

INFORMATION NOTE

BY MARK BROADMEADOW AND DUNCAN RAY OF FOREST RESEARCH JUNE 2005

SUMMARY



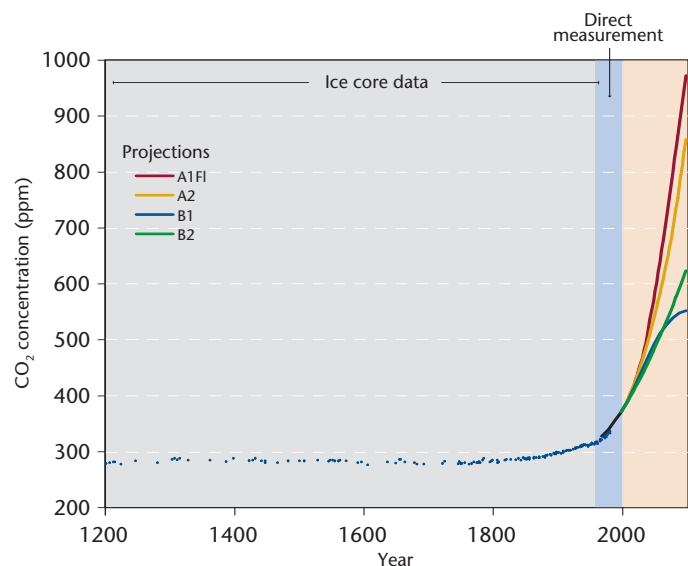
The global climate is changing as a result of human activity, caused primarily by the increased concentration of carbon dioxide in the atmosphere. The most recent predictions for the UK suggest an increase in temperature and changes in rainfall patterns, wind speed, cloud cover and humidity. This Information Note explains how these environmental changes may affect the growth of trees, including the distribution of individual species. Implications for woodland management and practice are outlined, and guidance is given on climate change adaptation.

GLOBAL CLIMATE CHANGE

The concentration of so-called 'greenhouse' gases (GHGs) in the atmosphere has been rising for more than 100 years as a result of human activity, particularly the burning of fossil fuels. The most important of these greenhouse gases is carbon dioxide (CO₂) which has risen from a concentration of approximately 270 parts per million (ppm) prior to industrialisation to the current value of 378 ppm, and is predicted to continue rising (IPCC, 2001: see Figure 1).

Figure 1

Observed atmospheric CO₂ concentrations (ppm) from 1200 to the present day together with a range of predictions to 2100 (IPCC, 2001). The blue and red lines represent the B1 and A1FI scenarios of IPCC (2000), respectively, equivalent to the Low and High emissions scenarios of UKCIP02 (see page 2).



The increase in greenhouse gas concentrations causes the atmosphere to trap a larger proportion of radiant energy from the sun. As a consequence, global surface temperatures are gradually rising, and the ten warmest years in the instrumented temperature record (1861–the present day) have all occurred since 1990. The gradual warming of the earth's climate also results in changes to other climatic variables such as rainfall, humidity and wind speed. Weather patterns and the seasonality of weather may also be affected. Models predicting future global climatic conditions have been developed and scenarios for changes to temperature and precipitation are now available. Predictions of climate change at a global scale are for a warming of some 3–5°C over the coming century. This magnitude and rate of change has not occurred since before the last ice age. The implications of this level of temperature change are further highlighted by the observation that, during the last ice age, mean northern hemisphere temperatures were only 5–6°C colder than they are now.

CLIMATE CHANGE SCENARIOS FOR THE UK

The prediction of climate change is subject to many uncertainties. The greatest uncertainty arises from an inability to predict the way that human society will change and, in particular, how effective the efforts to mitigate climate change will be. However, the climate change that will be experienced in the next 30–40 years will be due to past GHG emissions because of inertia within the global climate system. It is only beyond this timeframe that the magnitude of climate change will be determined by the emissions we allow now. This uncertainty is taken into

account by considering a number of feasible socio-economic scenarios of the future, each with an associated profile of GHG emissions. Further uncertainty arises from the inherent variability of climate. Climate change scenarios for the UK have been developed by the UK Climate Impacts Programme (the UKCIP02 scenarios: Hulme *et al.*, 2002) based on four of the scenarios published by the Intergovernmental Panel on Climate Change (IPCC, 2000). They range from *Low emissions* (B1: ‘global sustainability’ – rapid uptake of new technology and adoption of sustainable policies) to *High emissions* (A1FI: ‘world markets’ – an ongoing market-led economy reliant on fossil fuels). By definition, probabilities cannot be assigned to the four scenarios. UKCIP recommend that impact assessments should cover the full range of published scenarios.

The UKCIP02 scenarios are presented for four GHG emissions scenarios and three time slices: ‘2020s’ (2010–2039); ‘2050s’ (2040–2069); and ‘2080s’ (2070–2099). Predictions of seasonal changes to temperature and rainfall patterns are shown for the Low

and High emissions scenarios in Figure 2, and a summary of changes to other variables is given in Table 1. Mean annual temperature in the UK is expected to increase by between 3 and 6 °C by the 2080s, with larger increases in winter than summer. The number of frost days is predicted to decrease substantially throughout the UK by the 2080s. Summer rainfall is predicted to fall significantly (by up to 50%) and winter rainfall to increase by 10–40%, with the magnitude of predicted change largest in the south and east. In addition, inter-annual variation in rainfall and the duration of periods in summer without rain are likely to increase. As a result, summer droughts and winter flooding may become more commonplace. The wind speed predictions have higher associated uncertainty but indicate a southward movement of the storm-track and an increase in the number of deep depressions crossing the UK in winter. Increased temperatures will result in higher evapotranspiration than at present. Changes in temperature and humidity may also lead to reduced cloud cover in summer, particularly in the south, where sunshine duration is predicted to increase by up to 40%.

Figure 2

UKCIP02 climate change predictions for the 2020s, 2050s and 2080s Low and High emissions scenarios. Winter refers to the December, January, February quarter year, and summer to June, July, August. Units of temperature change are degrees Celsius relative to the 1961–90 baseline. Precipitation scenarios are expressed as percentage change relative to the 1961–90 baseline.

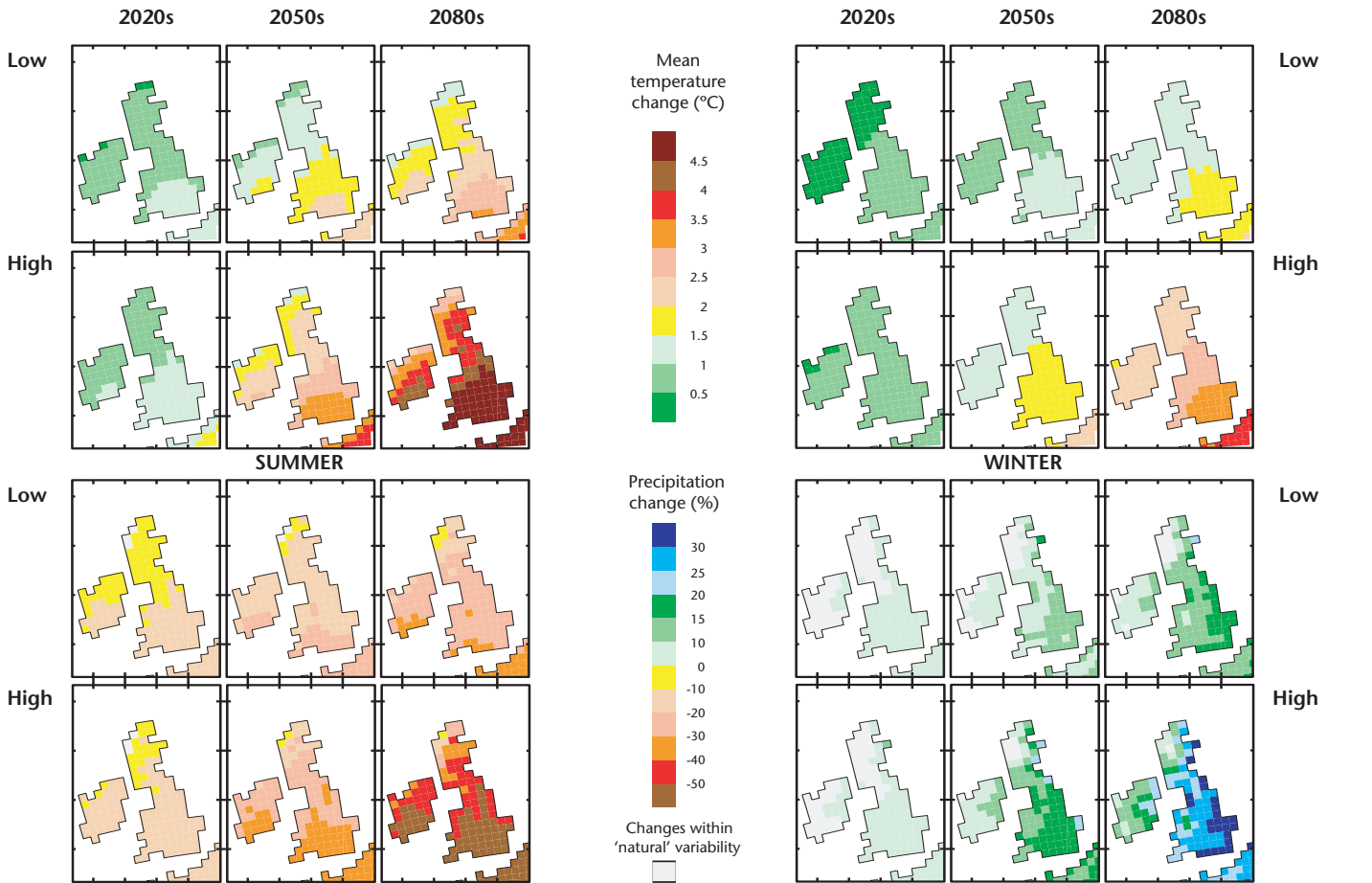


Table 1

UKCIP02 climate change predictions for the 2050s and 2080s 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. Positive changes are shown in red and negative changes in blue.

2050s	Low emissions scenario				High emissions scenario			
	Winter		Summer		Winter		Summer	
	Northwest	Southeast	Northwest	Southeast	Northwest	Southeast	Northwest	Southeast
Average min. temperature (°C)	+1.0	+1.2	+1.2	+1.8	+1.6	+1.9	+1.9	+2.8
Average max. temperature (°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	-	-
10 m mean wind speed (%)	+0.6	+2.3	-1.0	+0.3	+0.9	+3.7	-1.6	+0.5
Soil moisture content (%)	+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								
Average min. temperature (°C)	+1.4	+1.7	+1.7	+2.5	+2.7	+3.3	+3.3	+4.8
Average max. temperature (°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	-	-
10 m mean wind speed (%)	+0.8	+3.3	-1.4	+0.5	+1.6	+6.3	-2.8	+0.9
Soil moisture content (%)	+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

DIRECT EFFECTS OF A CHANGING CLIMATE ON TREES

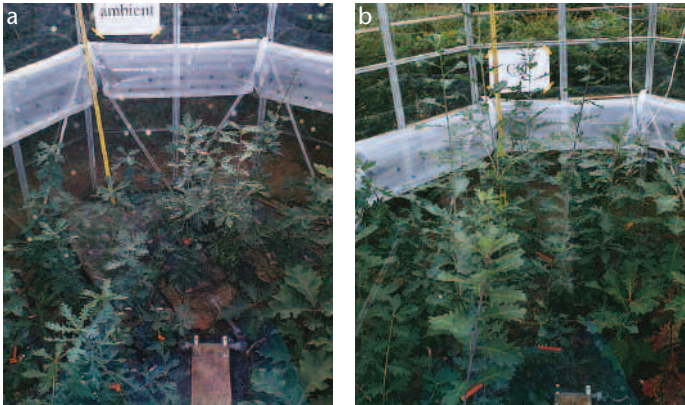
Rising CO2 levels

Before the effects of a changing climate are considered, it is important to note that the concentration of carbon dioxide in the atmosphere – the main driver of human-induced climate change – affects the growth of trees directly. Current concentrations of CO₂ are not optimum for photosynthesis and CO₂ emissions would therefore be expected to enhance growth rates assuming all other environmental conditions remained constant. Controlled environment experiments on young trees typically show that biomass production increases by 30–50% when the CO₂ concentration is doubled, as illustrated in Figure 3. 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 leading to reduced water use on a leaf area basis (Medlyn

et al., 2001), an increase in leaf area (Broadmeadow and Randle, 2002), possible changes in timber quality (Savill and Mather, 1990) and in the nutritional quality of foliage to insect herbivores (Watt *et al.*, 1996).

Figure 3

The effect of elevated CO₂ concentrations on tree growth. Seedlings of sessile, pedunculate and red oak were planted in open top chambers and exposed to (a) ambient (360 ppm) or (b) elevated (700 ppm) CO₂ concentrations for two growing seasons.

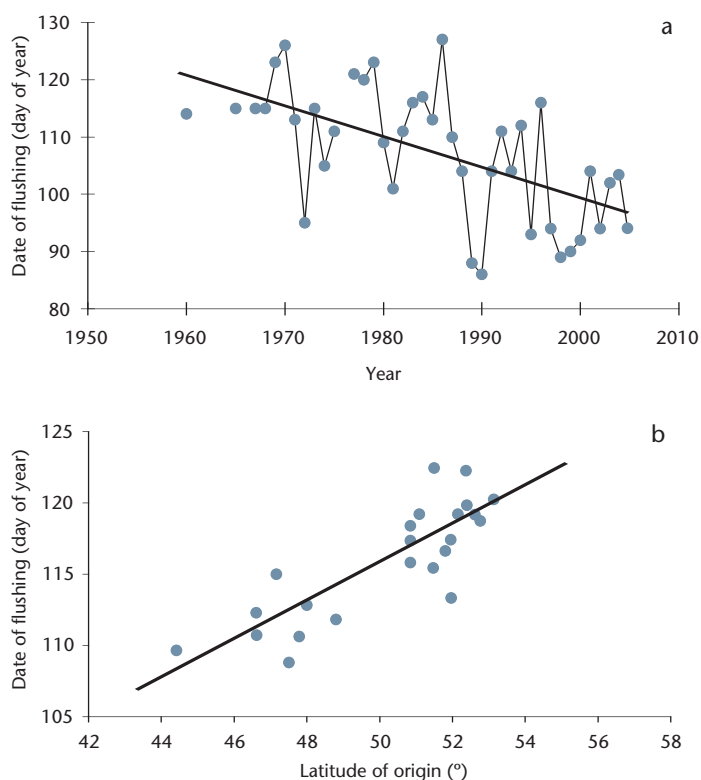


Increased temperature

For many tree species, budburst is likely to occur earlier in the year as a result of rising temperatures during winter months. This is already evident, with the flushing of oak advanced by up to two weeks compared with the 1950s, as shown in Figure 4a. Although a lengthening of the growing season would be expected to increase productivity in most years, early flushing increases the probability of frost damage, which may be serious in some years. The planting of more southerly provenances, which tend to flush earlier (Figure 4b), in anticipation of climate change could exacerbate this problem. Climatic warming may also lead to delayed or incomplete winter hardening, potentially resulting in more serious winter cold damage. In addition, warmer winters may mean that winter chilling requirements for flowering or seed germination are not met (Vegis, 1964), which could affect the success of natural regeneration. Seed germination is also dependent on seed moisture content (Gosling *et al.*, 2003) which could be affected by climate change. However, the interactions between changing temperature and rainfall patterns, together with the timing of seed germination for individual species, makes prediction of overall impacts impossible.

Figure 4

(a) Observed flushing date for oak in Surrey between 1959 and 2005 [source: T. Sparks, CEH and J. Coombs]; (b) relationship between flushing date in 2004 and latitude of origin for a provenance trial established at Chiddingfold, West Sussex in 1990.



Changing rainfall patterns

In the southeast of England, lower summer rainfall and an increased evaporative demand are likely to lead to longer periods of drought stress on trees. This issue of water balance is complicated by effects of rising CO₂ concentrations (see page 3), including an increase in leaf area and a change in the functioning of the stomatal pores which regulate water loss from leaves.

Increased winter rainfall will lead to more frequent winter waterlogging, in some cases resulting in reduced stability (Ray and Nicholl, 1998) and fine root death extending into surface soil horizons (Courtts and Philipson, 1978). The latter effect will also limit the ability of trees to take up water and exacerbate the problems of summer droughts. Winter waterlogging may also impact on the trafficability of forest soils and thus limit access of harvesting machinery for forestry operations if soil sustainability is to be maintained (Forestry Commission, 2003). Infection by various soil-borne pathogens, including species of *Phytophthora*, is promoted by fluctuating water tables (Lonsdale and Gibbs, 2002) and would be expected to become more prevalent.

Wind speed

Prediction of changes to the wind climate have high uncertainty associated with them. They do, however, indicate that mean wind speed may increase during autumn in the south of the country, contrasting with earlier predictions (UKCIP98: Hulme and Jenkins, 1998) of the largest changes in northwest Scotland. This is because the storm-track is predicted to move further south, together with a slightly increased frequency of deep depressions crossing the UK in winter. An increase in the occurrence of storms may make woodland more vulnerable to wind damage. However, reduced water availability in southern England and potential nitrogen deficiencies, resulting from reduced nitrogen deposition in response to the implementation of emissions control policies, may enhance allocation to roots thereby increasing anchorage. Most damage to forests is caused by extreme events and the frequency of these is very difficult to predict. It should, however, be noted that a small change in mean wind speed can have a significant effect on the frequency of extreme winds (Quine and Gardiner, 2002).

INDIRECT EFFECTS OF A CHANGING CLIMATE ON WOODLAND

Implications of climate change for pests and pathogens of woodland

Predicting changes to the impact of insect pest and disease outbreaks is difficult because of the fine balance between pest/pathogen, host tree and natural enemies. However, it is possible to make two generalisations – stressed trees are more susceptible to insect pests and diseases, and the majority of insect pests that currently affect UK forestry are likely to benefit from climate change as a result of increased activity and reduced winter mortality (Straw, 1995). The

impact of facultative pathogens such as sooty bark disease of sycamore may worsen, while some insect pests that are present at low levels, or currently not considered important, may become more prevalent. Examples of the latter include defoliating moths and bark beetles. In addition, the ‘effective’ range of existing pests or pathogens may change, including a northwards expansion of those with a southern distribution and the likely appearance of some from continental Europe. Firm predictions cannot be made for the reasons given above. However, expert judgement of forest pathologists and entomologists allows some assessment to be made of changes in the prevalence of certain diseases and insect pests, based on their current distribution and associated climatic conditions, known biology and epidemiology (Table 2a and b). Considerable caution should be exercised in extrapolating this analysis to a future climate.

Table 2a

Summary of inferred impacts of climate change on the activity and impact of woodland insect pests. Current status is given as a subjective assessment of the impact of a given insect pest on tree mortality, defoliation and amenity value, modified by its geographical extent. Key for current status: S = serious; M = minor; A = generally absent; T = affects timber value only.

Insect pest	Climatic driver	Current status	Likely trend	Comments
<i>Elatobium abietinum</i>	Milder winters	S	↑	Commercial spruce crops only.
<i>Hylobius abietis</i>	Hotter summers	S	↑	Small felling coupes in continuous cover forestry systems may moderate any increase in activity.
<i>Dendroctonus micans</i>	Summer drought	S	↑ (or ↓)	Principal predator may benefit more from a warmer climate.
<i>Ips acuminatus</i>	Summer drought	M	↑	Currently a secondary agent, but may become a primary agent in drought conditions.
<i>Ips cembrae</i>	Summer drought	M	↑	Currently limited to Scottish borders. Could cause serious damage to larch.
<i>Agrilus pannonicus</i>	Rising year-round temperature	M	↑	May be associated with oak decline when it may be the primary or secondary agent.
<i>Platypus cylindricus</i>	Various	T	–	Secondary pest affecting timber value. More impact if tree mortality increases.
Longhorn beetles	Summer drought	T	↑	Affect dead trees, but under extreme drought may attack living trees.
Tortrix and winter moth	Rising year-round temperature	M	↓	Climate warming could affect synchrony between emergence and budburst.
<i>Cameraria ohridella</i>	Hotter summers	M	↑	Hotter summers will increase the number of generations per year and hence the amount of damage. A warmer climate will extend geographic range northward.
<i>Agrilus planipennis</i>	Hotter summers	A	↑	Hotter summers will increase the number of generations per year and hence the amount of damage. A warmer climate will extend geographic range northward. Currently absent from UK but recent exotic pest in USA and Canada (from China).
<i>Anoplophora glabripennis</i>	Rising year-round temperature	A	↑	If introduced into woodland environment would benefit from climate warming. Absent from UK, but has been intercepted in imported wood packaging materials.
<i>Ips typographus</i>	Summer drought	A	↑	Summer drought likely to increase tree susceptibility to the pest and to increase the number of generations. Absent from UK, but intercepted frequently in wood imports.

Table 2b

Summary of inferred impacts of climate change on the activity and impact of fungal diseases and disorders of trees.

Disorder/pathogen	Predicted effect of climate change on prevalence
<i>Phytophthora</i> root diseases	Likely to become more prevalent and damaging, especially those which have higher growth temperature optima (28–30°C) such as <i>P. cinnamomi</i> .
Oak and beech decline	Incidence of these complex disorders is likely to increase because of the predicted increase in the frequency and severity of summer drought stress.
Damage to timber caused by blue stain fungi	Likely to increase as the bark beetle vectors are likely to be favoured by longer, hotter summers (more generations per year). Blue stain fungi also have growth temperature optima of 25°C and above.
Foliar diseases	The incidence of most foliar diseases will increase if climate change leads to wetter, warmer springs. This would apply to needle pathogens such as <i>Dothistroma (Scirrhia) pini</i> and shoot and foliar pathogens such as <i>Melampsora</i> , <i>Venturia</i> and <i>Marssonina</i> . However, foliar pathogens could become less damaging as a result of reduced rainfall and lower relative humidity in summer. The planting of more Corsican pine would also contribute to an increased incidence of <i>D. pini</i> if, as predicted, climate change increases its productive range.
Brunchorstia infection of Corsican pine	Likely to become less prevalent as a result of hotter, drier summers. This would have the effect of expanding the potential range of Corsican pine northwards and westwards.
Dutch elm disease	Higher summer temperatures likely to encourage more Dutch elm disease. Disease development is correlated with high temperatures, and the activity of vector beetles is also likely to increase.
Latent or endophytic pathogens	Disorders such as <i>Biscogniauxia</i> (strip cankers) and <i>Cryptostroma</i> (sooty bark disease) are likely to be expressed more frequently because of increases in summer temperatures. For example, each consecutive summer month that has a mean maximum temperature of 23°C increases the likelihood of damaging outbreaks of sooty bark disease in the UK.
Facultative pathogens	Climatic changes will encourage activity of facultative pathogens if trees are under stress.

For some pests and diseases, likely trends cannot be predicted even on the basis of expert judgement; in this category, and of particular concern, is *Phytophthora ramorum*, the agent responsible for sudden oak death. The higher level of uncertainty associated with the biology of fungi compared to insect pests is reflected in the less specific predictions of future trends in the incidence of fungal diseases and disorders.

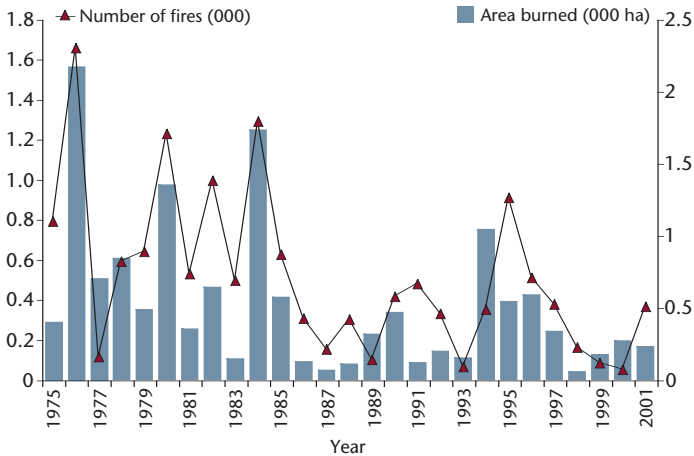
Damage caused by mammalian pests, particularly the grey squirrel (*Sciurus carolinensis*), may also increase in the future as a result of reduced winter mortality and increased seed availability. Pressure on populations of the red squirrel will therefore continue as the grey squirrel is at least as well adapted to a warmer climate as the red squirrel (*Sciurus vulgaris*), based on an analysis of current distributions. Populations of deer are also likely to increase, again as a result of reduced winter mortality, but also because advanced growth of the ground vegetation increases forage availability during the critical spring period (Langvatn *et al.*, 1996).

Climate change and forest fires

Currently, the most damaging forest fires are in spring with dry vegetation and litter from the previous growing season fuelling the fires (Cannell and McNally, 1997).

Rainfall in spring is not predicted to change markedly, and the earlier growth of ground vegetation as a result of climatic warming could reduce the incidence of forest fires in spring and early summer. However, extended summer droughts such as those experienced in 1976 and 1995 result in a secondary peak in available fuel in late summer as the ground vegetation dies and dries off. This is demonstrated in fire statistics, which show peaks in years such as 1976, 1984 and 1995 when severe drought was experienced in some regions (Figure 5).

Figure 5
Forest fire statistics: 1975–2001.



An increase in the frequency and severity of summer droughts would be expected to lead to an increase in the number of fires and forest area affected in those years. As urban and peri-urban woodland expands, the increasingly close relationship between human habitation and woodland may require that greater consideration is given to fire risk assessment and control.

The relationship between summer drought and forest fire incidence is set against a background of a downward trend in fire frequency. This is partly a result of the changing age structure of the forest estate. Since the late 1980s the area of thicket stage conifer plantation, which is generally more susceptible to fire than broadleaf woodland and mature woodland, has fallen. Thus weather conditions alone do not determine fire susceptibility and should be considered alongside woodland structure and land cover in the context of the wider landscape.

CLIMATE CHANGE AND FUTURE SPECIES SUITABILITY

Future species suitability can be modelled on the basis of performance under the present-day climate for regions which experience a climate similar to that predicted for the future at a given site. The Ecological Site Classification (ESC), a knowledge-based spatial decision support system, provides a framework to carry out such an analysis (Ray and Broome, 2003). ESC has been developed to guide decisions on commercial species selection and the restoration and expansion of native woodland; it is described in full by Pyatt *et al.* (2001). Predictions of species suitability have only been made for the 2050s High and Low scenarios of UKCIP02 as, beyond this timeframe, the climate change predictions are well outside the current knowledge-base and assessments cannot be made with any level of certainty. The possibility of further and more extreme changes to the climate in the latter half of the century should therefore be considered when the knowledge-base has been appropriately extended.

Suitability maps for individual species are shown as Figures 6 and 7, but a number of assumptions must be borne in mind when interpreting them (see Broadmeadow *et al.*, 2005). Firstly, the effects of rising atmospheric CO₂ levels would be expected to increase productivity and alleviate some of the effects of drought (Broadmeadow and Jackson, 2000), but are not considered by the model. Secondly, the predictions represent changes to average climate and do not consider the effects of extreme climatic

events. If, as some models suggest, the climate becomes more variable, the effects of climate change could be more dramatic than indicated in the suitability maps. Changes in the prevalence of insect and disease outbreak are also not considered, nor are the impacts of mammalian pest damage. Finally, spatial scales of less than the 5 km x 5 km grid are not modelled, and thus the maps should only be used to provide an indication of broad changes in species suitability rather than site specific assessments of suitable species for restocking or new planting.

Broadleaved species

The pattern of response to climate change of all species shown in Figure 6 (and for most conifers shown in Figure 7) is similar, with a reduction in productivity predicted in the south and east of Britain, contrasting with increasing growth rates across most of the wetter regions. The increase in productivity is particularly noticeable in eastern Scotland, where expansion of the commercially suitable range partly reflects the ability to grow at higher elevation. When comparing the ranges of the two native species of oak, it is clear that the range of pedunculate oak expands at the expense of sessile oak, although commercially acceptable levels of growth (GYC 4–6 m³ ha⁻¹ yr⁻¹) for the most suitable of the two species are maintained across most of Britain. This is not the case for beech, which is predicted to become unsuitable for commercial forestry across much of England. However, the knowledge-base of ESC reflects past practice and the current preponderance of sites that may be more prone to the effects of drought. The ability of beech to survive in hotter, drier climates is not in doubt, given its natural and productive ranges in France (Broadmeadow *et al.*, 2005). The effects of drought are likely to be minimal where roots have accessed water in underlying chalk (Roberts and Rosier, 1994), while future planting on more moisture retentive soils would also limit the effects of the predicted increase in the frequency and intensity of summer drought. Statements that beech will disappear from southern England as a result of climate change are thus alarmist. However, its future as a commercial species in southern England will be limited to specific soil types and the distribution of beech woodland will change.

Under the 2050s Low emissions scenario, the productivity of ash is predicted to rise across much of eastern England. However, under the High emissions scenario, this growth enhancement is lost, and productivity is predicted to fall across western England, Wales and East Anglia compared to the baseline.

Figure 6

Effects of climate change on the productivity expressed as general yield class (GYC: $\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$) of (a) oak, (b) beech and (c) ash as predicted by ESC for the UKCIP02 2050s Low and High emissions scenarios. The maps interpret only the direct effects of climate change on the baseline (1961–90) suitability maps. The identity of the most suitable broadleaf species is shown in (d), where suitability is defined as predicted productivity class relative to the maximum potential productivity of that species in the UK.

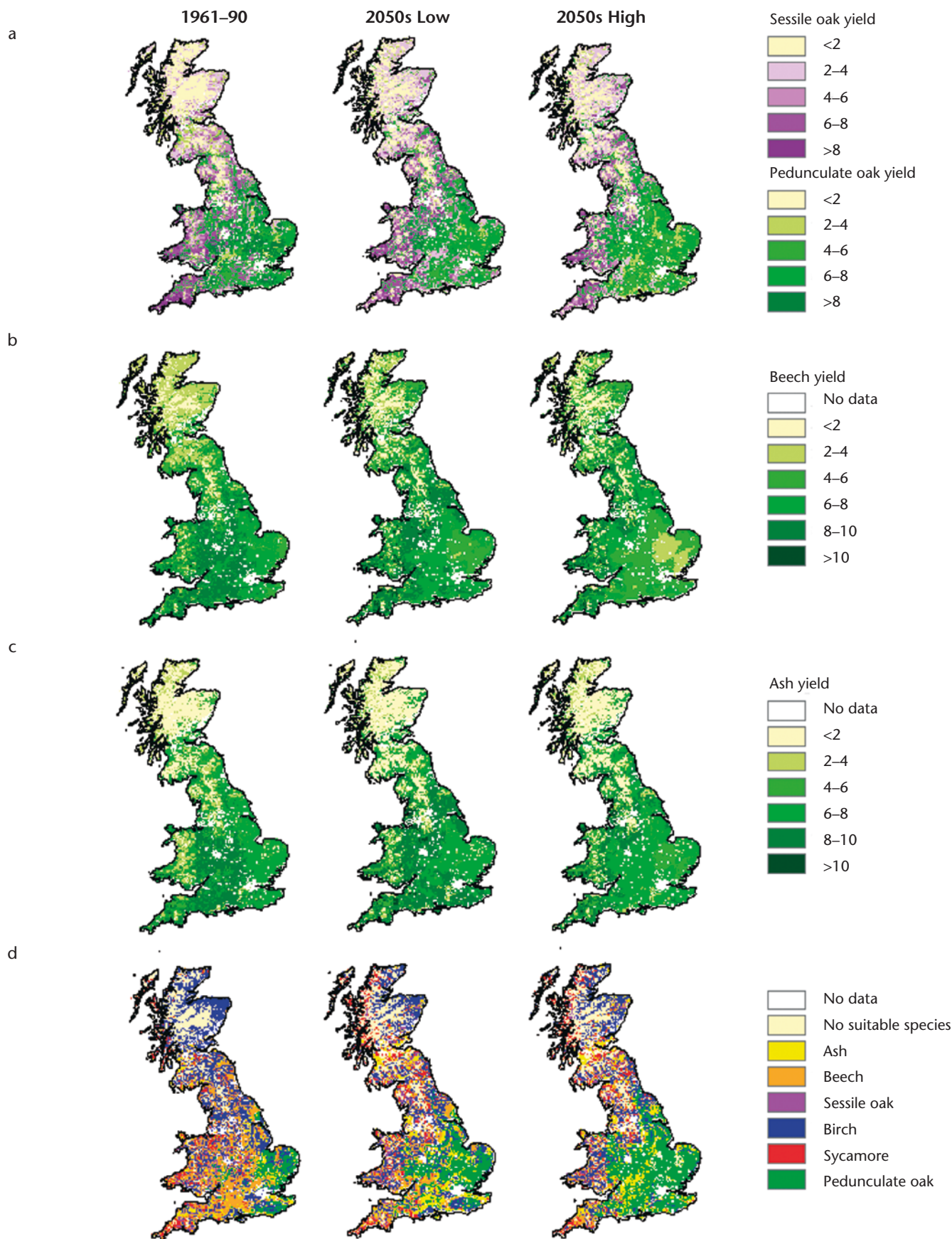
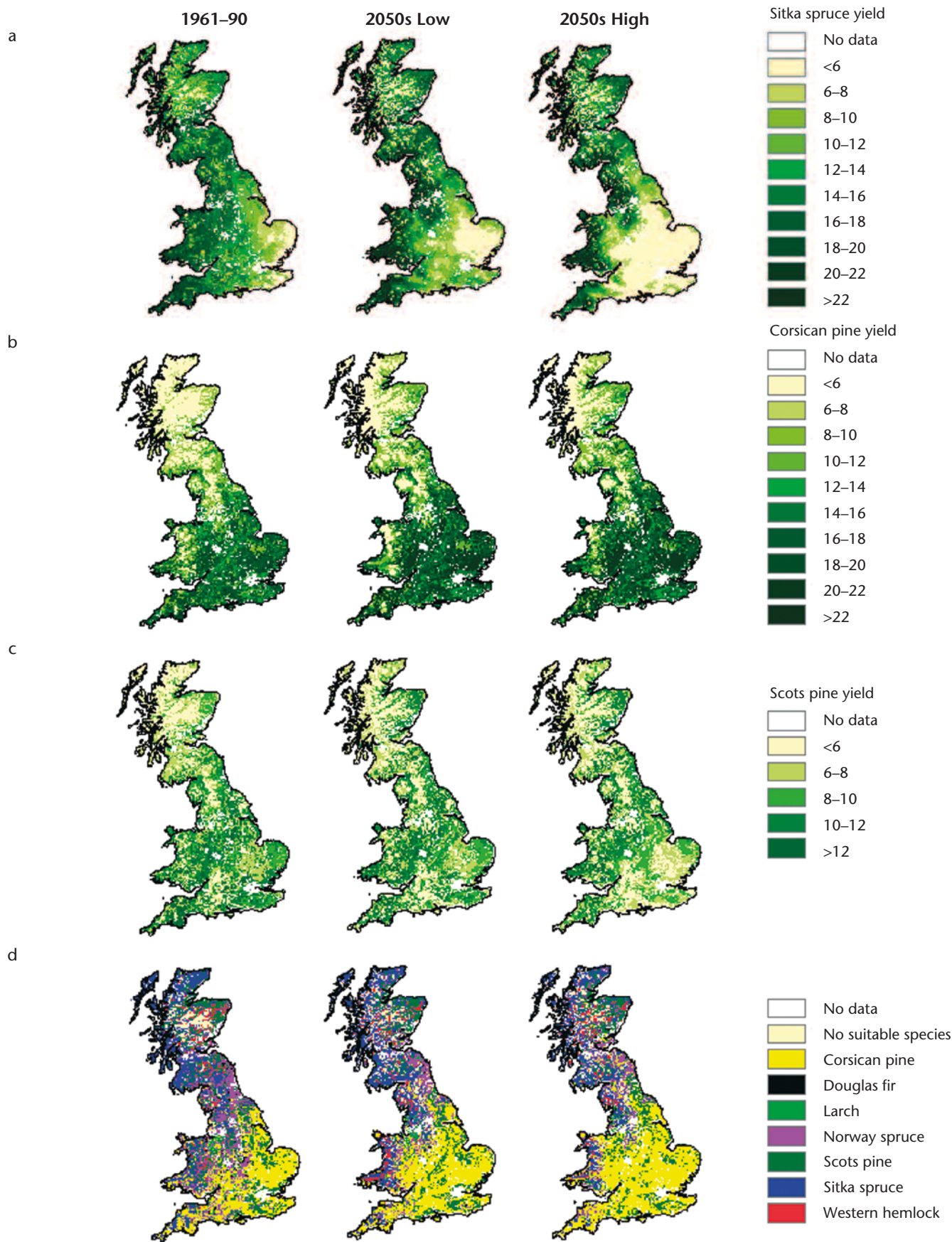


Figure 7

Effects of climate change on the productivity expressed as general yield class (GYC: $\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$) of (a) Sitka spruce, (b) Corsican pine and (c) Scots pine as predicted by ESC for the UKCIP02 2050s Low and High emissions scenarios. The identity of the most suitable conifer species is shown in (d), where suitability is defined as predicted productivity class relative to the maximum potential productivity of that species in the UK.



Since climate change is predicted to affect different species to a greater or lesser degree, the most suitable species on a given site is also predicted to change as global warming progresses, as shown in Figure 6d. Here, the ‘most suitable’ species is defined as that closest to its maximum productivity for the UK at the location in question. Under the 2050s Low emissions scenario, ash is predicted to replace beech as the most suitable species across much of southern England, in turn being replaced by pedunculate oak under the High emissions scenario. Other notable changes include sycamore being replaced by silver birch as the most suitable species in much of central Wales and northern England, but replacing silver birch in the west of Scotland. Silver birch is also replaced by ash as the most suitable broadleaf species across much of the central belt of Scotland.

Conifer species

The predicted increase in summer soil moisture deficit leads to the commercially suitable range of Sitka spruce being restricted in England to the southwest peninsula and the North West, while increased productivity is predicted for Wales, southwest Scotland and northeast Scotland. The suitable range of Scots pine also contracts in England, but not to the same extent as for Sitka spruce. As is the case for most broadleaf species, the predicted increase in productivity is most marked in northeast Scotland. Of the individual species shown in Figures 6 and 7, Corsican pine is the only one that becomes more suitable across most of Britain, even under the 2050s High emissions scenario.

When a wider range of species is considered (Figure 7d), it is evident that there is less effect of climate change on the identity of the most suitable conifer species, compared to broadleaf species. The most notable prediction is an expansion of the area where Corsican pine is the most suitable species, including a displacement of Sitka spruce in parts of Wales and the southwest peninsula. Scots pine is predicted to remain suitable across most regions of England, and increase its suitable range in eastern Scotland. As might be expected given the common occurrence of disorders such as ‘top-dying’ (Redfern and Hendry, 2002) in the recent past, the area where Norway spruce is the most suitable species contracts to a relatively small area in southeast Scotland under the 2050s High emissions scenario.

Although the species suitability maps indicate that climate change will have an impact on the identity of the most appropriate species for a given site, it is clear that commercial timber production, for both broadleaf and

conifer species, should continue to be viable across the whole of Britain, using the range of species that are commonly planted at present. However, informed species choice can help to optimise productivity and mitigate against the effects of extreme weather events.

Process-based models of forest growth

Models of forest growth that include representation of physiological processes, including photosynthesis, transpiration, and nutrient allocation and cycling, provide an alternative approach to integrating the many predicted changes to the woodland environment. These models, of which ForestGrowth (Evans *et al.*, 2005) is an example, have the ability to account for changes in atmospheric composition and pollutant deposition as well as the predicted changes in climate. They are also able to evaluate changes in stand dynamics. A major drawback of process-based models is that they are ‘data-hungry’, requiring both intensive data input and detailed species and site characterisations. Simulations using this type of model indicate that GYC increases of 1–2 m³ ha⁻¹ yr⁻¹ (beech and Sitka spruce: Murray and Thornley, 2003) or 2–4 m³ ha⁻¹ yr⁻¹ (oak and Sitka spruce: Broadmeadow and Randle, 2002) might be expected in the UK by the end of this century, where water availability is not a limiting factor. An additional role that process based models can play is in providing estimates of the water use of woodland and how this may change as a result of climate change.

CLIMATE CHANGE AND WOODLAND ECOSYSTEMS IN THE LANDSCAPE

The tree species making up the overstorey represent only one element of the woodland ecosystem. When interpreting the likely effects of climate change on woodland habitats, it is at least as important to consider impacts on the function and distribution of other plants and animals that constitute the wider woodland ecosystem. This analysis must cover both the direct effects of climate change on individual species and an assessment of how competition between species may be affected by climate change, potentially altering the character of woodland habitats. Two approaches to projecting how climate change may affect woodland ecosystems are thus available, based on either an analysis of the climatic and edaphic distribution of species assemblages or on the ‘climatic envelope’ of individual species.

ESC predictions of native woodland suitability

The ESC simulations shown in Figures 6 and 7 provide predictions of the status of the principal tree species under which woodland ecosystems develop. ESC also provides guidance on suitable woodland types for establishing new native woodlands, based on the National Vegetation Classification system (NVC: Rodwell, 1991). NVC woodland types are described in terms of species assemblages with suitability assessed on the basis of the same climatic and edaphic drivers used for predicting commercial productivity. Examples are given in Figure 8, which shows how climate change (2050s Low and High emissions scenarios) may affect the suitability for lowland and upland oak woodland (W10 oak-bracken-bramble and W11 oak-birch-wood sorrel, respectively), as predicted by ESC.

Where a woodland type is classed as marginal, this indicates that changes in the ground flora composition are likely. Of particular note is the very restricted suitable range of W11 upland oakwoods under the 2050s High emissions scenario, indicating a more fundamental change to the nature of the vegetation community. These maps of future NVC woodland type suitability indicate where it

Figure 8
ESC predictions of the effect of climate change on the suitability of sites for (a) NVC W10 and (b) W11 oak woodland.



may prove difficult to manage to the current NVC prescription. However, they should not be used as an indicator of which woodland type should be the objective of management for the future; it is likely that new vegetation associations will develop as a result of changing competitive advantage of individual species.

Climatic envelopes of individual species

Detailed projections of the response of individual plant, mammal and bird species to climate change have been modelled on the basis of their current European distribution as part of the MONARCH project (Modelling natural resources responses to climate change: Harrison *et al.*, 2001) using the SPECIES model. This work suggests that some species will benefit and some will lose out. It is important to note that only climatic envelopes for individual species are considered in this analysis with no representation of competition between species. An indication of the direction of response for those woodland species assessed as part of the MONARCH project is given in Table 3. For beech, outputs from ESC and SPECIES show good agreement of areas where the species is predicted to become commercially suitable or fall outside its natural climatic envelope, respectively, as a result of climate change.

Table 3
Summary of responses of woodland fauna and flora to climate change (UKCIP98 High scenario: Hulme and Jenkins, 1998) as predicted by the SPECIES v1 model. + and – indicate an expanding or contracting range for that species in the UK and, 0, little change to its distribution. (+)(–) indicates that the distribution of the species in the UK will change, but with no net gain or loss of habitat [source: after Harrison *et al.*, 2001].

Scientific name	Common name	Response
<i>Geranium sylvaticum</i>	Wood crane’s-bill	– – –
<i>Salix herbacea</i>	Dwarf willow	– –
<i>Trollius europaeus</i>	Globeflower	– –
<i>Orthilia secunda</i>	Toothed wintergreen	– –
<i>Linnea borealis</i>	Twinflower	– –
<i>Sanicula europea</i>	Sanicle	0
<i>Blechnum spicant</i>	Hard fern	0
<i>Dryopteris aemula</i>	Hay-scented buckler fern	(–)(+)
<i>Sitta europea</i>	Nuthatch	(–)(+)
<i>Luscinia megarhynchos</i>	Nightingale	(–)(+)
<i>Parus montanus</i>	Willow tit	(– –) (+ +)
<i>Taxus baccata</i>	Yew	+
<i>Sciurus vulgaris</i>	Red squirrel	+ +
<i>Fagus sylvatica</i>	Beech	+ + +

Woodlands in the wider landscape

Although some knowledge of individual species responses is informative for adapting site management to climate change, it is also important to maintain ecosystem robustness at a landscape level. Larger areas of woodland within a mosaic of woodland and associated natural ecosystems, through which species can move, provide an improved capacity for adaptation and facilitate migration. This is because physical obstacles (e.g. roads) or functional barriers (e.g. areas of intensive agriculture) limit both the robustness and adaptability of ecosystems by restricting dispersal and migration. Assessments of the probable impacts of climate change on woodland ecosystems, and any responses to limit these changes, should thus not be restricted to the woodland in isolation, but should consider it in the context of the wider landscape.

PRACTICAL MEASURES IN THE FACE OF CLIMATE CHANGE

Practical responses to the threats posed by climate change cover two principal areas – *adaptation* and *mitigation*. Adaptation measures minimise the effects of climate change as it progresses, while mitigation is an attempt to limit the magnitude of climate change. Both are relevant to woodland management and the forestry sector and should be carefully considered.

Adaptation strategies for UK woodland

Given the magnitude and rate of predicted climate change, at a national scale trees and woodlands will be significantly affected. Adaptation is therefore an important issue and should be addressed at the earliest opportunity. This is particularly the case for woodlands and the forestry sector because of the long time-frame associated with any management decisions. The difficulty lies with ensuring that decisions made now, particularly relating to species and provenance choice, are appropriate to both the current and future climate. Decisions should also consider landscape scale issues. As discussed previously, the size and connectivity of woodlands affect their sensitivity to environmental change. A number of other issues are prominent at the landscape scale, and will need to be considered in forest planning. Foremost of these is water availability. The water use of trees is generally greater than that of arable crops or grassland, while canopy interception of rainfall by broadleaf species is typically less than that by conifers, especially during the

winter months (Nisbet, 2005). Water use and availability should therefore be given consideration in forest design plans in regions where water shortages are predicted, including decisions over species choice.

It would be premature to develop prescriptive guidance on climate change adaptation strategies for woodland until firmer predictions of both climate change and how woodland is likely to respond are available. However, it is possible to identify some ‘no-regret’ options that should be implemented now and follow from good practice and a basic understanding of the predictions of climate change.

Planting stock – species and provenance choice

Alternative provenances or species could be planted to respond positively to the predicted warmer climate (see Cannell *et al.*, 1989). It is important to recognise that the adoption of new varieties or the wider use of some that are already planted will require careful balancing against commitments to the use of native species and origins. Furthermore, where species or provenances originating from hotter, drier climates are planted, performance under a future climate must be balanced with performance under the current climate. This is of particular importance for frost tolerance, as has been clearly demonstrated by unsuccessful provenance selection of both Sitka spruce and *Nothofagus* spp. in the past. Frost damage limits growth and results in poor form and reduced timber quality. The phenology of species and provenances planted in anticipation of climate change is thus an important element of their choice. However, growth potential is not the only consideration for climate change adaptation, particularly on sites of ancient or semi-natural woodland. Implications for the genetic resource within Britain, including the maintenance of the genetic and species biodiversity of woodlands, are equally important.

As indicated above, approaches to climate change adaptation will vary, and it is thus essential to consider the principal purpose(s) of the woodland when assessing the available options:

- If timber production is an important objective, species and provenance should be well adapted to both the current and future predicted climate. Non-native species could be considered, particularly in southern Britain and on more freely draining soils.
- If the retention of high forest for leisure and amenity use is an important objective, then the considerations should be similar to those for timber production, although a wider range of species could be included.

- If the restoration or maintenance of semi-natural woodland, together with associated ground flora is the main objective, native species should be planted. However, in southern Britain, non-native provenances could be considered and an assessment of the long-term suitability of the woodland type on a given site should be made in the context of the climate change predictions. The character of the associated vegetation community is, however, likely to change.
- If the maintenance of the genetic resource native to Britain is the principal objective, then only seed from native, ancient woodland should be planted, after due consideration of its likely ability to survive predicted climate change. The long-term potential of survival for 'genetic reserves' should also be assessed. The translocation of genetic material to regions with colder wetter climates could be considered in advance of climate change.

Management of existing woodland

Although the choice of planting stock — for restocking, the restoration of semi-natural woodland, or woodland expansion — is an important element of climate change adaptation, there are also options for the management of existing woodland. Productivity across much of the north and west is predicted to rise, both as a result of increased warmth and rising CO₂ levels. Rotation length and the timing of thinning may therefore need adjustment, particularly in areas subject to wind damage. Forestry in the UK has adapted to the windy climate experienced here and management tools (e.g. ForestGales: Dunham *et al.*, 2000) are available. However, practice and guidance may need some adjustment should the wind speed distribution relative to the mean (see Quine and Gardiner, 2002) or the regional pattern of windiness change significantly as a result of climate change. The most likely drivers for changes to the wind risk of a specific site are an increased susceptibility to windthrow as a result of higher winter rainfall and thus soil waterlogging, or an increase in leaf area (in response to rising CO₂ levels) enhancing canopy resistance. Increased winter rainfall and soil waterlogging may also require a change in management practice, further limiting harvesting access to minimise compaction. In time, establishment practice may need to change, while aftercare of amenity and street trees, in particular, will become more important.

Summary of adaptation measures

Some of the steps for climate change adaptation described above represent a major change to woodland management. However, there are also a number of basic measures that

require little change to best practice and these no-regret options should be built into decision-making in forestry, as standard:

- Climate change predictions must be considered in the choice of planting stock.
- Tree species and woodland types should be well matched to site; if currently at the dry end of their suitable range, they should not be planted.
- Mixtures of species and/or provenance will provide some insurance against climate change since not all will be affected to the same extent.
- At a landscape level, larger, better connected woodland should be an objective.

Climate change mitigation and the role of woodland in the UK

Woodland has the ability to absorb CO₂ from the atmosphere through photosynthesis, converting some of it into wood. In addition, the carbon content of woodland soils is generally higher than that associated with most other vegetation covers. In the UK, a maximum carbon stock of about 250 tC ha⁻¹ can be achieved in biomass in 'old-growth' woodland (Broadmeadow and Matthews, 2003). In contrast, woodland conventionally managed for timber production only achieves about half this value. When woodland is mature, losses of carbon through respiration and decay balance uptake through photosynthesis. At this stage, the woodland is no longer an active carbon 'sink', but does represent a significant store of carbon.

To place the potential role of woodland in the UK in context, the total carbon stock associated with above ground woody biomass (~130 MtC) is less than the total of fossil fuel emissions in a single year. However, the net uptake of carbon in UK woodland (~2.5 MtC yr⁻¹) is significant in comparison with national emissions reductions commitments made under the Kyoto Protocol (20 MtC yr⁻¹). Therefore, although small in absolute terms, woodland can play a significant role in emissions reductions in the short term, and 'buy time' to allow new, low carbon, technologies to be developed. However, the conclusion has to be that climate change mitigation at a global scale is unlikely to be effective over the short to medium term, and significant climate change is unavoidable. This last point is reinforced by the fact that the degree of climate change that we will experience over the coming 30–40 years is dominated by past emissions. Actions that we take now will mainly take effect beyond this timeframe.

Woodland has an additional role to play in climate change mitigation by providing alternatives to fossil fuels or materials that have high fossil fuel inputs associated with their production. Short rotation forestry and the increased utilisation of woodfuel as a renewable bioenergy resource are examples of the former, while an increased use of timber in the construction industry is an example of the latter.

The positive role that woodland can play in a changing climate

Some woodlands in the UK are likely to be detrimentally affected by climate change, requiring the implementation of adaptation measures. Nevertheless there will also be opportunities for trees, woodland and the forestry sector to help in minimising the wider effects of climate change on the environment. For example, woodland has a potential role to play in flood management through flood-plain woodland attenuating downstream peak water flows, while riparian woodland has the potential to reduce water temperature in summer through its shading effect; this role of riparian woodland may become increasingly important in protecting fish populations as climatic warming progresses. Woodland also has the capacity to reduce soil erosion which could become more prevalent as a result of higher rainfall in winter and drier soils in summer.

The role of trees and woodland in built-up areas will also become more important as climate change makes the environment of our towns and cities increasingly unpleasant during heat waves. Trees provide shade, limit the ‘urban heat island effect’ and remove pollutants, some of which are predicted to increase, partly as a result of climate change (NEGTA, 2001).

Monitoring climate change

Monitoring is an essential element of any adaptation or mitigation strategy. Information relevant to climate change monitoring is available from a range of sources including the Forest Condition Survey (Hendry *et al.*, 2004) and the Intensive Forest Monitoring network (Durrant, 2000). ‘Official’ climate change indicators have also been developed for the UK (Cannell *et al.*, 1999). They include both direct climatic measures (i.e. trends in temperature, sunshine and rainfall patterns), and a range of ‘response’ indicators, three of which are directly relevant to forests and woodland:

- Health of beech trees: the data are derived from the Forest Condition Survey, in which crown transparency is assessed. Beech is relatively drought sensitive and direct effects of climate may be apparent. However,

any trend in crown density is more likely to be related indirectly to weather through its influence on seed production, which is strongly correlated with reduced canopy development in beech. Hot, dry summers generally promote seed production the following year, particularly if preceded by a wet summer (Piovesan and Adams, 2001). To date, no significant trend is apparent.

- Flushing date of oak: flushing date is highly dependent on temperature in spring and has already advanced by 10–15 days relative to the 1950s.
- Incidence of outdoor fires: outdoor fires are more commonplace in hot, dry summers, such as those of 1976 and 1995. These data are mirrored by forest fire statistics (see Figure 5). However, the changing age and species structure of the forest estate may weaken the climate change-driven signal, as discussed on page 7.

CONCLUSIONS: THE FUTURE OF UK WOODLAND IN THE 21st CENTURY

Although there is considerable uncertainty over the progression of climate change in the 21st century, it is clear that the response of woodland will vary from region to region. Scotland, northern England and much of Wales are likely to see increased productivity as a result of rising CO₂ levels, a longer growing season and a generally warmer climate. However, across much of England, the predicted increase in the frequency and severity of summer droughts suggests that growth rates of many common species will decrease and species suitability will change. The impacts of storms and severe pest and disease outbreaks could, potentially, be more serious than the effects of a gradual change to our climate. However, these predictions are very uncertain because of their complexity and rarity, so only very general guidance can be given. The character and composition of our native woodland is likely to change, with new species assemblages developing. Adaptation through evolution and migration can be aided by landscape level planning providing larger areas of functionally connected woodland.

Where woodland is planted with production of timber, wood fibre or biomass a stated objective, careful consideration will have to be given to species choice. On some of the more freely draining soils in southern England, many native species may no longer be silviculturally viable choices. ESC can provide general guidance on future species suitability; this knowledge should be used in conjunction with an assessment of on-site conditions.

The use of non-native provenances of some native species may provide one adaptation measure, but non-native species also warrant consideration. Avoiding undue reliance on a single species or provenance in forest design plans will improve resilience whatever the degree of climate change, and also provide insurance against current uncertainty in the response of woodland to it. Given the magnitude of potential changes described here, good practice would be to consider the climate change predictions in current forest design plans.

Climate change does not solely represent a threat to woodland and the forestry sector and opportunities will arise. For example, our forests have a small, but potentially important, role to play in climate change mitigation. Woodland can also contribute to flood and erosion control, while its contribution to improving the urban environment should not be underestimated. In some regions, timber production may also increase significantly.

It is clear that climate change will affect both our semi-natural woodland and commercial plantations. In many cases the effects are likely to be detrimental but there are options for adaptation that should be considered, though not necessarily implemented, now. The most difficult decisions will be in identifying where adaptation is necessary and, more critically, when to act.

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