Research Note

Impacts of climate change on forestry in Scotland – a synopsis of spatial modelling research

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Climate change is now one of the greatest global challenges, and research is underway to establish the likely impacts on all aspects of the environment. Forestry Commission Scotland has commissioned Forest Research to determine how forests and forestry in Scotland will be affected by climate change. This Research Note provides an initial synopsis of the likely impacts, with preliminary recommendations to support development of a climate change action plan for forestry in Scotland. Climate change will create many challenges and opportunities for Scotland's forest industry. Productivity will increase in some areas and a wider selection of species will become suitable. However, there are also potential threats, including drought, increased insect and disease damage, and wind damage, hence new techniques to combat these will be necessary. There are many uncertainties associated with climate change, and its likely impact on trees, management systems and forest operations. A key basis for risk planning and management is diversification; from broadening the choice of genetic material, mixing tree species in stands, to varying management systems and the timing of operations. Scotland's aspiration to expand woodland from 17% to 25% of land area by 2050 provides an opportunity to target reforestation within habitat networks. This will reduce woodland fragmentation and thereby help improve the resilience of woodland ecosystems to climate change.

Introduction

As trees take many decades to mature, forestry must anticipate further ahead than other land management sectors. Although our knowledge about the likely effects of climate change is continually improving, it is important that today's policy is informed by predictive research, albeit imperfect. This work represents an initial exploration of climate change impacts and the consequent opportunities and threats for forestry in Scotland.

This information has been compiled from the knowledge of forest scientists as well as tree species suitability modelling using the decision-support tool Ecological Site Classification (ESC) (Pyatt, Ray and Fletcher, 2001). The ESC species suitability distributions have been derived from knowledge-based models. The maps are indicative and use coarse-resolution soil data with future climate variables derived from climate change scenarios published by the UK Climate Impacts Programme (UKCIP) at 5 km resolution. It is very important that the maps are used only to infer trends, and that forest planning for the future climate involves careful site- and stand-based consideration.

This Research Note is supplemented by further information online – details of this and other relevant sources are provided throughout the report.

Assumptions

In this Research Note we make the following assumptions.

- Climate change in the manner described by the Intergovernmental Panel on Climate Change (IPCC) and UKCIP is accepted.
- For exploration of potential impacts, the most extreme of the four UKCIP scenarios is used – the High-emission scenario.
- The models provide an assessment of tree species' suitability to climatic averages, not extreme events.
- The modelling work relies on coarse-resolution data and cannot be applied reliably to individual sites.
- These are preliminary assessments of impacts and considerable uncertainty remains.

Key findings

- The expected warmer climate will improve tree growth nationally, but particularly in southern and eastern Scotland. Productivity will increase generally, and this could be by 2–4 m^3 per hectare per year for conifers on sites where water and nutrients are not limiting.
- The climate of southern and eastern Scotland will be more favourable for growing high-quality broadleaved trees on suitable deep, fertile soils.
- Droughty soils in eastern Scotland will become unfavourable for Sitka spruce and other drought-sensitive species.
- Changes in the seasonal distribution of rainfall will cause more frequent summer drought and winter flooding.
- Changes in the frequency of extreme winds may cause more wind damage. However, wind scenarios have high uncertainty attached.
- The incidence of pest and disease outbreaks will change with the climate; for example, more frequent green-spruce aphid attacks may reduce growth in eastern and southern Scotland.

Emerging recommendations

- Low-impact silvicultural systems (LISS) and the use of mixtures could provide the basis for adaptation strategies.
- Where other management systems are used, a wider range of species and a broader range of genetic material within a species will increase stand resilience in a changing climate.
- Acceptance of natural colonisation of woodlands by some non-native tree species may be a valid adaptation strategy, but this must be reviewed where conservation is a major objective.
- Forest nurseries in eastern Scotland will have to adapt to the drier summers (for example by using more irrigation) and to wetter winters (for example by avoiding soil damage).
- Contingency plans need to provide an adequate response to increasing risks of catastrophic wind damage, fire, and pest or disease outbreaks.
- The upper wind exposure limit, defined in terms of the detailed aspect method of scoring (DAMS), for productive conifer plantations may need to be reduced.

Climate change and climate predictions for Scotland

The concentration of carbon dioxide (CO_2) in the Earth's atmosphere is rising rapidly due to emissions from human activities. Currently at 380 ppm, atmospheric CO_2 concentration is now higher than at any time in the past 400,000 years (Petit *et al.*, 1999). The burning of fossil fuels is the main cause for this rapid increase, and concentrations of greenhouse gases (which include CO_2) are expected to rise further throughout this century (IPCC report, 2007). Atmospheric greenhouse gases trap energy in the atmosphere and this has caused global surface temperatures to rise. The warming is in turn causing changes in other climatic variables such as rainfall, humidity and wind speed.

Climate change will have a significant effect in Scotland, in particular:

- summers will become warmer and winters milder
- the rainfall distribution will change, leading to drier summers in eastern Scotland, particularly the eastern and southeastern lowlands, and wetter winters in eastern Scotland
- increased frequency of very dry summers in eastern Scotland leading to drought, depending on soil and site conditions
- increased frequency of high-intensity rainfall leading to increased occurrence of landslips, wetter soils, soil erosion, and sedimentation of watercourses
- decreased winter cold, and fewer frost days
- changes in wind climate, with more frequent strong winds

Three climate variables – temperature, rainfall and wind – are particularly important for tree species suitability, productivity and forest management.

1. Accumulated temperature (AT) is a measure of the degree of warmth for plant growth throughout the growing season. Over the past 40 years this has increased significantly over all regions of Scotland (Barnett *et al.*, 2006). The projections of climate change from the UKCIP (Hulme *et al.*, 2002) High-emissions scenario have been used to calculate AT for the future 30-year periods centred on the years 2050 and 2080 (Figure 1). The results show a doubling of AT for some areas of the eastern lowlands by the latter part of the century, with Caithness receiving as much warmth for tree growth as the southeastern lowlands received on average between 1961 and 1990.

2. Moisture deficit (MD) is the monthly maximum accumulated excess of evapotranspiration over rainfall in the summer months. This also has been calculated for the baseline period 1961–1990 and for the 30-year periods centred on the years 2050 and 2080. Figure 2 shows a projected increase in MD in south and eastern Scotland, and a reduction in western Scotland. As these are climate projections for a 30-year period, it is clear that eastern and southern Scotland is likely to experience more frequent summer drought than occurred in the baseline climatic period.

Figure 1
Accumulated temperature distribution of Scotland's climate: a) baseline climate, 1961–1990; b) projection for 2050; c) projection for 2080.

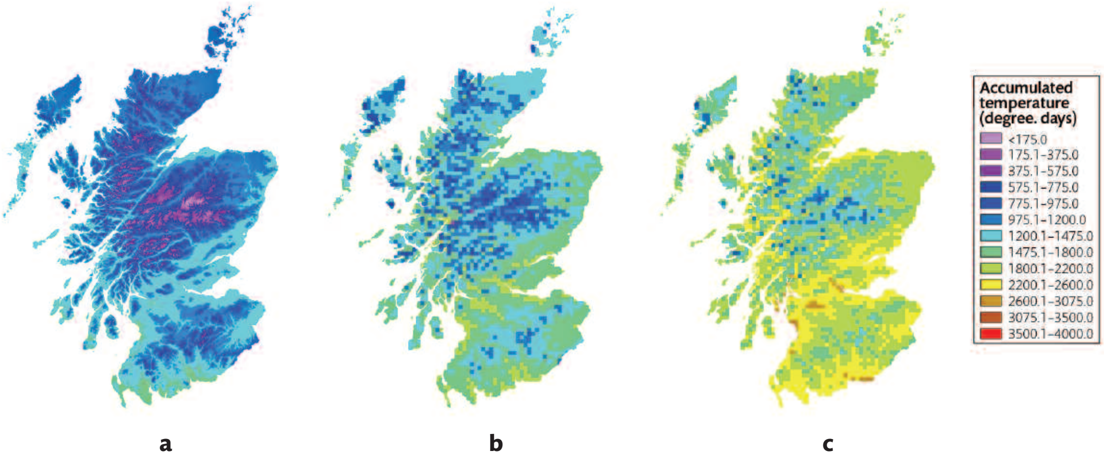
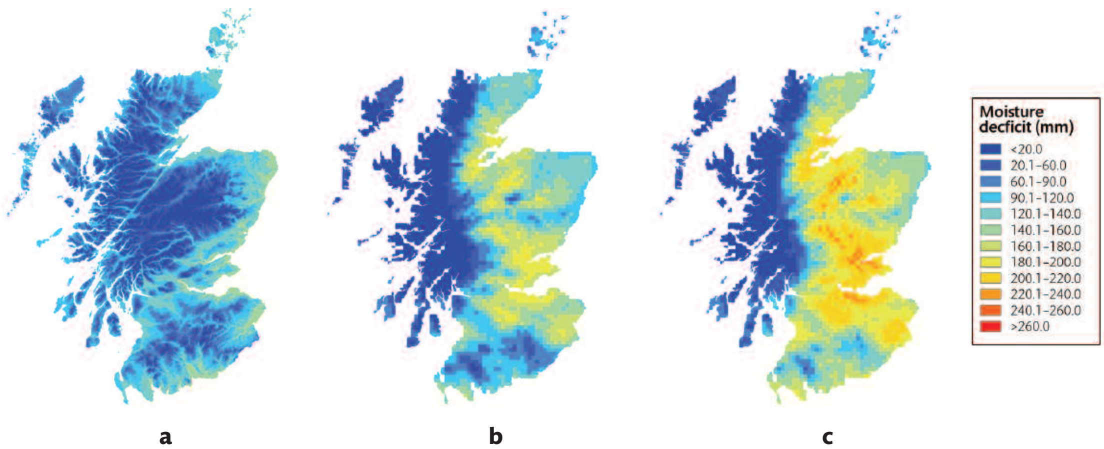


Figure 2
Moisture deficit distribution of Scotland's climate: a) baseline climate, 1961–1990; b) projection for 2050; c) projection for 2080.



Note: Figures 1 and 2 show average climatic conditions simulated for a 30-year period. Climate projections suggest a significant change in summer rainfall and evaporation in central, eastern and southern Scotland, leading to drier summer conditions and more frequent summer drought. In the northwest of Scotland, the level of summer rainfall is expected to be maintained or to increase. Both Figures are based on projections from the UKCIP High-emissions scenario.

3. Changes in the windiness of the climate are less certain. The climate projections suggest only minor changes in the future mean wind speed. However, from the known relationship between mean wind speed and extreme events, it is possible that a small change in the mean could have a large influence on the frequency of extreme events.

Impacts of climate change on forests and species choice

A warmer climate will improve forest productivity for many tree species. A general increase in growth has been observed over the past 40 years (Cannell, 2002), which has been attributed to increased warmth, increased CO_2 concentrations and improved silviculture. Recent research suggests that this increasing productivity is also due to higher nitrogen availability through decomposition and atmospheric deposition (Magnani *et al*., 2007); however, in dry summers, productivity declines. Climate change will affect the suitability and therefore choice of tree species and provenance (i.e. origin). For example, drought affects Sitka spruce, particularly the timber quality, due to stem cracking. Climate change will also have an impact on the management of forests, particularly in terms of species suitability and growth, disturbance and management, and coping with uncertainty.

Species suitability and growth

- Productivity is likely to increase (by 2–4 m^3 per hectare per year likely for Sitka spruce) as a result of warmer summers where nitrogen and water resources are not limited.
- The suitability distribution of Sitka spruce (and other species) will change in Scotland, with declining suitability in eastern Scotland. Where Sitka spruce is planted in Scotland, the choice of provenance, predominantly Queen Charlotte Island, should not be changed at this stage.
- Initial investigations suggest that climate change is unlikely to have a significant effect on the proportion of structural-grade Sitka spruce timber in Scotland.
- For other tree species grown in Scotland, current provenance recommendations may need to be reviewed to allow for the changing climate. Material from more southerly origins may become more suited to future Scottish conditions.
- The growing season will lengthen, and for some species of tree bud-burst will occur earlier and dormancy will occur later, with more frequent and prolonged lammas (late season) growth.
- With milder winters, some tree species may not enter full dormancy, leading to the possibility of damage during cold periods of winter.
- Using plant material from a wide range of families will help maintain and improve genetic diversity.

Disturbance and management

- Fire frequency and the annual area of forest burnt both increase in drought years, and the future climate will feature a greater frequency of hot and dry summers in eastern and southern Scotland.
- Deer numbers are likely to increase. Milder winters with fewer frost days will reduce winter mortality, increase recruitment of young deer, and increase browsing damage.
- Scrub and extensive areas of natural regeneration following fire and wind damage will provide more secure cover for deer.
- A number of pests and diseases will become more prevalent in Scotland. Milder winters will increase the size of over-wintering populations. For some species, longer and warmer growing seasons will increase the number of lifecycles per year, and warmer conditions and increased CO_2 will provide more food – often shortening time to maturity.
- Opinion favours mixing tree species within stands to reduce the impact of pests and pathogens over an area.
- Tree stability will become more critical as a result of wetter winters and more frequent intense gales, leading to an increase in endemic wind damage, and more frequent catastrophic wind damage in forests.
- On imperfectly or poorly draining soil types, drought stress will become more critical when winter waterlogging is followed by summer drought.

Coping with uncertainty

Decision-support guidance is required to help forest managers adapt and manage for climate change and to inform national and local risk management strategies.

The suitability distribution of most tree species will change in Scotland. Figure 3 shows a selection of outputs of changing species suitability from the ESC spatial model. The figures are indicative, assuming the UKCIPO2 High-emissions scenario and based on attributes of the Soil Survey of Scotland digital soil map at low resolution (mapped at a scale of 1:250,000). Maps showing the predicted change in suitability of a wider range of species can be found at www.forestresearch.gov.uk/climatechangescotland.

Provenance choice will become an increasingly important consideration for some species, particularly those that perform better in a drier and warmer climate (Hubert and Cottrell, 2007). However, for species that respond to temperature cues for bud-burst and dormancy, it will be necessary to consider and assess the risk of frost damage against other objectives.

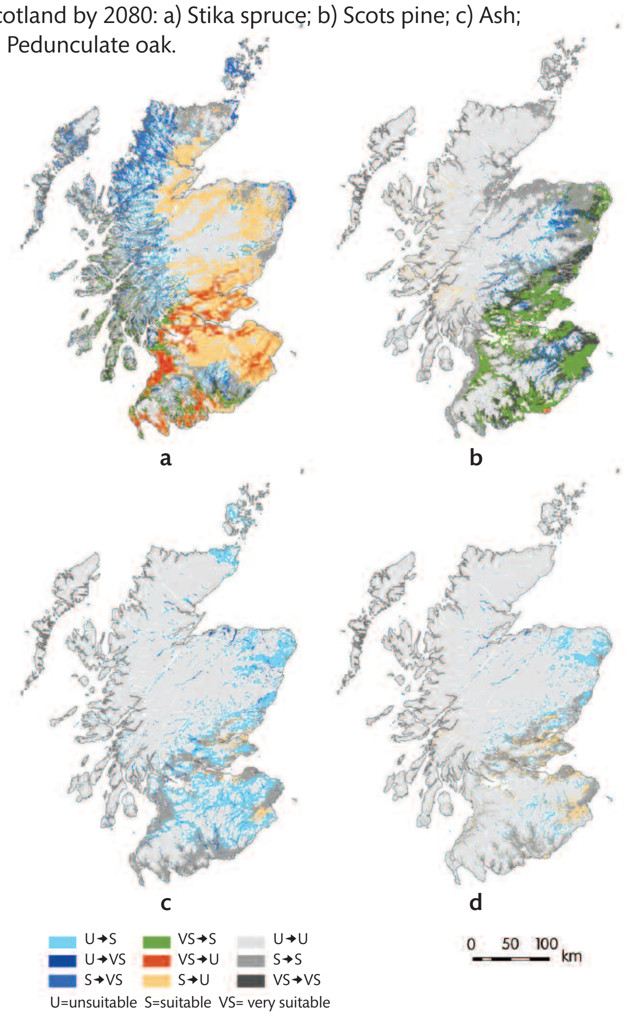
Southerly provenances of Sitka spruce (such as Washington and Oregon) are quite prone to autumn frost damage from initial establishment to canopy closure. Currently, across most of Scotland, the Queen Charlotte Island provenance is as productive as Washington with less risk of frost damage in the autumn (Samuel, Fletcher and Lines, 2007), but this should be kept under review. Despite the prediction that frost will occur less frequently in the future, some risk will remain, particularly in inland areas away from the west coast of Scotland.

With a changing seasonal rainfall distribution, it is likely that some forests and woodlands in the east of Scotland will become increasingly stressed as a result of increased winter wetness followed by summer drought. Many tree species are particularly unsuitable on sites with seasonally fluctuating water tables. The increased frequency of summer drought in eastern and southern Scotland is of particular concern. The national digital soil map at a scale of 1:250,000[1] is not sufficiently detailed to show many of the important soils for forestry. An analysis of the physical properties of soil series underlying forests in the east and south of Scotland has provided information on those most sensitive to drought. Further details are available in the full report at www.forestresearch.gov.uk/climatechangescotland. The report also includes a table that may assist operational decisions on potential drought risk, productive species choice, and native woodland suitability.

All the emissions scenarios suggest that winters will be wetter in many regions of Scotland, resulting in more waterlogged soil conditions in southwest, southern and eastern Scotland. Figure 4 shows the forest areas at risk of increased winter soil wetness, and suggests the location of imperfectly draining soils likely to become waterlogged by the 2080s under the High-emissions scenario. The increased winter rainfall will impair root growth and rooting depth for many tree species, due to the presence of anaerobic conditions in which roots will not survive.

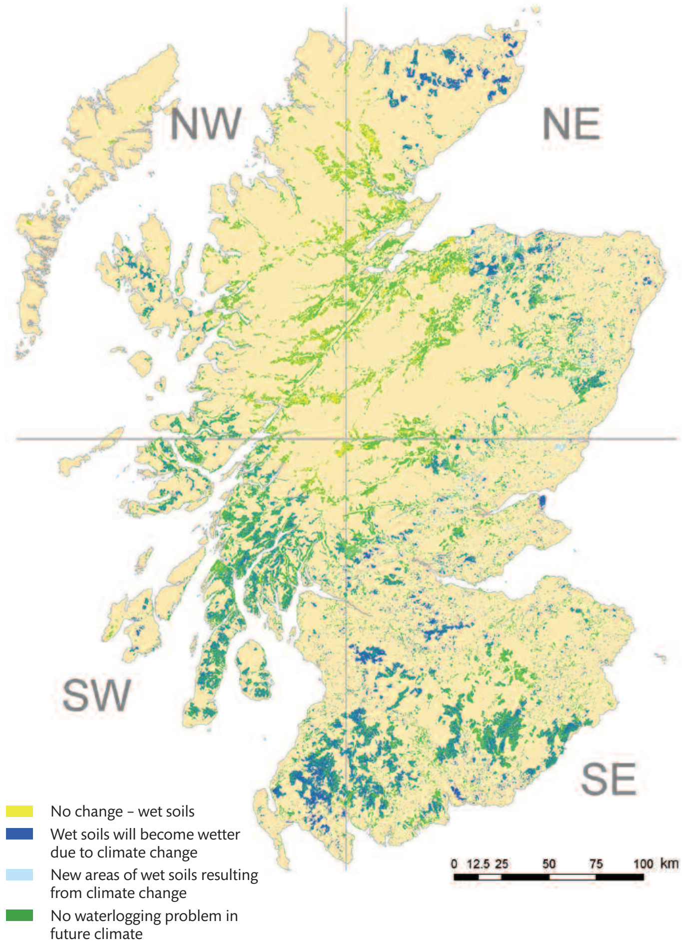
There is evidence of increasing forest-fire frequency and an increase in the area of woodland damaged by forest fire in dry summers (Broadmeadow and Ray, 2005). As the frequency of droughty summers increases, and given that forests are being increasingly visited and used for recreation by people, it is likely that the occurrence of fires will increase.

Figure 3
Indicative changes in the suitability of four species of tree in Scotland by 2080: a) Stika spruce; b) Scots pine; c) Ash; d) Pedunculate oak.



Note: These maps are based on the UKCIP High-emissions scenario, and are indicative maps using soil-quality data derived from the Soil Survey of Scotland digital data at a scale of 1:250,000.

Figure 4
The relationship between poorly draining (wet) soils and forests or woodlands in Scotland.



Note: This is an indicative map for a 2080 High-emissions scenario, using soil-quality data derived from the Soil Survey of Scotland digital data at a scale of 1:250,000. It is likely that the coarse-resolution soil data exaggerate the total area of wet forest soils in Scotland.

[1] **Soil Survey of Scotland, Macaulay Institute, Aberdeen.**

Impacts on silviculture and operations

Models suggest that the climate will become more variable, with greater risk of extreme events (IPCC report, 2007). Therefore, a primary objective of silviculture and management should be to spread risk in a way that reduces the impact of damaging events and increases the resilience of Scottish forests. This will require predictive forest planning informed by knowledge of the types of damaging event likely for the region, and the sites being managed. In this section, options for adapting forestry systems are considered, particularly in terms of stand management, site operations and coping with uncertainty.

Stand management

Low-impact silvicultural systems (LISS) may become more appropriate where carbon conservation is a high priority or where a reduction in the extent of change to the microclimate of woodland sites can increase the robustness of the forest system. Mixing species in stands, regardless of management system, will help to spread the risk associated with biotic and abiotic impacts. Wind exposure and the risk of windthrow is the main constraint, as LISS is not usually an option on the windiest sites (with a DAMS value greater than 15). Where LISS is inappropriate, use of mixed species within stands can help spread risk under clearfell-restocking management systems. Managing stands to maintain a more continuous and even canopy roughness will also help to reduce the risk of wind damage, as will early and more frequent thinning interventions.

The increasing variability of the wind climate is likely to reduce the productive potential of the most exposed areas of forest. Table 1 shows the amount of forest on the most exposed site types in Scotland. In the future climate, the distribution of extreme wind speeds will change, so Scotland is likely to be exposed to an increased frequency of high-magnitude events. Therefore, the productive limit in terms of DAMS will need to be reviewed if evidence emerges of increased windthrow risk on exposed sites. Over 32,000 ha of Scotland's current forest cover is located on sites between DAMS 18 and 19.

We need to increase our knowledge of site suitability in Scotland for a wider range of species that may have a role in the future. Several alternative species for a warmer climate might be suited on specific site types in Scotland. These include: Monterey pine, Maritime pine, Southern beech (rauli and roble) and walnut. These could be mixed on suitable sites, with 'known' species.

Site operations

- The management of forest operations on wet soils will become more challenging. In particular, the timing of operations involving heavy machinery might need to be re-scheduled for late summer. Any operations on sites liable to winter waterlogging should be carefully monitored, with work managed to avoid unacceptable soil damage. Careful site and operations planning will be needed to maintain compliance with the UK Forestry Standard.
- The window for lifting nursery stock will be reduced by the lengthening growing season and wetter winter conditions. There will be a much greater need for irrigation systems in Scotland's easterly tree nurseries. The back-end planting of bare-root spruce and larch will be reduced, but there will be an extension of the planting of containerised trees later into the autumn. The spring planting time for bare-root stock may be curtailed on drought-prone eastern sites.
- There will be more weed competition on many sites. For poorly and imperfectly draining soils, mounding is likely to remain the most effective type of cultivation. Scarification or mounding will be suitable for freely draining soils.

Coping with uncertainty

Contingency plans need to provide an adequate response to increasing risks of: a) widespread windthrow from severe storms, b) fire outbreaks and c) outbreaks of pests/disease. These challenges will require increased sector awareness and training.

Table 1 The most exposed forest area (ha) expressed by DAMS score (Quine and White, 1993), by Conservancy.

	Central Scotland	Grampian	Highland	Perth and Argyll	South Scotland	All Scotland
DAMS 18	5025	463	5400	7369	14 356	32 613
DAMS 19	2331	100	2631	6087	5269	16 418
DAMS 20	938	18	2050	4019	1650	8675
DAMS 21	194	0	800	1775	600	3369
DAMS 22	25	0	675	537	262	1499
Total	**8513**	**581**	**11 556**	**19 787**	**22 137**	**62 574**

Native woodland management

Native woodlands provide a core resource for the conservation of woodland biodiversity, particularly those on ancient woodland sites. Well-managed native woodlands may also provide an important resource of timber, non-timber forest products and locations for people to enjoy natural history. The changing climate is likely to affect different types of woodland in different ways, as described below.

Pinewoods

- Summer drought may favour drier sub-communities in the west and central Highlands.
- Warmer summers may encourage the colonisation of broadleaved species (e.g. oak, birch and rowan) as well as vascular plants not associated with pinewood communities.
- Where land-use and grazing pressure allows, there may be an increase in scrub above the current treeline and a broadening of the upper scrubby edge of pinewoods. Juniper and montane willows may establish at higher elevation on suitable sites in the complex montane soil mosaic.
- There may be an increase in the frequency of natural disturbance from fire, particularly in pinewoods adjacent to heather moor and in woodlands popular with visitors.

Oakwoods

- Atlantic oakwoods on the western seaboard may experience milder winters, more severe winter gales and warmer and drier summers, leading to loss of epiphytes.
- Increased natural disturbance from gales may break branches, and blow over trees with less firm root systems.
- Stands may have frequent gap openings, allowing colonisation of oak, birch, hazel and rowan, producing a more 'scrubby' woodland ecosystem – given adequate light and rigorous deer management.
- Milder winters, springs and autumns may allow a wider range of broadleaved species to colonise (e.g. beech in Atlantic oakwoods, and sycamore in eastern Scotland).

Birchwoods

- In the central and eastern Highlands, and in eastern Scotland, birch and oak may be encouraged to provide shelter (from increased storminess) and shade (from summer heat) within pasture, as a more extensive semi-natural woodland type within agri-environment schemes.
- Many upland birchwoods have been recently planted, and it may be necessary to introduce more competitive species, such as oak and hazel, where seed sources don't exist, so that they may be more resilient to climate change.

Mixed broadleaved woodlands

- On heavier soils, the frequency of natural disturbance through damage in winter storms may increase, and woods may become shrubby where this occurs.
- Increased winds may do no more than reduce the number of old trees in woodlands on drier and sheltered sites.
- In a warmer climate, bramble may become rank and more dominant.
- Fire damage may become more widespread, as many of these woodlands are used by people.
- The frequency of sycamore and beech may increase in mixed broadleaved woodlands, as beech-seed viability improves in the warmer climate, and sycamore is able to out-compete oak, ash and elm.
- It may become increasingly appropriate to accept beech and sycamore as naturalised species in the mixed broadleaved woodlands of Scotland.

Ashwoods

- Ashwoods occur on freely draining, but slowly percolating, fertile, heavy soils. In west Scotland, as for oakwoods, more frequent natural disturbance events may occur, creating canopy openings with colonisation of a greater range of plants.
- Ash is very shade-tolerant as a seedling and young sapling, and can regenerate and compete successfully in the intense shade of dense woodland. Therefore, although tree-species composition may change in the warmer climate, this may happen more slowly in ashwoods than in other woodland types, even though the age structure may broaden in response to more frequent disturbance.

Wet woodlands

- Wet woodlands can be dominated by species of alder, willow and birch, with the proportions being dependent on biophysical conditions including climatic warmth, soil wetness and fertility.
- Winter flooding may become more frequent, and may affect the lower floodplains of many of the river systems of eastern Scotland.
- The projected climate changes should help to maintain wet woodland in major valleys, with plentiful groundwater and a high water table expected throughout the year. Wet woodlands in the lower reaches of major catchments are also dependent on rainfall occurring in the headwater tributaries, often in the central Highlands.
- There may be an increasing role for wet-woodland management in many river catchments, to help provide a natural defence against flooding.

Coping with uncertainty

Many woodlands remain fragmented. Reforestation that seeks to link woodlands at the landscape-scale within habitat networks will reduce fragmentation and increase the resilience of woodland ecosystems.

Conclusion

Our research into the impacts of climate change will continue, so that we can further modify and refine our estimates of its consequences. Future outputs from this research programme will be used in policy development and best practice guidance. In this way we will continue to adapt best forestry practice to suit the needs of the environment and maintain a strong, viable, sustainable and carbon-efficient forest industry in Scotland.

A more detailed account of the impacts of climate change on forests and forestry in Scotland, and possible adaptation strategies, can be found at www.forestresearch.gov.uk/climatechangescotland and www.forestry.gov.uk/climatechange.

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