of Forest Science, 58, 265-277.

Mason, W.L.., MacDonald, F., Parratt, M., McLean, J.P. (2018) What alternative tree species can we grow in western Britain? 85 years of evidence from the Kilmun Forest Garden. Scottish Forestry, 72 , 1, Spring/Summer 2018.

McLaughlin BC, Ackerly DD, Klos PZ, Natali J, Dawson TE, and Thompson SE. (2017). Hydrologic refugia, plants, and climate change. Global Change Biology, 23, 2941-2961.

Met Office (2019) UK Climate Change Projections 2019 Headline findings Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp-headline-findings-v2.pdf

Moffatt, A.J., Morison, J., Nicoll, B., Bain, V. (2012) Climate Change Risk Assessment for the Forestry Sector. Defra, London

National Tree Safety Group (2011) Common sense risk management of trees: Guidance on trees and public safety in the UK for owners, managers and advisers. Forestry Commission, Edinburgh. 103pp. Available at: https://www.forestresearch.gov.uk/research/common-sense-risk-management-of-trees/

Moore, M.N. (2015). Do airborne biogenic chemicals interact with the PI3K/Akt/mTOR cell signalling pathway to benefit human health and wellbeing in rural and coastal environments? Environmental Research, 140:65–75.

Morison, J.I.L. and Matthews, R.B. (eds.) (2016) Agriculture and Forestry Climate Change Impacts Summary Report. Living with Environmental Change. Available at: www.nerc.ac.uk/research/partnerships/ride/lwec/report-cards/agriculture

Nicoll, B and Gardiner, B. (2019). Wind and forests: The evolution of research since the 1950s. Chartered Forester, Summer 2019, 18-20.

Nicoll, B. (2016). Risks for woodlands, forest management and forestry production in the UK from climate change. LWEC Agriculture and Forestry Climate Change Report Card - Technical Paper 8. July 2016. Available at: www.nerc.ac.uk/research/partnerships/ride/lwec/report-cards/agriculture-source08

Nicoll, B.C., Connolly, T., and Gardiner, B.A. (2019). Changes in spruce growth and biomass allocation following thinning and guying treatments. Forests, 10 (3), 253.

Nisbet, T.R., Silgram, M., Shah, N. et al. (2011). Woodland for water: woodland measures for meeting Water Framework Directive objectives, Forest Research Monograph No. 4, Forest Research, Alice Holt, Farnham

NRW (2017a) Forest Resilience Guide 1: Improving the structural diversity of Welsh woodlands March 2017. Good Practice Guide 6. Sustainable Land Management Team, Natural Resources Wales.

NRW (2017b) Forest Resilience Guide 2: Improving the tree species diversity of Welsh woodlands March 2017. Good Practice Guide 7. Sustainable Land Management Team, Natural Resources Wales.

NRW (2017c) Forest Resilience Guide 3: Managing the genetic diversity of Welsh woodlands March 2017. Good Practice Guide 8. Sustainable Land Management Team, Natural Resources Wales.

NRW (2017d) Rhondda trial case study, Healthy Hillsides. Natural Resources Wales Available at: https://naturalresources.wales/media/679661/rhondda-case-study-healthy-hillsides.pdf

Park, B.J., Furuya, K., Kasetani, T., Takayama, N., Kagawa, T. and Miyazaki, Y. (2011). Relationship between psychological responses and physical environments in forest settings. Landscape and Urban Planning, 102:24–32.

Petr, M., Boerboom, L.G., van der Veen, A. and Ray, D. (2014). A spatial and temporal drought risk assessment of three major tree species in Britain using probabilistic climate change projections. Climatic Change, 124(4), pp.791-803.

POST (2019) POSTNote 603: Climate Change and UK Wildfire, The Parliamentary Office of Science and Technology, Westminster, London, 7pp. Available at: www.parliament.uk/post.

Pramova, E., Locatelli, B., Djoudi, H. and Somorin, O. (2012). Forests and trees for social adaptation to climate variability and change. Wiley Interdisciplinary Reviews: Climate Change, 3(6):581–596

Pyatt, G., Ray, D., Fletcher, J. (2001) Forestry Commission Bulletin 124 An Ecological Site Classification for Forestry in Great Britain, Forestry Commission. Available at: https://www.forestresearch.gov.uk/documents/6593/FCBU124.pdf

Quine, C.P., Coutts, M.P., Gardiner, B.A., and Pyatt, D.G. (1995). Forests and wind: Management to minimise damage. Forestry Commission Bulletin 114. Forestry Commission, HMSO, London 27pp.

Ray, D. (2008). Impacts of climate change on forestry in Wales. Forestry Commission Research Note 31, Forestry Commission. Available at: https://www.forestresearch.gov.uk/documents/943/fcrn301.pdf

Ray, D., Bathgate, S., Moseley, D., Taylor, P., Nicoll, B., Pizzirani, S., Gardiner, B. (2014) Comparing the provision of ecosystem services in plantation forests under alternative climate change adaptation management options in Wales. Regional Environmental Change 15 (8)

Ray, D., Petr, M., Mullett, M., Bathgate, S., & Marchi, M., Beauchamp, K. (2019). A simulation-based approach to assess forest policy options under biotic and abiotic climate change impacts: A case study on Scotland's National Forest Estate. Forest Policy and Economics. 103. 17-27.

Ray, D., Sing, L. and Nicoll, B. (2016) Forest Ecosystem Services and Climate Change in Agriculture and Forestry Climate Change Report Card Technical Paper. Forest Research, Roslin.

Read, D.J., Freer-Smith, P.H., Morison, J.I.L., Hanley, N., West, C.C., Snowdon, P., (eds), (2009). Combating climate change – a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change, National Assessment of UK Forestry and Climate Change Steering Group 2009,The Stationary Office, Edinburgh.

Roberts, M., Gilligan, C.A., Kleczkowski, A., Hanley, N., Whalley, A.E. and Healey, J.R. (2020) The Effect of Forest Management Options on Forest Resilience to Pathogens. Frontiers in Forests and Global Change, 3:7. 21pp.

Royal Forestry Society (2018) Planting for Resilient Woods Insight Report November 2018 Royal Forestry Society. Available at: https://www.rfs.org.uk/media/530355/our-woodlands-are-changing-rfs-insight-report-2018.pdf

Savill, P., Wilson, S.McG., Mason, W.L., and Jinks, R. (2016) Silver firs (Abies spp.) of Europe and the Near-East: species, silviculture, and utilisation potential. Quarterly Journal of Forestry, 110, 16-27.

Savill, P.S. (2015). Cryptomeria japonica (Thunb. Ex L.f.) D.Don – Japanese red cedar or Sugi: silviculture and properties. Quarterly Journal of Forestry, 109 (2) 97-102

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D., Petr, M., Honkaniemi, J., Lexer, M.J., Trotsiuk, V., Mairota, P., Svoboda, M., Fabrika, M., Nagel, T.A., Reyer, C.P.O., (2017). Forest disturbances under climate change. Nature Climate Change 7, 395-402.

Sibley, A.M. (2019) Wildfire outbreaks across the UK during summer 2018. Weather, 74:397-402.

Snowdon, P., (2009). Forestry, climate change, and sustainable development, in: Combating Climate Change: A Role for UK Forests. HMSO, Edinburgh, pp. 192–200.

Stevens R.B. (1960) Pages 357-429 in Plant Pathology, an Advanced Treatise, volume 3. J.G. Horsfall and A.E Dimond (editors). Academic Press, New York.

Stokes, V. and Kerr, G. (2009). The evidence supporting the use of CCF in adapting Scotland's forests to the risks of climate change. Report by Forest Research to Forestry Commission Scotland. Forest Research, Alice Holt Lodge

Surminski, S., Style, D., Di Mauro, M., Townsend, A., Baglee, A., Cameron, C., Connell, R., Deyes, K., Haworth, A., Ingirige, B., Muir-Wood, R., Proverbs, D., Watkiss, P., and Sze Goh, L. (2016). UK Climate Change Risk Assessment Evidence Report: Chapter 6, Business and Industry. Report prepared for the Adaptation Sub-Committee of the Committee on Climate Change, London.

Thurm, E.A., Uhl, E., Pretzsch, H., (2016). Mixture reduces climate sensitivity of Douglas-fir stem growth. Forest Ecology and Management, 376, 205–220.

WEAG (2012) Report Of The Woodland Expansion Advisory Group To The Cabinet Secretary For Rural Affairs And Environment, Richard Lochhead, MSP. Available at: https://scotland.forestry.gov.uk/images/corporate/pdf/WEAGFinalReport.pdf

Trumbore, S., Brando, P. and HartMann, H. (2015). Forest health and global change. Science 349, 814-818.

Van Oijen, M. and Zavala, M.A. (2020). Probabilistic drought risk analysis for even-aged forests. Chapter 9 in J. Sillman, S. Sippel and S. Russo (Eds.) Climate Extremes and Their Implications for Impact and Risk Assessment, Elsevier, p.159-176.

Ward-Thompson, C, Roe, J., Aspinall. P., Mitchell, R., Clow, A. and Miller, D. (2012). More green space is linked to less stress in deprived communities: Evidence from salivary cortisol patterns. Landscape and Urban Planning, 105:221–229.

Welsh Government (2018) Woodlands for Wales Strategy, The Welsh Government's Strategy for Woodlands and Trees

Welsh Government (2019) Prosperity for all a climate conscious Wales. Second Climate Change Adaptation Programme Available at: https://gov.wales/sites/default/files/publications/2019-11/prosperity-for-all-a-climate-conscious-wales_0.pdf

Wilson, S. McG., Mason, W.L., Savill, P., and Jinks, R. (2018) Alternative oaks (Quercus spp.). Quarterly Journal of Forestry, 112, 93-105.

Xenakis, G. (2019). Drought impacts research. Chartered Forester, Winter 2019, 18-19.

Other documents in this report series (in Report/Annex order):

Beauchamp, K., Jenkins, T.A.R., Alison, J., Bathgate, S., Bell, C., Braban, C., Broome, A., Bursnell, M., Burton, V., Dickie, I., Doick, K.J., Evans, C.D., Fitch, A., Griffiths, R., Hall, C., Healey, J.R., Jones, L., Keith, A.M., Kerr, G., Kuyer, J., Maskell, L.C., Matthews, R.W., Morison, J., Nicoll, B., Nisbet, T., O'Brien, L., Old, G.H., Pagella, T., Perks, M.P, Robinson, D.A., Saraev, V., Smart, S.M., Smith, A.R., Siriwardena, G.M., Swetnam, R., Thomas, A.R.C., Tye, A., Valatin, G., Warren-Thomas, E.M., Wong, J. & Emmett, B.A. (2020). Environment and Rural Affairs Monitoring & Modelling Programme (ERAMMP). ERAMMP Report-32: National Forest in Wales - Evidence Review. Report to Welsh Government (Contract C210/2016/2017)(UK Centre for Ecology & Hydrology Project 06297)

Beauchamp, K., Alison, J., Broome, A., Burton, V., Griffiths, R., Keith, A.M., Maskell, L.C., Siriwardena, G. & Smart, S.M. (2020). Environment and Rural Affairs Monitoring & Modelling Programme (ERAMMP). ERAMMP Report-33: National Forest in Wales - Evidence Review Annex-1: Biodiversity. Report to Welsh Government (Contract C210/2016/2017)(UK Centre for Ecology & Hydrology Project 06297)

Kerr, G. (2020). Environment and Rural Affairs Monitoring & Modelling Programme (ERAMMP). ERAMMP Report-34: National Forest in Wales - Evidence Review Annex-2: Managing Undermanaged Woodland. Report to Welsh Government (Contract C210/2016/2017)(UK Centre for Ecology & Hydrology Project 06297)

Beauchamp, K., Bathgate, S., Burton, V., Jenkins, T.A.R., Morison, J., Nicoll, B. & Perks, M.P. (2020). Environment and Rural Affairs Monitoring & Modelling Programme (ERAMMP). ERAMMP Report-35: National Forest in Wales - Evidence Review Annex-3: Future-proofing our Woodland. Report to Welsh Government (Contract C210/2016/2017)(UK Centre for Ecology & Hydrology Project 06297)

Matthews, R. (2020). Environment and Rural Affairs Monitoring & Modelling Programme (ERAMMP). ERAMMP Report-36: National Forest in Wales - Evidence Review Annex-4: Climate Change Mitigation. Report to Welsh Government (Contract C210/2016/2017)(UK Centre for Ecology & Hydrology Project 06297)

Beauchamp, K., O'Brien, L., Hall, C., Dickie, I., Swetnam, R., Jenkins, T.A.R., Doick, K.J., Nisbet, T.R., Old. G., Evans, C.D., Nicoll, B., Jones, L., Braban, C., Robinson, D.A., Burton, V, Tye, A., Smith, A.R., Pagella, T. & Perks, M.P. (2020). Environment and Rural Affairs Monitoring & Modelling Programme (ERAMMP). ERAMMP Report-37: National Forest in Wales - Evidence Review Annex-5: Ecosystem Services. Report to Welsh Government (Contract C210/2016/2017)(UK Centre for Ecology & Hydrology Project 06297)

Saraev, V., Beauchamp, K., Bursnell, M., Fitch, A., Kuyer, J., Thomas, A., Dickie, I., Jones, L., Valatin, G. & Wong, J. (2020). Environment and Rural Affairs Monitoring & Modelling Programme (ERAMMP). ERAMMP Report-38: National Forest in Wales - Evidence Review Annex-6: Economics and Natural Capital Accounting. Report to Welsh Government (Contract C210/2016/2017)(UK Centre for Ecology & Hydrology Project 06297)

Emmett, B.A., Beauchamp, K., Jenkins, T.A.R., Alison, J., Bathgate, S., Bell, C., Braban, C., Broome, A., Bursnell, M., Burton, V., Dickie, I., Doick, K.J., Evans, C.D., Fitch, A., Griffiths, R., Hall, C., Healey, J.R., Jones, L., Keith, A.M., Kerr, G., Kuyer, J., Maskell, L.C., Matthews, R.W., Morison, J., Nicoll, B., Nisbet, T.R., O'Brien, L., Old, G.H., Pagella, T., Perks, M.P, Robinson, D.A., Saraev, V., Smart, S.M., Smith, A.R., Siriwardena, G.M., Swetnam, R., Thomas, A.R.C., Tye, A., Valatin, G., Warren-Thomas, E.M. & Wong, J. (2020). Environment and Rural Affairs Monitoring & Modelling Programme (ERAMMP). ERAMMP Report-39: National Forest in Wales - Evidence Review Annex-7: Integrated Assessment. Report to Welsh Government (Contract C210/2016/2017)(UK Centre for Ecology & Hydrology Project 06297)

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