# Climate change and British woodland: what does the future hold?

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There is now convincing evidence that the climate is changing at an unprecedented rate for modern times, at both a global and a national scale. Models predict that this change will continue, causing parts of the UK to be subject to climatic extremes beyond those experienced since before the last ice-age. The potentially serious consequences of predicted climate change for British woodland are reviewed here, together with their implications for future species suitability.

Open-top chamber used for air pollution and climate change research

Frost damage to Norway spruce

Forest fires may be more of a cause for concern in the future

## Background

In 2001, the Intergovernmental Panel on Climate Change (IPCC) stated that *'the earth's climate system has demonstrably changed on both global and regional scales since the pre-industrial era, with some of these changes attributable to human activity'* (IPCC, 2001). Although the magnitude of the global rise in temperature of 0.6 $^{o}$C may seem small, the rate of change is unprecedented. The global temperature increase has been accompanied by a similar change in the UK, with the 1990s the warmest decade on record (about 0.5 $^{o}$C above the 1961–90 average), and six of the seven warmest years since 1659 having occurred between 1989 and 2002 (the Central England Temperature Record: CET). The rise in global temperature has been attributed to the emission of carbon dioxide ($CO_2$) and other greenhouse gases resulting from human activities including deforestation and fossil fuel burning, and is expected to continue.

The predictions of ongoing climate change are based on global development 'story-lines' linked to emissions scenarios which range from an environmentally sustainable global future with the rapid uptake of renewable energy, to a continuing reliance on fossil fuels and a global market economy (IPCC, 2000; IPCC, 2001). In turn, these emissions scenarios are used as input to global climate models (GCMs), with the output of one (HADCM3: developed by the UK Meteorological Office) used to generate climate change scenarios for the UK.

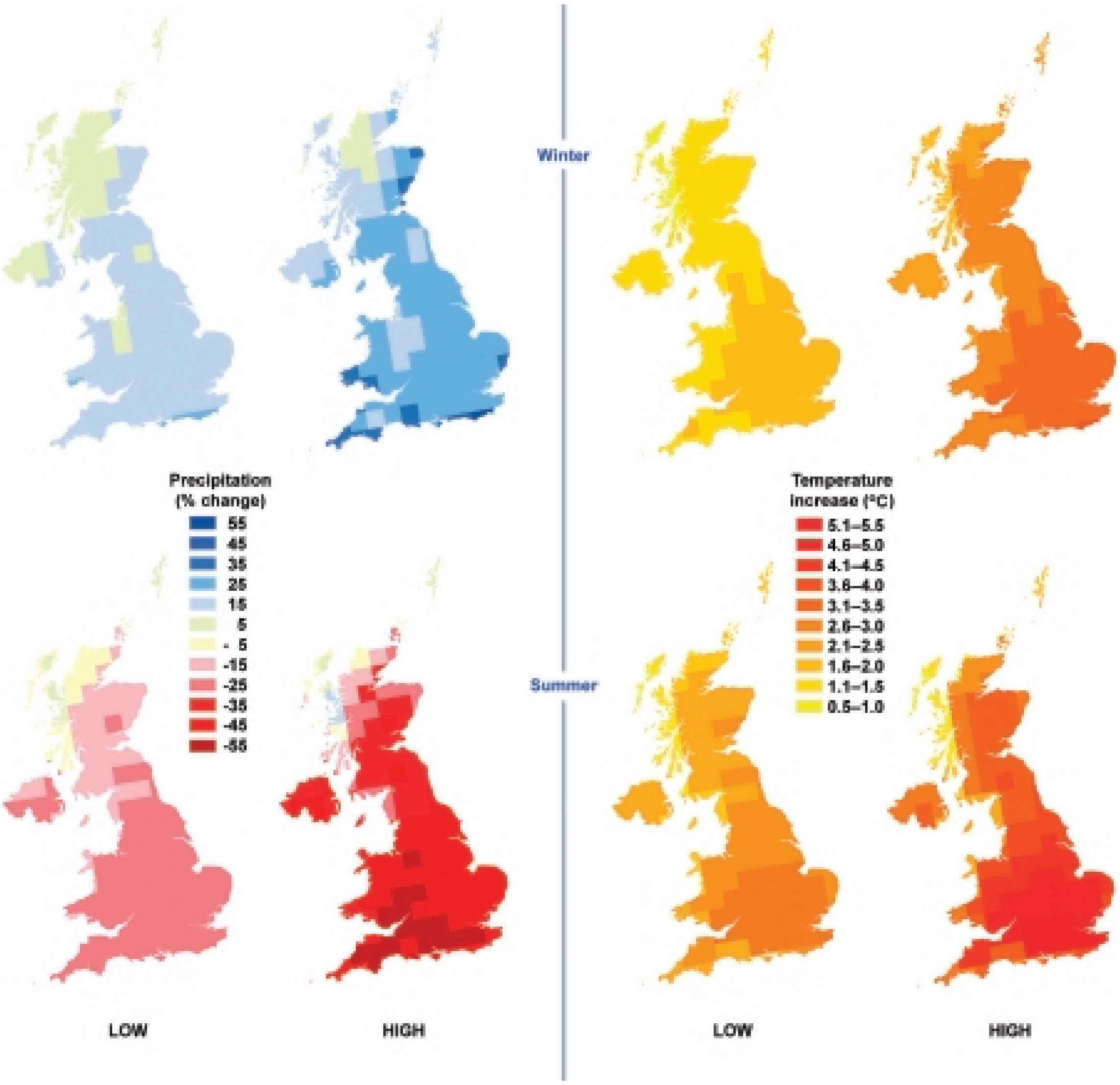
## The UKCIP02 scenarios

New climate scenarios for the UK were produced by the Tyndall and Hadley Centres on behalf of Defra and published in May 2002 (Hulme *et al.*, 2002). These new scenarios include a better spatial representation of the UK than the earlier UKCIP98 scenarios (Hulme and Jenkins, 1998), being based on a series of 96 50 x 50 km grid squares covering the UK land-mass. The scenarios provide predictions of mean climate, together with an indication of inter- and intra-annual variability in some variables over 30 year time-slices centred on the 2020s, 2050s and 2080s. For each time-slice, data are presented for four of the emissions scenarios given in IPCC (2000), and it is recommended that any assessment of the consequences of climate change covers the full range of scenarios. The scenarios are qualitatively similar to the earlier scenarios, although the magnitude of change is slightly larger. The climate of the late 21st century is predicted to be hotter and drier in summer, and milder and wetter in winter. The drier summer climate is now predicted to extend across the entire country, with the most extreme changes occurring in the south and east of England.

The global climate model on which the UKCIP02 scenarios are based has a detailed representation of the ocean currents, including an assumed weakening of the Gulf Stream. It is thought unlikely that the Gulf Stream will switch off completely, and that over the coming century the greenhouse gas forcing of the climate will outweigh any effects of changing ocean currents in the Atlantic. Maps showing changing temperature and precipitation patterns are shown in Figure 1 and a summary of changes to key meteorological variables for the northwest and southeast of Great Britain is given in Table 1.

**Figure 1**

**Maps showing the UKCIP02 seasonal rainfall and temperature predictions for the 2080s Low and High emissions scenarios relative to the 1961–90 baseline. [Source: Hulme *et al.* (2002), produced by the Tyndall and Hadley Centres on behalf of Defra.]**



The predictions of a 2 °C to 4.5 °C rise in temperature by the 2080s may seem small, but the magnitude of these predicted changes needs to be placed in context. Figure 2 shows summer and winter climate data for the UK Meteorological Office affiliated weather station at Alice Holt Research Station, Hampshire, together with the predictions of mean climate under the 2080s Low and High emissions scenarios. Over the past 50 years, the average summer temperature predicted for the Low emissions scenario in the 2080s has not been approached, including the extreme years of 1976, 1995 and 2003. The predictions for changes to winter temperatures are less extreme, but still highly significant. As a result of the high inter-annual variability in rainfall, predicted changes to winter rainfall are difficult to distinguish from natural variability, while for summer rainfall, a number of years (including 1976 and 1995) would fall into the ‘normal’ category for the 2080s under both the Low and High emissions scenarios.

**Table 1**

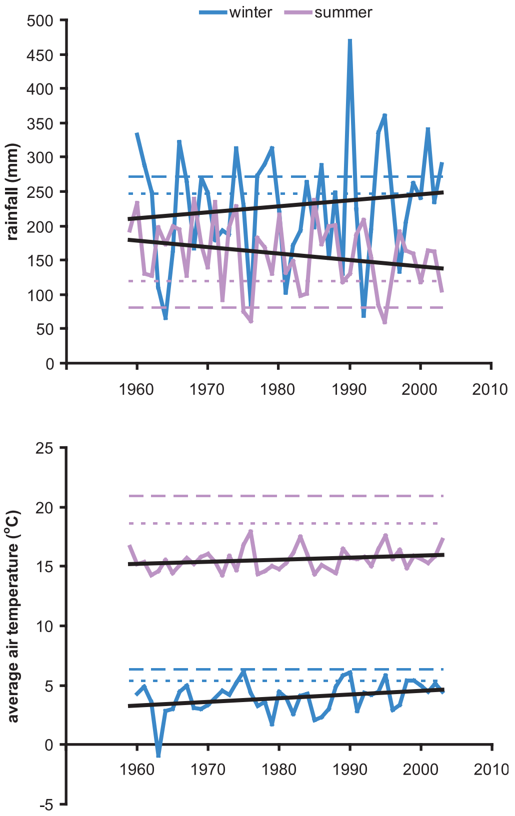
**UKCIP02 climate change predictions for the 2050s and 2080s for the Low and High emissions scenarios. Units of temperature change are degrees Celsius relative to the 1961–90 baseline, while all other variables are given as percentage change relative to the baseline. Southeast values are for the 50 km x 50 km grid-square in which Alice Holt Research Station, Hampshire is situated, while the northwest grid-square is centred on Fort William, Highland Region.**

| 2050s | Low emissions scenario | | | | High emissions scenario | | | |
|---|---|---|---|---|---|---|---|---|
| | winter | | summer | | winter | | summer | |
| | northwest | southeast | northwest | southeast | northwest | southeast | northwest | southeast |
| Minimum temp. (°C) | +1.0 | +1.2 | +1.2 | +1.8 | +1.6 | +1.9 | +1.9 | +2.8 |
| Maximum temp. (°C) | +0.9 | +1.2 | +1.4 | +2.3 | +1.5 | +1.8 | +2.2 | +3.7 |
| Precipitation (%) | +4.3 | +8.4 | -7.6 | -18.0 | +6.8 | +3.4 | -12.1 | -28.6 |
| Snowfall (%) | -26.2 | -40.0 | - | - | -41.7 | -63.6 | - | - |
| Wind speed (%) | +0.6 | +2.3 | -1.0 | +0.3 | +0.9 | +3.7 | -1.6 | +0.5 |
| Soil moisture (%) | +2.0 | -1.5 | -2.4 | -16.7 | +3.1 | -2.4 | -3.9 | -28.6 |
| Relative humidity (%) | -0.3 | -0.9 | -1.0 | -5.1 | +0.5 | +1.5 | -1.6 | -8.1 |
| Absolute humidity (%) | +6.6 | +7.5 | +7.1 | +4.4 | +10.6 | +11.9 | +11.2 | +7.0 |
| Cloud cover (%) | +0.4 | 0 | -1.7 | -5.6 | -0.9 | 0 | +2.0 | -9.0. |

| 2080s | Low emissions scenario | | | | High emissions scenario | | | |
|---|---|---|---|---|---|---|---|---|
| | winter | | summer | | winter | | summer | |
| | northwest | southeast | northwest | southeast | northwest | southeast | northwest | southeast |
| Minimum temp. (°C) | +1.4 | +1.7 | +1.7 | +2.5 | +2.7 | +3.3 | +3.3 | +4.8 |
| Maximum temp. (°C) | +1.3 | +1.6 | +1.9 | +3.3 | +2.6 | +3.2 | +3.7 | +6.4 |
| Precipitation (%) | +6.1 | +11.9 | -10.8 | -25.5 | +11.8 | +23.1 | -21.0 | -49.5 |
| Snowfall (%) | -37.2 | -56.8 | - | - | -72.1 | -100 | - | - |
| Wind speed (%) | +0.8 | +3.3 | -1.4 | +0.5 | +1.6 | +6.3 | -2.8 | +0.9 |
| Soil moisture (%) | +2.8 | -2.1 | -3.5 | -23.6 | +5.5 | -4.1 | -6.7 | -45.8 |
| Relative humidity (%) | -0.4 | -1.3 | -1.5 | -7.2 | -0.8 | -2.6 | -2.9 | -14.0 |
| Absolute humidity (%) | +9.4 | +10.6 | +10.0 | +6.3 | +18.3 | +20.6 | +19.5 | +12.2 |
| Cloud cover (%) | +0.6 | 0 | -2.4 | -8.0 | +1.1 | 0 | -4.7 | -15.4 |

**Figure 2**

**Average summer and winter temperature (top) and rainfall (bottom) for Alice Holt Research Station, Hampshire. In each case, the general trend over the period 1959–2003 is indicated by the linear regression (solid line). The dotted and dashed lines represent the UKCIP02 Low and High emissions scenarios for the 2080s.**



## The likely effects of climate change on woodland in the UK

A changing climate has the potential to affect a woodland ecosystem in many ways, as summarised in Table 2. However, before the effects of a changing climate are considered, it is important to note that the atmospheric concentration of carbon dioxide – the main driver of human-induced climate change – affects the growth of trees directly. Current levels of $CO_2$ do not saturate photosynthesis, and so $CO_2$ emissions would be expected to enhance growth rates assuming all other environmental conditions remained constant. Experiments with young trees indicate that a doubling of the $CO_2$ concentration in the atmosphere may increase biomass production by 30–50%. Although mature trees are unlikely to respond as much in a forest environment (Oren *et al.*, 2001), some increase in productivity is likely and will be accompanied by a range of other effects including lower stomatal conductance and thus water use on a leaf area basis (Medlyn *et al.*, 2001), an increase in leaf area (Broadmeadow and Randle, 2002) and possible changes to timber quality (Savill and Mather, 1990) and the nutritional quality of foliage to insect herbivores (Watt *et al.*, 1996). Other important elements of atmospheric change that may affect trees and woodland are predicted increases in the concentration of ground-level (tropospheric) ozone, and changes to the pattern of nitrogen deposition.

Ozone is a phytotoxic pollutant which reduces forest productivity across Europe by up to 10% at current concentrations. The complex chemical reactions in the atmosphere which lead to its formation are linked to climate and global emissions of nitrogen oxides and volatile organic compounds (VOCs). Predictions are for an approximate doubling of concentrations by the end of this century (NEGTAP, 2001). At low levels of deposition, nitrogen enhances growth, but at higher concentrations it can affect woodland ecosystems by altering the competitive balance between species comprising the ground vegetation and by altering the susceptibility of trees to a number of factors including insect herbivory and frost damage (Kennedy, 2003). The effects of a narrow definition of climate change should thus not be viewed in isolation, but as one element in the wider process of environmental change.

Climatic and site factors determine which plant species will grow in a given location thus influencing the community structure and the identity of native woodland types, as well as the productivity of timber plantations. Climate change also has the potential to affect forestry activities by altering site conditions as summarised below.

### Winter rainfall

In recent years, heavy winter rainfall has been suggested as indicative of a changing climate. For forestry, winter waterlogging affects the trafficability of forest soils and limits access of harvesting machinery for forestry operations if soil sustainability is to be maintained (Nisbet, 2002). Stands on waterlogged soils are more prone to windthrow (Ray and Nicholl, 1998), while waterlogging leads to the death of fine roots (Coutts and Philipson, 1978) thus accentuating the effects of high summer soil water deficits. Infection by various soil-borne pathogens including species of *Phytophthora* is promoted by fluctuating water tables (Lonsdale and Gibbs, 2002). Phytophthora diseases would thus be expected to become more prevalent on the basis of the predictions of wetter winters and drier summers.

### Water availability in summer

In contrast, significantly less summer rainfall is predicted in southern England. Longer growing seasons and shorter winter recharge periods, together with higher evapo-transpiration during warmer summer months, will enhance soil moisture deficits in summer, with drought conditions becoming more severe and frequent. In addition to affecting some tree species directly, stress caused by drought will make trees more susceptible to pathogens, especially weak pathogens such as sooty bark disease of sycamore, and thus mortality is likely to increase. The effects of drought are likely to be observed initially on the establishment of young trees and trees in hedgerows and the urban environment. As climate change progresses, even established trees may be affected and thus the suitability and distribution of some species will change.

A further consequence of the predicted increase in the incidence and severity of summer droughts is a likely increase in forest fire damage (Nisbet, 2002). Although the majority of forest fires occur in early summer, severe and extended droughts can result in significant fire outbreaks in late summer, as was the case in 1976 (Cannell and McNally, 1997).

### Snow and winter cold

Snowfall and thus snow damage will become less frequent as a result of rising temperatures. However, concerns have been raised that wetter snow and heavier falls will occur, potentially counteracting the benefits of climate change. Winter cold injury will become less frequent, but there is evidence to suggest that a predicted advance in flushing of up to one month could make some species more susceptible to spring frost damage. Higher temperatures in autumn may delay hardening and again make tissue, particularly the lammas growth of conifers, more susceptible to frost damage.

### Wind climate

Predictions of the changes in the wind climate are among the least certain of the UKCIP02 scenarios. They do, however, indicate that the largest increases are likely to be in autumn in the south of the UK, contrasting with the earlier predictions of the largest changes in northwest Scotland. This is because the storm track is predicted to move further south together with an increased frequency of deep depressions crossing the UK in winter. Most damage to forests is caused by extreme events, and the frequency of these is still more difficult to predict. It should, however, be noted that a small change in mean wind speed can have a significant effect on the DAMS (Detailed Aspect Method of Scoring: Quine and White, 1993) wind exposure classification. Therefore, although the predictions for wind speed are far from robust, a changing wind climate in the uplands could impact on forestry.

### Effects on pests and diseases

The effects of climate change on the incidence of pest and disease outbreaks are more difficult to predict because of the number of potential interactions. However, it is clear that existing pests such as the green spruce aphid are likely to become more prevalent as a result of lower winter mortality and increased fecundity and number of generations in a single year (Straw, 1995; Straw *et al.*, 2000). Potentially more worrying is the threat from insect pests and disease-causing agents which currently are not established in the UK. Both the Asian longhorn beetle *(Anoplophora glabripennis)* and the eight-

**Table 2**

**Summary of the effects of predicted climate change on woodland and forestry. Indicative responses to changes in each environmental variable are given, but specific cases may differ from the general responses outlined.**

| Variable | Beneficial effects | Detrimental effects |
|---|---|---|
| **Atmospheric $CO_2$** | Increase in growth rate<br>Reduction in stomatal conductance and lower water use on a leaf area basis | Reduction in timber quality<br>Increase in leaf area and thus higher wind resistance and water use; lower light transmission also affects character of ground vegetation<br>Possible nutrient imbalances |
| **Ozone pollution** | | Reduction in growth rate<br>Impaired stomatal function and thus increased susceptibility to drought |
| **Temperature** | Longer growing season<br>Higher potential productivity<br>Lower risk of winter cold damage<br>Less snow damage<br>Potential for use of species which are not hardy at present | Delayed hardening<br>Risk of spring and autumn frost damage possibly increased<br>Longer growing seasons reducing winter soil water recharge period<br>Reduced winter mortality of insect and mammalian pests<br>More rapid development and increased fecundity of insect and mammal pests<br>Potential for exotic/alien pests to spread to the UK |
| **Rainfall** | Reduced intensity of some foliar pathogens | Winter waterlogging limiting access for forest operations and reducing stability<br>Root death increasing susceptibility to drought and soil-borne pathogens<br>Summer drought-induced mortality<br>Facultative pathogens more damaging in stressed trees<br>Possible increase in forest fires |
| **Wind** | | Increased number of deep depressions increasing risk of wind damage, particularly in England |
| **Cloud cover** | Increased potential productivity | Increased diurnal temperature range in autumn increasing risk of frost damage |

toothed spruce beetle *(Ips typographus)* have been recorded in recent years, while the recently discovered *Phytophthora ramorum* (the cause of sudden oak death in the USA) has been identified in nurseries and some isolated trees in Britain. Although the global nature of the timber trade rather than climate change may be the main factor behind their arrival, predictions are for the climate of the UK to be more favourable for the establishment of populations of some insect pests and pathogens. The potential interactions between pests, diseases and climate change are further explored by Evans *et al.* (2002) and Webber and Evans (2003).

## Predictions of future species suitability

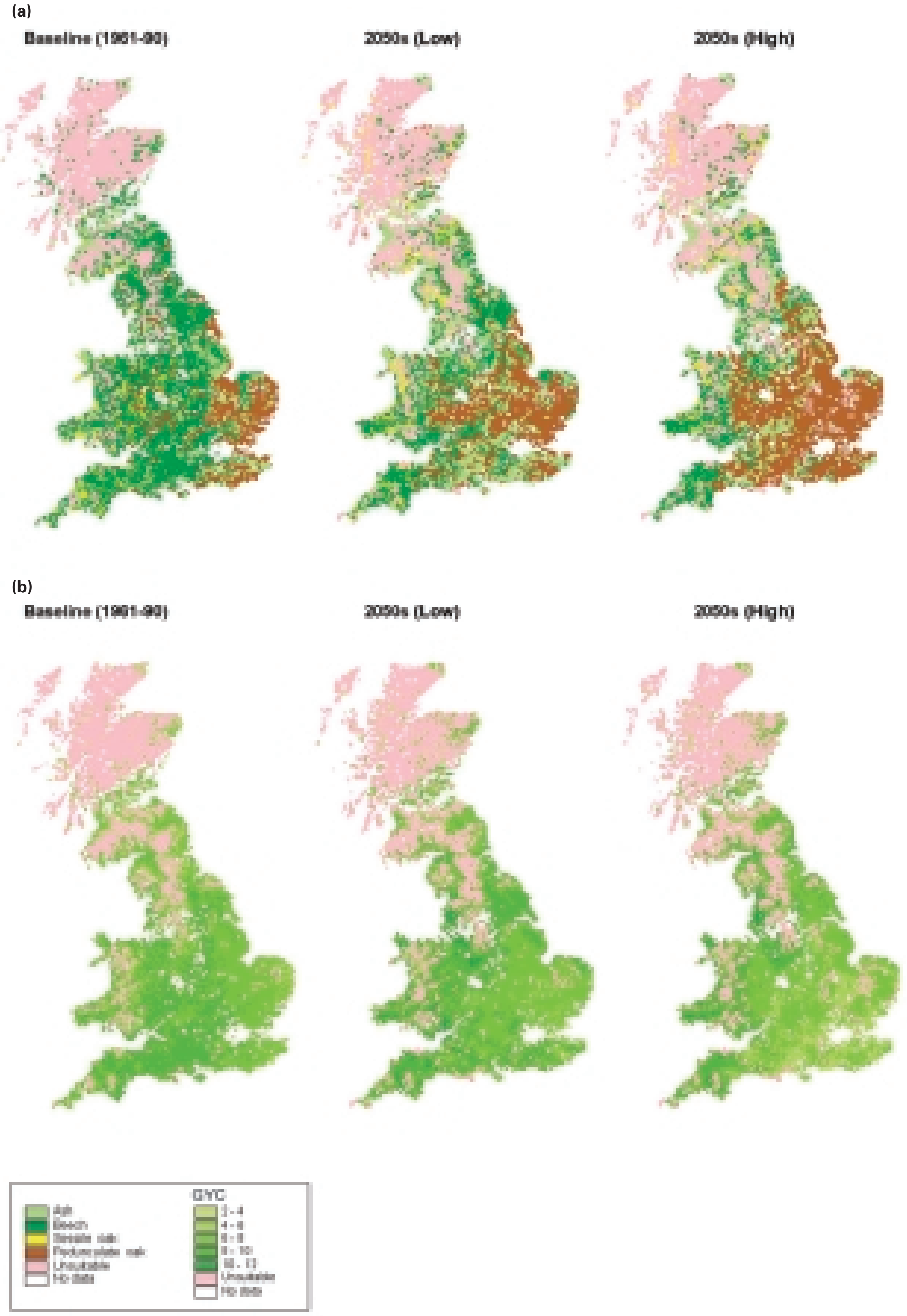
Predictions of future species suitability have been made using the knowledge-based spatial decision support system, Ecological Site Classification within a Geographical Information System (ESC-GIS: Ray and Broome, 2003). ESC has been developed to support the UK forestry industry in commercial species selection and the restoration and expansion of native woodland. It is a knowledge-based model in which suitability or yield class is predicted on the basis of four climatic (accumulated temperature, wind exposure, moisture deficit and continentality) and two edaphic (soil moisture regime and soil nutrient regime) factors. In the case of commercial suitability as defined here, accumulated temperature (AT) is assumed to be the principal determinant of yield, with the product of AT and the next most limiting factor providing a site level assessment of suitability (see Ray and Broome, 2003). A full description of ESC is given by Pyatt *et al.* (2001). The 2050s High and Low emissions scenarios of UKCIP02 have been incorporated as the underlying climate data, replacing the UKCIP98 climate scenarios reported by Ray and Broome (2003). A number of assumptions and simplifications have been made that should be considered when interpreting the suitability maps in the context of climate change predictions (see Ray *et al.*, 2002). In particular, the following have not been considered:

- The direct effects of rising atmospheric $CO_2$ concentrations on growth and evapo-transpiration.
- The effects of a possible change in the frequency of severe pathogen or insect pest outbreaks.
- Changes to the frequency of extreme climatic events.
- The predicted increase in **winter** wind speed; the DAMS wind hazard classification system is based on mean **annual** wind speed and thus the effects of changing exposure may be underestimated.
- Changing soil moisture quality index; although a changing soil moisture deficit is included in the analysis (one of the four climatic factors), the edaphic soil moisture (wetness) factor has not been adjusted to account for climate change in these simulations.
- Spatial scales finer than the 5 km grid are not explored; variability in soil quality means that these maps cannot be applied to site-based assessments and should only be used to indicate general trends.

Keeping in mind the assumptions outlined above, the maps of species suitability given in Figures 3–5 represent changes to the potential suitability for commercial forestry as a result of changes to meteorological variables alone. Rising atmospheric $CO_2$ concentrations will ameliorate the negative effects and reinforce the positive effects of climate change on species suitability to some degree. In contrast, ozone pollution together with predictions for extreme climatic events to become more commonplace and the likelihood that pest and pathogen outbreaks will become more significant, may mean that the effects of environmental change could be more far-reaching than the simulations indicate.

**Figure 3**

**Effects of climate change on the potential suitability of broadleaf species as predicted by ESC for the UKCIP02 2050s (2041-2060) High and Low emissions scenarios. (a) The broadleaf species most suited to the ESC climatic and edaphic factors for each scenario and (b) the productivity class (GYC: m$^3$ ha$^{-1}$ yr$^{-1}$) of that species.**



(a)

Baseline (1961-90)

2050s (Low)

2050s (High)

(b)

Baseline (1961-90)

2050s (Low)

2050s (High)

**Figure 4**

**Effects of climate change on the potential suitability of conifer species as predicted by ESC for the UKCIP02 2050s (2041-2060) Low and High emissions scenarios. (a) The conifer species most suited to the ESC climatic and edaphic factors for each scenario and (b) the productivity class (GYC: m$^3$ ha$^{-1}$ yr$^{-1}$) of that species.**

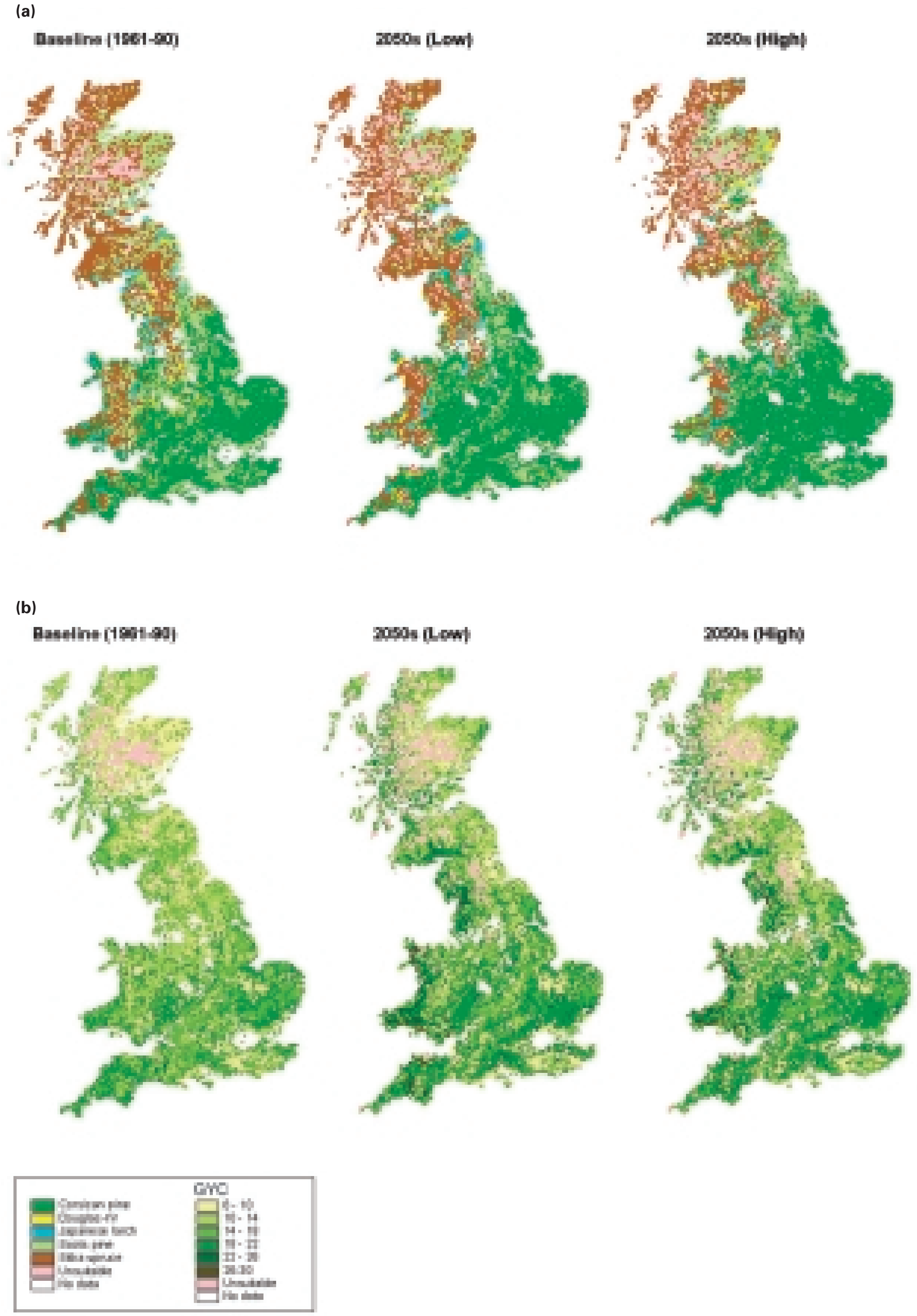


**Figure 5**

**Effects of climate change on the identity of the most productive conifer species as predicted by ESC for the UKCIP02 2050s (2041-2060) Low and High emissions scenarios.**

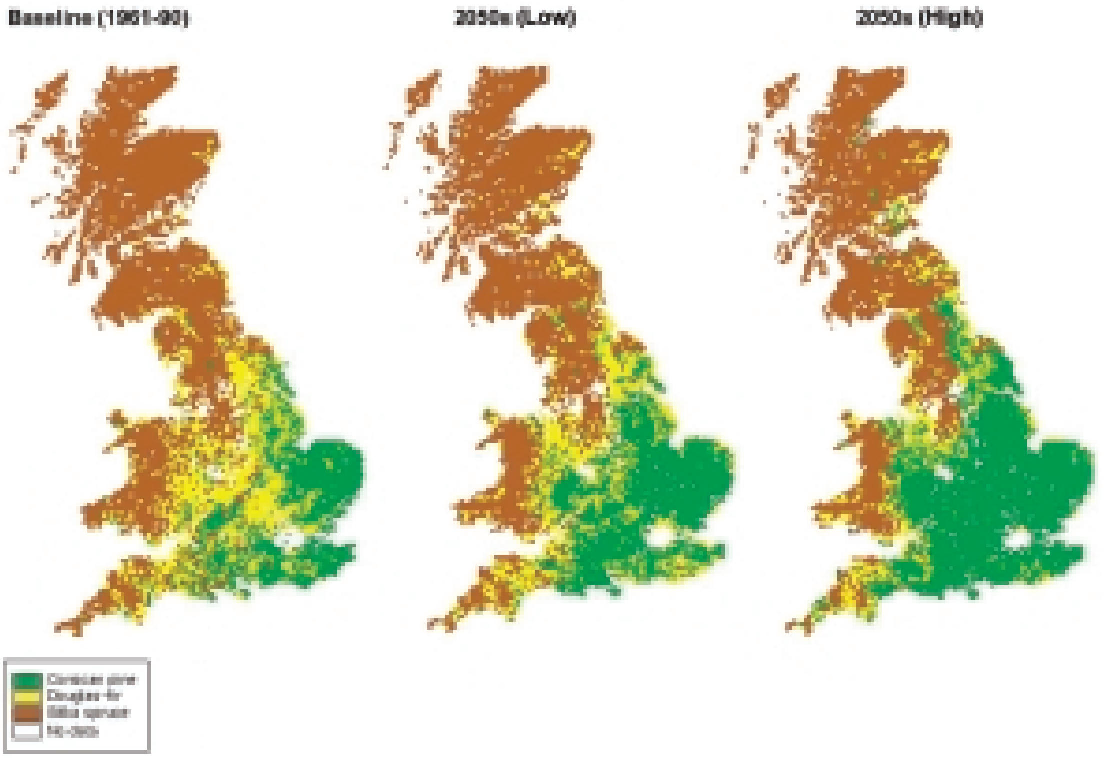


Figure 3a presents simulations of the most suitable broadleaf species for a given locality, where suitability is defined as the ratio of general yield class (GYC) to maximum GYC for that species in the UK, i.e. the species best suited to the site conditions but not necessarily the most productive species. In the baseline scenario (i.e. for the climate of 1961–90), the area where pedunculate oak *(Quercus robur)* is the most suitable species is restricted largely to East Anglia, Kent and Sussex. A regional basis for the distribution of ash is less clear, presumably on the basis of soil quality rather than climatic factors limiting its suitability. Sessile oak *(Quercus petraea)* is the most suitable species in upland areas across most of western England and Wales and southern Scotland, while beech *(Fagus sylvatica)* is predicted to be the most suitable species in lowland areas across all but the driest parts of England. In the 2050s Low scenario, the area in which beech is the most suitable species retreats north and westwards, such that in the High emissions scenario, this area is largely restricted to Wales and the southwest peninsula. Sessile oak shows a similar westwards retreat. In central and southern England, beech is replaced by ash *(Fraxinus excelsior)* and pedunculate oak as the most suitable species in the 2050s, with ash predominating in the Low emissions scenario, and pedunculate oak in the High emissions scenario. In northern England and southern Scotland, beech gives way to a combination of ash and sessile oak by the 2050s under both scenarios. Changes in the suitability distribution in Wales and west England are less obvious. In terms of the productivity of the most suitable species (Figure 3b) ESC predicts a slight reduction in GYC across southeast England, but an increase in the west country, west Wales, northwest England and eastern and central Scotland. It is clear that the climate change scenarios are predicted to have little effect on where broadleaf species can be grown on a commercial basis. However, species selection is likely to become increasingly important across much of England.

Less change is predicted to the suitability distribution of conifer species than for broadleaf species (Figure 4a). The area where Corsican pine *(Pinus nigra)* is the most suitable expands to the north and west, in most places replacing Scots pine *(Pinus sylvestris)*. Scots pine is also replaced as the most suitable species by a combination of Sitka spruce *(Picea sitchensis)* and Corsican pine across much of Wales. Douglas-fir *(Pseudotsuga menziesii)* becomes the most suitable species over large areas of eastern Scotland in the 2050s High emissions scenario, but is largely replaced by a variety of species in central and northern England. Of most concern to the forest industry is the ESC prediction that the Sitka spruce heartland of western Scotland becomes less favourable through the 21st century, while there is also an increase in the area classed as unsuitable in upland Scotland and northern England as a result of increased wind exposure. When species suitability is mapped on the basis of absolute productivity rather than ESC suitability class (Figure 5), changes in suitability become clearer with the range of Corsican pine expanding dramatically to the north and west, largely replacing Douglas-fir. The areas in which Sitka spruce is the most productive species also contract to a small extent, being replaced by Douglas-fir. In terms of productivity of the most suitable species (Figure 4b) there is a general increase in productivity across the whole of Great Britain for commercial conifer species.

## Conclusions

It is clear that climate change has the potential to dramatically affect forestry in the UK. Predictions of the impacts of storms and severe pest and disease outbreaks cannot be made because of their near random nature, although general guidance can be given and inferences made. Rising concentrations of carbon dioxide in the atmosphere will be beneficial to tree growth, as will increasing temperatures and thus longer growing seasons in the uplands. Snow damage and winter cold injury will become less important with time. However, the most serious consequences of climate change are likely to be related to moisture availability. In England, species suitability will change over large areas, not necessarily resulting in widespread mortality but, certainly, reduced productivity in some species and a greater susceptibility to other environmental factors. ESC can provide general guidance on future species suitability, but this knowledge should be used in conjunction with an assessment of on-site conditions. Given the magnitude of potential changes described here, it is advisable for climate change predictions to be considered in current forest design plans. At this stage, it would be prudent to avoid species monocultures, providing some protection against uncertainty in the responses of woodland to climate change, and in the predictions of climate change itself. In addition, the possibility of further and more extreme changes to the climate in the latter half of the century should be considered and, where possible, accommodated.

### Acknowledgements

Thanks are due to Pam Berry and Nathalie Butt (Environmental Change Institute, Oxford University) for the provision of processed climate change scenario data, and also to the many observers who have collected meteorological data at Alice Holt over the years.

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