Climate change and the future for broadleaved tree species in Britain

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Abstract

The most recent climate change predictions for the UK indicate a warming of between 2 and 5°C by the end of this century, with drier summers and wetter winters also anticipated across the majority of the country. Changes are predicted to be more extreme in the southern half of the UK, where severe summer droughts will become commonplace. Although rising atmospheric CO_2 levels are likely to increase productivity through 'fertilizing' photosynthesis, water limitation in southern England is likely to lead to an overall reduction in growth and increase in drought-induced mortality. Incorporation of, the climate change scenarios within the GIS model Ecological Site Classification indicates that in isolation, the effects of climate change will result in significant changes in species suitability. Under current definitions the majority of native broadleaf species are predicted to become unsuitable for commercial timber production in southern England. Genetic variability in local native populations may enable a degree of adaptation. Existing trials of ash *(Fraxinus excelsior* L.) suggest that the best performing provenances are those from regions with a climate similar to that of the trial site. The selection of a provenance for climate change adaptation should be from a region with a current climate well matched to a planting site's predicted climate of the future. Climate matching analysis indicates that coastal areas of western France experience a climate similar to that predicted for southern England by 2050, while the more extreme scenarios predict climates better matched to the Mediterranean region at high elevation by the end of the century. The scale of climate change predictions indicates that, in southern England, native broadleaf species may be unsuitable for timber production on some soils. The planting of non-native species may need to be considered to maintain woodland cover and ensure a viable hardwood timber industry.

Introduction

There is now convincing evidence that the global climate is changing at an unprecedented rate (IPCC, 2001). A large proportion of the observed rise in global temperatures of ~0.6°C has been attributed to human activities, principally land clearance and fossil fuel burning, which have released large quantities of greenhouse gases into the atmosphere. The most important of the greenhouse gases is carbon dioxide (CO_2) which has risen from a pre-industrialization concentration of 270 ppm to the current value of ~375 ppm Future socio-economic development pathway scenarios associated with predicted greenhouse gas emissions suggest that this trend is likely to

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continue (IPCC, 2000). The concentration of carbon dioxide in the atmosphere is predicted to rise to between 525 and 750 ppm by the end of this century (IPCC, 2001), although some authors suggest that a carbon cycle feedback (the loss of tropical forest biomass and soil carbon) could raise the concentration to over 900 ppm over the same time-frame (Cox *et al.*, 2000).

In the UK, climate change predictions forecast hotter drier summers and milder wetter winters, with the magnitude of change largest in the south and east of the UK (Hulme *et al.*, 2002). A summary of the predicted changes to the climate of the UK is given in Table 1, based on the UKCIP02 climate change scenarios (Hulme *et al.*, 2002). Although there is a possibility that changes in ocean circulation could lead to a cooling of the climate, the UKCIP02 scenarios do include an assumed weakening of the north Atlantic thermohaline circulation (the 'Gulf Stream'), and the balance of informed opinion is that this will be outweighed by the predicted warming of the climate. This paper assumes that future climate warming will continue as outlined in the UKCIP02 scenarios.

The likely effects of climate change on tree function and growth have been reviewed elsewhere (Cannell *et al.*, 1989; Eamus and Jarvis, 1989; Norby *et al.*, 1999; Broadmeadow, 2002). The direct effects of rising concentrations of carbon dioxide (the 'CO_2 fertilization effect') will enhance photosynthesis, and experimental evidence indicates a growth enhancement of 30–50 per cent for young trees (Broadmeadow and Randle, 2002). It is unlikely that the same level of productivity increase will be observed for mature

Table 1: UKCIP02 climate change predictions for the 2050s and 2080s Low- and High-emissions scenarios

	Low-emissions scenario				High-emissions scenario			
	Winter		Summer		Winter		Summer	
	North-west	South-east	North-west	South-east	North-west	South-east	North-west	South-east
2050s								
Average minimum temperature (°C)	+1.0	+1.2	+1.2	+1.8	+1.6	+1.9	+1.9	+2.8
Average maximum 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 minimum temperature (°C)	+1.4	+1.7	+1.7	+2.5	+2.7	+3.3	+3.3	+4.8
Average maximum 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

Units of temperature change are degrees Celsius relative to the 1961–1990 baseline, while all other variables are given as percentage change relative to the baseline. 'South-east' values are for the 50 km × 50 km grid-square in which Alice Holt Research Station, Hampshire is situated, while the 'north-west' grid-square is centred on Fort William, Highland Region.

forest stands, which has been confirmed by some studies in which forest stands are subjected to free air CO_2 enrichment (Oren *et al.*, 2001). Other observed impacts of rising CO_2 levels include reduced stomatal conductance (Medlyn *et al.*, 2001), increased leaf area (Broadmeadow and Jackson, 2000), altered nutritional status (Curtis and Wang, 1998) and timber quality (Donaldson *et al.*, 1987; Hättenschwiler *et al.*, 1996). There is also some evidence that elevated CO_2 may limit the temperature response of flushing in Sitka spruce (Cannell and Smith, 1984) and oak (M.S.J. Broadmeadow, unpublished data), and also alter the nutritional quality of foliage to insect herbivores (Watt *et al.*, 1996). Climatic warming is also likely to increase productivity by extending the length of the growing season (Cannell *et al.*, 1998) in addition to increasing the warmth of the growing season. This has a two-fold impact on accumulated temperature, a major determinant of tree growth rate (Pyatt *et al.*, 2001).

In contrast to the largely positive effects of climate change described above, global climatic warming is predicted to result in altered rainfall patterns which, in the UK, are likely to be manifested as an increase in the frequency and severity of summer drought across much of the UK. Droughts are predicted to be most significant in southern England, with a 50 per cent reduction in summer rainfall and 60 per cent increase in moisture deficit forecast under the most extreme scenario by the 2080s (Table 1). Although the scenarios indicate a modest increase in mean wind speed in winter, these predictions are among the least certain (Hulme *et al.*, 2002) and their impact is difficult to assess. The scenarios also indicate a more variable climate in general, and it is likely that the most dramatic impacts on tree growth and forest productivity will occur in extreme years. Well-documented examples of these extreme events include the droughts of 1976 and 1995 (Cannell and McNally, 1997) and the storms of 1989 in England and 2000 in France. Not only are the short-term effects on growth or survival in extreme years important, but the long-term impact on productivity that can arise over the course of a rotation should also be considered. Evidence of a significant reduction in beech productivity following the drought of 1976 in the west of England is given by Peterken and Mountford (1996).

Possible adaptation measures include changes to establishment practice and forest management, the planting of species mixtures, better matching of species to site, both under current and future climates, and the planting of non-native species and provenances in anticipation of climate change (Broadmeadow *et al.*, 2003). Current UK policy encourages the planting of local provenances of native species (Ennos *et al.*, 2000), citing adaptation of provenances to local conditions, and the requirement to maintain biodiversity and a native genetic base. However, local provenances may not be able to adapt to a changing climate, particularly given the rate of change predicted. Sourcing planting stock from regions with a current climate similar to that predicted for the future may provide one option, although care must be taken to ensure that suitable provenances are selected which are not at risk from, for example, spring frost damage as a result of early flushing (Redfern and Hendry, 2002).

In this paper, the modelled predictions of the impact of climate change on broadleaf timber productivity and the suitability of individual species are presented. Regions of Europe with current climates similar to those predicted for the future for specific sites in the UK are identified, and the reported productivity of broadleaf timber species are compared with that predicted for the future in the UK. Finally, evidence is presented which highlights the importance of ensuring that provenances are well matched to the climate in which they are growing.

Predictions of species suitability

Model description

Ecological Site Classification (ESC) was initially developed as a site-based decision support system to provide guidance on species choice and native woodland suitability in Britain (Pyatt *et al.*, 2001). For a given site, species suitability is predicted on the basis of four climatic (accumulated temperature, exposure, moisture deficit and continentality) and two edaphic (soil moisture and soil nutrient quality) factors. Yield is modelled as a function of accumulated temperature and the next most limiting factor reducing the maximum potential yield of a given species in the UK. ESC has also been programmed as an extension to the ArcView (ESRI, California, USA) Geographical Information System (GIS) to model species and NVC woodland (Rodwell, 1991) suitability and species yield from digital spatial data. The underlying climate data represent the 1961–90 average climate at a spatial resolution of 10 km. The data have been modified by incorporating the UKCIP02 climate change scenarios (Hulme *et al.*, 2002) to provide predictions of the effects of climate change on broadleaf species suitability for timber production. The suitability models for individual species are based on productivity data for the UK, together with expert judgement. There is some evidence that estimates of productivity from ESC are lower than recorded productivity. It should also be appreciated that predictions can only be made to the 2050s as a result of the climate data falling outside the parameter range of the knowledge-based models beyond this time-frame. There are also a number of assumptions and limitations to this analysis that should be considered in any interpretation of the suitability maps. Firstly, and most importantly, the effects of rising atmospheric CO_2 levels are not considered. These predictions may thus represent the worse-case, since rising CO_2 levels would be expected to increase productivity and alleviate some of the effects of drought (Broadmeadow and Jackson, 2000). On the other hand, 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 (see Evans *et al.*, 2002) are also not considered. Finally, spatial scales of less than the 10 km × 10 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.

Interpretation of suitability maps

ESC predictions of changes in suitability of hardwood timber species indicate that there are likely to be significant changes in productivity and, probably, survival. Most species show similar patterns of changes to suitability under the High-emissions scenario for the 2050s, with significant reductions in productivity across much of south-east, south and central England, but with modest increases to the north and west of these areas (Figures 1 and 2). The species assessed in this study represent ~75 per cent of broadleaf woodland in the UK (Table 2; Forestry Commission, 2003), with the remainder primarily consisting of mixed woodland. The impact on individual species should be placed in the context of how widely the species is planted and, also, its spatial distribution. Table 2 presents data on species breakdown for the individual countries comprising the UK, and also for the two regions for which the implications of climate change are likely to be most serious for timber production (south-east and east England).

Of the species shown, the model predictions are most serious for beech in southern and central England, with yields of over 6 $m^3\ ha^{-1}\ yr^{-1}$ exceeded in few localities by the 2050s under the High-emissions scenario (Figure 1a). Furthermore, the increase in productivity predicted under the Low-emissions scenario for north-east England, particularly the North York Moors, is negated under the High-emissions scenario. A significant reduction in productivity is also predicted for beech across the south-west peninsula, while the direct effects of climate change are largely neutral for most of Wales. These predictions for beech are thus in line with observations following the droughts of 1976 (Peterken and Mountford, 1996) and 1995 (Redfern *et al.*, 1996; Cannell and McNally, 1997). In contrast, the productivity of beech is predicted to increase across much of east and south Scotland.

The direction of changes to the productivity of ash is predicted to vary with scenario (Figure 1b) and time-frame (data not shown). Under both the Low- and High-emissions scenarios for the 2020s and 2050s, the high productivity of ash in west England is reduced to 8–10 $m^3\ ha^{-1}\ yr^{-1}$, although this is contrasted by an increase in productivity in south-east and north-east England and much of Scotland. Again, the effects of climate change are largely neutral in Wales, and only in the fenlands of east England is ash productivity predicted to fall below 4 $m^3\ ha^{-1}\ yr^{-1}$ as

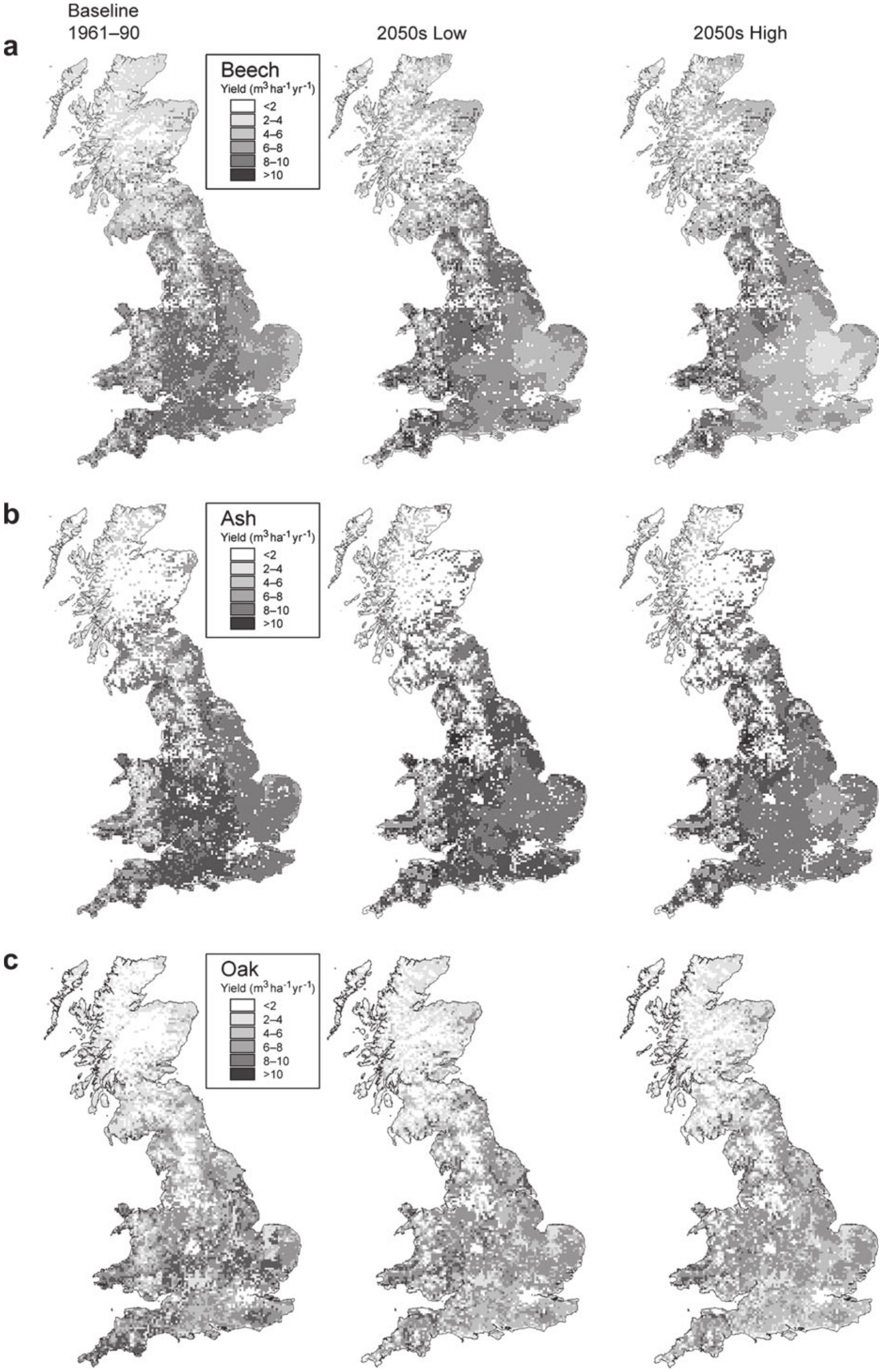

Figure 1. ESC suitability maps for (a) beech (*Fagus sylvatica*), (b) ash (*Fraxinus excelsior*) and (c) oak (*Quercus* spp.) under the baseline (1961–1990), 2050 Low- and 2050 High-emissions UKCIP02 scenarios.

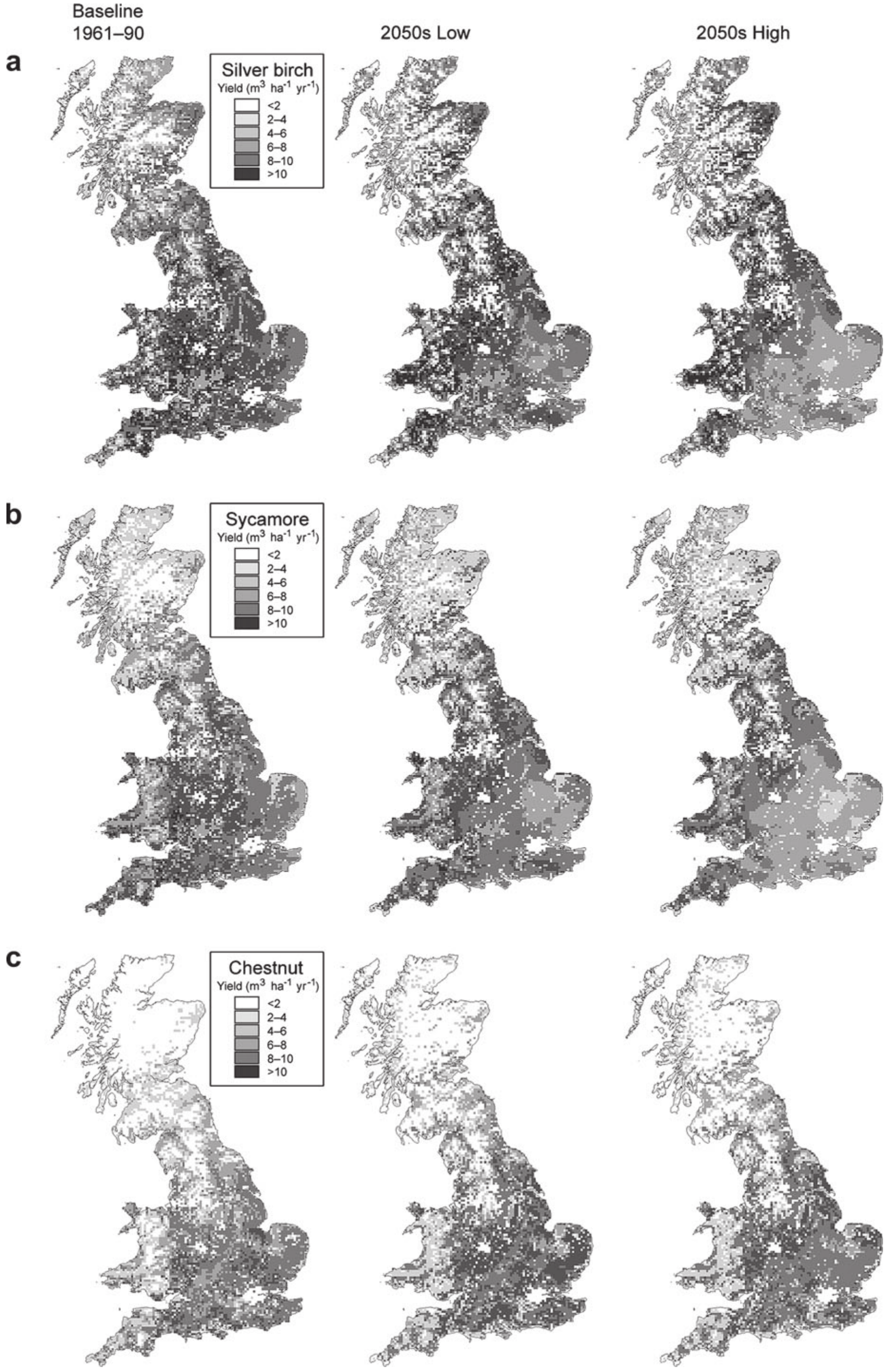

Figure 2. ESC suitability maps for (a) silver birch (*Betula pendula*), (b) sycamore (*Acer pseudoplatanus*) and (c) sweet chestnut (*Castanea sativa*) under the baseline (1961–1990), 2050 Low- and 2050 High-emissions UKCIP02 scenarios.

Table 2: Species breakdown of high forest by country and, in some cases, by region

Species	Area of high forest (ha)					
	GB	Wales	Scotland	England	South-east England	East England
Oak	206 154	38 092	20 215	147 847	44 326	19 231
Ash	119 232	18 181	4 763	96 288	26 624	12 136
Beech	76 551	7 369	8 610	60 572	23 425	4 946
Birch	155 355	10 813	75 996	68 546	25 469	6 761
Sycamore	61 357	6 124	10 200	45 033	5 937	6 185
Sweet chestnut	10 800	532	77	10 191	5 032	2 021
Total	629 449 (71%)	81 111 (78%)	119 861 (63%)	428 477 (73%)	130 813 (78%)	51 280 (73%)

The percentage of total broadleaf woodland represented by the six species reported is also given.
Data sourced from the *National Inventory of Woodland and Trees* (Forestry Commission, 2001; 2002a–d; 2003).

a result of increased moisture deficits. Productivity of the two native species of oak is also predicted to increase in the north and the west, and fall in the south and east of the UK (Figure 1c), with significant changes in the identity of the most productive of the two species (Figure 3). Pedunculate oak is predicted to replace sessile oak as the most productive of the two species over much of south, east and central England. However, it is clear that oak is likely to remain, at least, suitable across the majority of England. Similar impacts are predicted for both silver birch and sycamore (Figure 2a and b), with productivity in both cases maintained above 4 m^3 ha^{-1} yr^{-1} across most of southern England. However, both species are susceptible to drought-related mortality (Nisbet, 2002), and significant losses in extreme years (in climatic terms) could have more significant impacts on productivity at a stand scale than the trends in mean climate would suggest. For birch, evidence of significant drought-related mortality in extreme years is again provided by Peterken and Mountford (1996). Currently, sweet chestnut accounts for only 1.7 per cent of broadleaf woodland in England, or 1.2 per cent across the UK (Forestry Commission, 2002a; 2003: see Table 2). The species is grown widely in France, and predictions are for climate change, in the first instance, to increase its productivity in southern England (Figure 2c). However, as is the case for ash, this increase in productivity predicted under the 2050s Low scenario is lost under the 2050s High scenario.

Climate matching

The identification of locations which currently experience climates similar to those predicted for the UK has the potential to provide guidance on the likely effect of climate change on tree growth in Britain, and whether a given species is likely to prove suitable for hardwood timber production in the climate of the future. In addition, this information will identify those areas from which seed material could be collected for provenance trials focusing on climate change adaptation. However, some caution should be applied to the climate matching analysis presented here, as it is highly unlikely that future climates for the UK can be matched exactly to the full range of variables of existing climates, including day length and solar radiation input.

Data sources and analysis

To maintain data consistency for current and future coverage and ensure the availability of climate data across Europe, a global gridded data-set at a resolution of 10 minutes was used. The interpolated data-set is based on the climate records from between 12 783 (temperature) and 27 075 (precipitation) weather stations at which data were available for the period 1961–1990 and has been developed and made available by the Climatic Research Unit of the University of East Anglia (CRU; New *et al.*, 2002). The predicted future climate is based upon the UK Climate

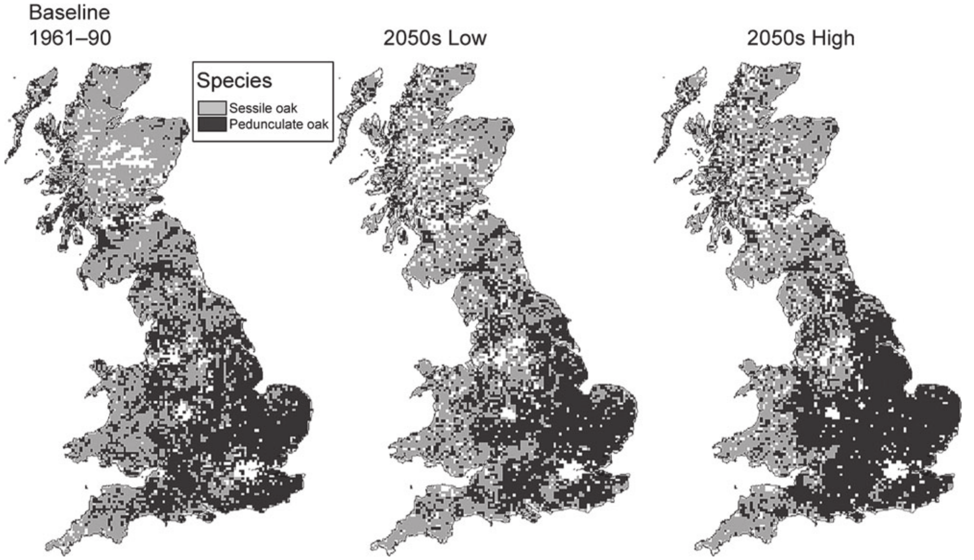

Figure 3. Identity of the most suitable of the two native species of oak (*Quercus robur* and *Q. petraea*) under the baseline (1961–1990), 2050 Low- and 2050 High-emissions UKCIP02 scenarios.

Impacts Programme 2002 scenarios (UKCIP02; Hulme *et al.*, 2002), with the 'Low' and 'High' scenarios for the 2050s and 2080s covered. The UKCIP02 Low scenario corresponds to the IPCC SRES B2 scenario, and the UKCIP02 High, to the IPCC SRES A1F1 scenario (IPCC, 2000).

Climate matching analysis was carried out for four of the 20 sites comprising the UK Intensive Forest Health Monitoring network (Durrant, 2000). The four sites (Brechfa, south Wales; Kelty, central lowland Scotland; Alice Holt, southern England; Thetford, East Anglia) were chosen to provide an indication of the range of future climates that may be experienced across the range of current climates in which broadleaf species are grown for timber. For each site, the UKCIP02 climate change scenarios, taken from the 50-km gridded data-set, were applied to the CRU monthly mean (1961–1990) climatology for the grid-square for mean temperature ($\overline{T}$), precipitation ($\overline{R}$) and diurnal temperature range ($\overline{DTR}$). The location of the grid-square currently best matched to the predicted climate of the future was identified by minimizing the sum of squares of differences between the current and predicted future monthly mean (1961–1990) climate variables, creating a climatic difference index (*CD*). The climate variables were weighted according to the range of monthly values under the current climate. $\overline{T}$ and $\overline{DTR}$ were both weighted on the basis of $\overline{T}$, as both contribute equally to describing the climatology of a given location. For $\overline{R}$, values were natural log transformed to normalize the distribution of annual rainfall totals across the data-set (equation 1):

$$CD = \left(\frac{\sum_{i=1}^{12} \{ (\overline{T}_i^{o} - \overline{T}_i^{f})^2 \}}{(\overline{T}_{\max}^{c} - \overline{T}_{\min}^{c})^2} \right) + \left(\frac{\sum_{i=1}^{12} \{ (\overline{DTR}_i^{o} - \overline{DTR}_i^{f})^2 \}}{(\overline{T}_{\max}^{c} - \overline{T}_{\min}^{c})^2} \right) + \left(\frac{\sum_{i=12}^{12} \{ (\ln \overline{R}_i^{o} - \ln \overline{R}_i^{f})^2 \}}{(\ln \overline{R}_{\max}^{c} - \ln \overline{R}_{\min}^{c})^2} \right) \tag{1}$$

where ^{o} denotes data corresponding to the site and scenario for which the climate is being matched, ^{c} denotes the current (1961–1990) climate data for the site, and ^{f} data from any other grid-square within the data-set.

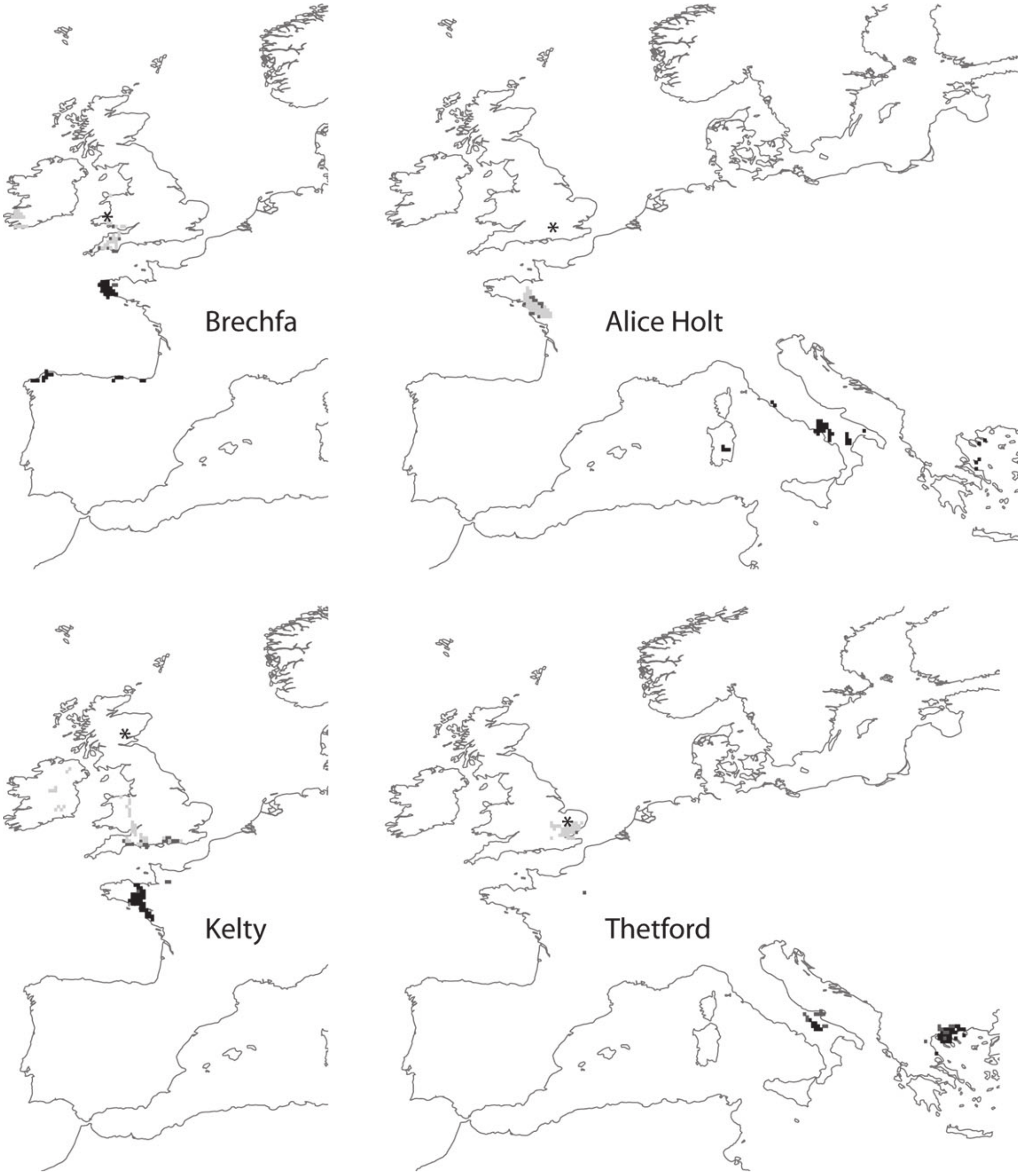

Figure 4. Best-matched climates for those predicted under the 2050s Low (light grey), 2050s High (dark grey) and 2080s High (black) emissions scenarios of UKCIP02 (Hulme *et al*., 2002) for four of the UK Intensive forest health monitoring plots (marked with an asterisk).

Results of climate-matching analysis

The location of current climates best matched to the predicted climate for the four Intensive Forest Health Monitoring sites is shown in Figure 4. The maps show the best-matched 0.2 per cent of grid-squares within Europe. As this is strictly an area-based analysis, the closeness of matching is not equal for all sites and under all scenarios, and the maps therefore only provide a qualitative analysis of matched climates. Under the 2050s Low scenario, the climate of Brechfa is predicted to be similar to that of much of the south-west peninsula and south-west of Ireland, reflecting the moist climate of south Wales. However, under the 2050s High scenario, this area is predicted to move southwards into areas of Cornwall experiencing lower rainfall, and also the Brittany peninsula. Under the most extreme of the scenarios (2080s High), the combination of warm winters, and very high winter rainfall (~200 mm per month) compared with summer rainfall (~50 mm per month) results in the climate being best matched to that of northern Spain at relatively high elevation (~500 m). For Kelty, implications of predicted climate change appear less significant than for Brechfa, with the Welsh borders (2050s Low) and southern England (2050s High) currently having similar climates to those predicted. However, under the 2080s High scenario, the climate is best matched to that of southern Brittany. By the 2050s the climate of Alice Holt is predicted to be similar to that of southern Brittany and the northern Loire under both scenarios. The predicted low summer rainfall and warm winters result in the climate under the 2080s High scenario being best matched to that of central southern Italy, Sardinia and northern Greece, but again at high elevation. The consequences for Thetford appear even more extreme as a result of the already low rainfall (<600 mm yr^{-1}) with a climate similar to that of central southern Italy and northern Greece predicted by the 2050s for the High-emissions scenario. However, this interpretation should be viewed with extreme caution as energy balance is significantly different at lower latitudes, and a number of important variables including rainfall intensity and relative humidity, which would be expected to differ, have not been included in the climate-matching analysis. Potential evapotranspiration (PET) and maximum soil moisture deficit (SMD) provide a test of how well matched a climate may be, since PET is dependent on a more extensive range of climate variables including humidity, solar radiation input and wind speed, as well as temperature and rainfall. PET has been calculated for the four UKCIP02 scenarios (2050s Low and High, 2080s Low and High) for two contrasting sites (Alice Holt and Kelty) mapped in Figure 4, and these values are compared with PET and SMD (cumulative PET less *R*) calculated for the best-matched grid-square under each of the scenarios (Figure 5). It is apparent that PET of the matched grid-squares is higher than the predicted future climate of the individual sites, particularly for Alice Holt and for matched sites at lower latitudes. However, when maximum SMD is calculated, the fit is improved for the lower latitude sites. The generally good agreement for both PET and SMD indicates that the climate-matching exercise has identified regions with broadly similar climates across a wide range of climatic variables.

To provide further insight into the likely effects of climate change, it is valuable to consider timber productivity in those regions of France which experience climates similar to those predicted for parts of the UK by the 2050s. Figure 6 shows the productivity of ash, beech and sycamore for which data are presented as average yield class for individual départements. These data suggest that for ash, productivity will at least be maintained at Kelty and Brechfa under the 2050s High scenario if their climates tend towards that of Brittany as indicted in the climate-matching exercise. However, the future climate of Alice Holt is predicted to be closer to that of the Loire, where ash is limited to 0–2 $\text{m}^3\ \text{ha}^{-1}\ \text{yr}^{-1}$, presumably as a result of high moisture deficits. Beech also appears to grow reasonably in Brittany, and better than ash in the southern Loire. However, in the northern Loire, productivity is low. Although sycamore appears to grow well across Brittany and the Loire, indicating that the species should perform well in the southern UK in the medium term, beyond this time-frame its low yield class (0–2 $\text{m}^3\ \text{ha}^{-1}\ \text{yr}^{-1}$) or the absence of data further south indicates that the species may suffer. The small area of central northern

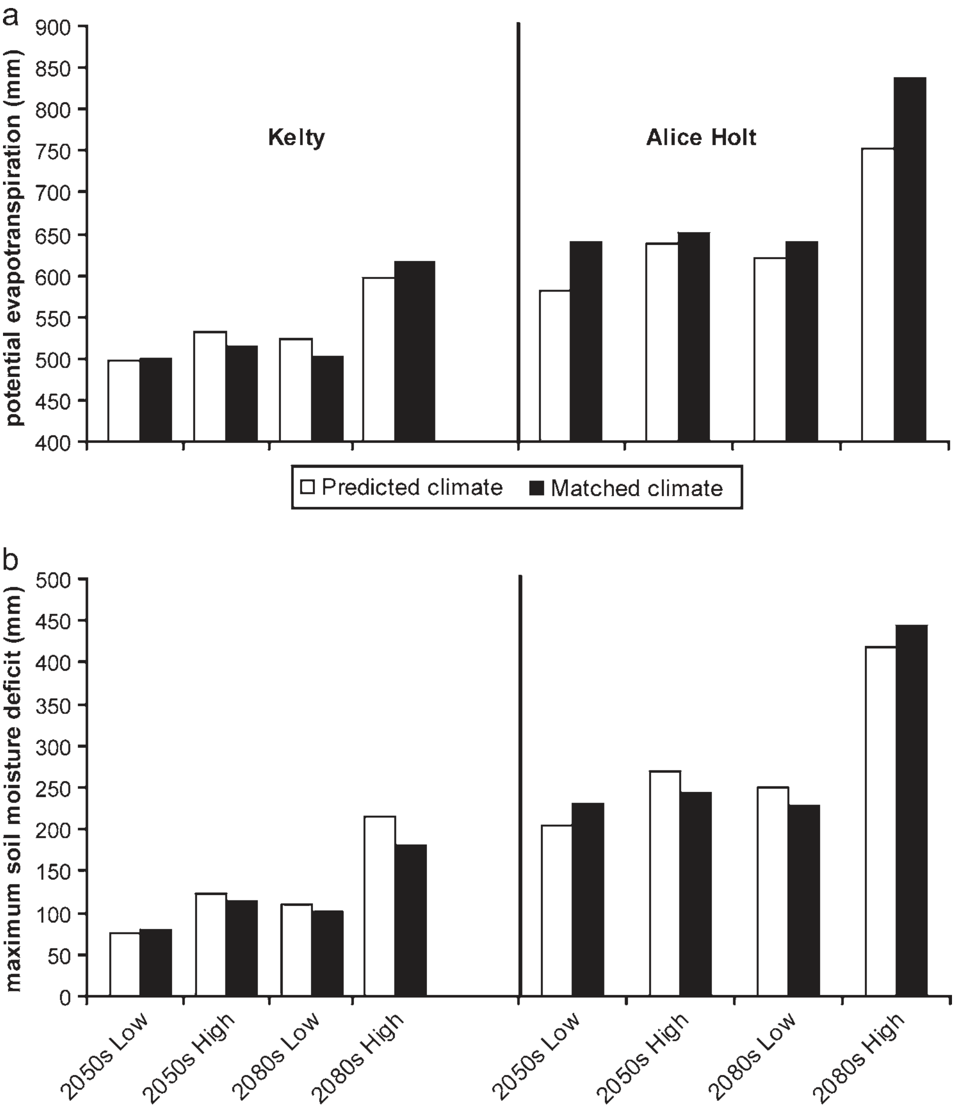

Figure 5. Potential evapotranspiration (PET) (a) and maximum soil moisture deficit (SMD) (b) predicted for the four UK Intensive Forest Health Monitoring plots under the UKCIP02 scenarios compared with values for the best-matched grid-square in Europe under current conditions according to the climate-matching analysis.

France matched to the predicted climate for Thetford in the 2050s appears to support reasonably to high productivity for all three species. It is also apparent that yield classes of 2–4 or 4–6 m^3 ha^{-1} yr^{-1} are maintained in the extreme south-west of France, and also Corsica/Sardinia which experience climates matched to those predicted for Brechfa and Alice Holt under the more extreme 2080s High scenario. These data therefore support the conclusions drawn from the ESC suitability maps that productivity may fall across much of southern

England, but that a reduced level of productivity is likely to be maintained.

Climate change and provenance selection

Experiment description

A series of ash provenance trials was established at six sites across England and Wales between 1993 and 1996 (Cundall *et al*., 2003). Five UK and six continental provenances (see Figure 7) for this experiment were raised for 1 year (continental provenances) and 2 years (UK provenances) at Headley nursery in Hampshire (51.2° N, 0.85° W). Irrigation was provided when necessary (soil moisture deficit of greater than 0.1 MPa as indicated by soil tensiometers) and nutrient supply was maintained through top dressing with a nitrogen fertilizer four times during each growing season. Further details are given in Cundall *et al*. (2003). The growth data for this plant material thus represent potential growth without water or nutrient limitation under the climate of southern England (mean annual temperature 9.6°C; annual precipitation 840 mm; annual potential evapotranspiration (PET) 494 mm). Climate data for each of the provenance origins are given in Table 3.

Provenance trial interpretation

For the UK provenances, PET at place of origin was positively correlated with height growth ($R^2 = 0.87$, $P = 0.02$; Figure 8a), while a negative correlation was observed for the continental provenances ($R^2 = 0.92$, $P \leq 0.01$). The two data-sets were treated separately as a result of different experimental periods and pre-treatments, with both plotted as a percentage of the maximum growth observed for each set of provenances. The PET at each of the sites of origin of the provenances was calculated from the CRU gridded data-sets according to Penman (1948) as described in MAFF (Ministry of Agriculture, Fisheries and Food) (1967). Calculated PET at Headley nursery (494 mm) is higher than that of the site of origin of all the British provenances, but lower than that of all the continental provenances. It thus appears that origin PET may provide a predictor of performance, although this conclusion is only valid under conditions where water and nutrients are non-limiting, as in this study. When height growth

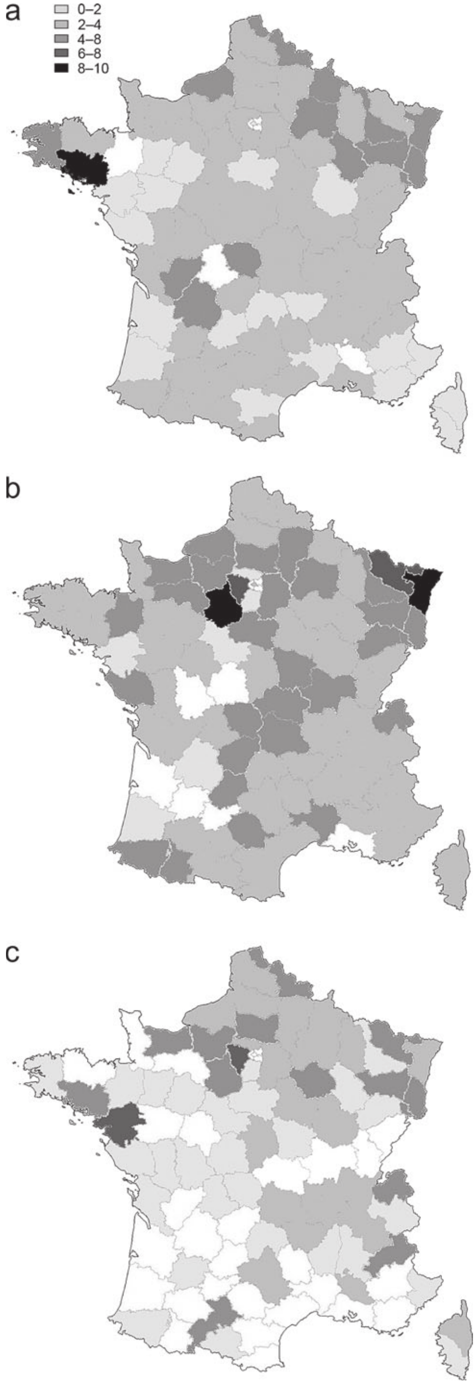

Figure 6. Average productivity (m^3 ha^{-1} yr^{-1}) for (a) beech, (b) ash and (c) sycamore for individual départements in France.

Figure 7. Location of the 11 provenances raised at Headley nursery.

is regressed on maximum soil moisture deficit (SMD) calculated as the sum of PET minus precipitation, similar relationships to those for PET are apparent for both the UK ($R^2 = 0.92$, $P \leq 0.01$) and continental provenances ($R^2 = 0.71$, $P = 0.035$) as shown in Figure 8b. Again, the relationship was different for the UK and continental provenances, with a positive relationship between SMD and height growth for the former, and a negative relationship for the latter. Although the relationships are less clear than for PET, particularly for the continental provenances, it is apparent that those provenances from regions with water balance regimes significantly different to that of Headley perform poorly (Table 3). In the case of the continental provenances, the poorly performing provenances are those from regions with both high PET and high summer rainfall. The poorly performing UK provenances are those from cooler, moister regions. This analysis therefore confirms that local provenances may be best adapted to the climate of a region under a constant climate (Ennos *et al.*, 2000). However, given the predictions of significant changes to the climate including both PET and SMD (see Table 1), the analysis indicates that local provenances are unlikely to be best adapted to the climate of the future. In order to maintain highly productive stands, provenances from regions with a current climate similar to that predicted for the future for a given site should be selected. Although the need for this approach has been demonstrated, the difficulty lies in identifying the period in time and thus provenance that should be selected. Over a typical rotation of 100–150 years, a broadleaf stand would be subjected to a large range of climates given the rate and scale of predicted climate change. The selection of seed material that might be adapted to the climate predicted for the later stages of the rotation would be inappropriate, while an adaptation measure addressing only the first 20–30 years of a rotation could be seen as short-sighted. Selecting provenances experiencing a climate to that predicted for a mid-rotation

Table 3: Source climate data for each of the UK and continental provenances included in the seedling trial at Headley

	Monthly mean temperature (°C)		DTR	Rain	PET	SMD	Max. day-length (h)		Sunshine
	Min.	Max.	(°C)	(mm)	(mm)	(mm)	Dec.	June	duration (h yr^{-1})
Baccheiddon	1.7	12.9	6.8	1932	394	0	7.8	16.7	1066
Dunnottar	2.8	13.3	6.5	823	401	25	6.9	17.8	1253
Grimsthorpe	3.1	15.9	8.2	610	483	110	7.7	16.8	1340
Powis Castle	3.0	14.8	7.2	1010	451	45	7.8	16.8	1146
Settrington	2.7	14.8	7.2	737	461	69	7.5	17.1	1298
Alsace	0.0	17.8	8.4	713	588	86	8.4	16.0	1634
Champagne	2.0	17.9	9.2	890	591	106	8.3	16.2	1683
Basse Normandie	4.1	17.5	8.1	782	633	194	8.4	16.0	1829
Haute Saone	0.1	18.0	8.6	857	589	46	8.5	15.9	1701
Palobe	−1.5	18.6	9.0	525	675	220	8.2	16.3	1670
Picardie	2.9	17.5	7.7	690	586	159	8.2	16.3	1685

Table 4: Location of the grid square where the current climate is best matched to that predicted for each of the UK provenances included in the seedling trial at Headley

	Location of best-matched current climate	
Provenance	2050s Low	2050s High
Powis Castle	Devon 50.9° N 3.4° W	South Brittany 47.8° N 2.8° W
Dunnottar	Perthshire 56.8° N 2.8° W	Dorset/Devon 50.8° N 2.9° W
Baccheiddon	Llandovery 52.1° N 3.8° W	Brecon Beacons 51.8° N 3.4° W
Grimsthorpe	Northamptonshire 52.4° N 0.6° W	North Greece 41.1° N 23.8° E
Settrington	Shropshire 52.8° N 2.9° W	Brittany 48.1° N 1.9° W

time-frame may thus represent the lowest risk strategy.

The climate-matching analysis presented in Figure 4 has been extended for the 2050s High- and Low-emissions scenarios to include the five UK provenances included in the trial at Headley (Table 4). On the basis of this analysis, it is clear that the variation in vigour, introduced by moving provenances into climates to which they are poorly matched in this experiment, is small in comparison to the magnitude of predicted changes to the climate of all but the Dunnottar and Baccheiddon provenances.

Discussion

It is difficult to make precise predictions of the overall effects of climate change on the productivity of broadleaf timber species. These uncertainties arise because of the counteracting effects of rising atmospheric CO_2 levels and an increasing frequency of summer droughts over much of the UK, the overriding effects of extreme climatic events as opposed to trends in climate, the potential for pest and disease outbreaks to change in frequency and severity, and a lack of certainty in the predictions of climate change. However, it

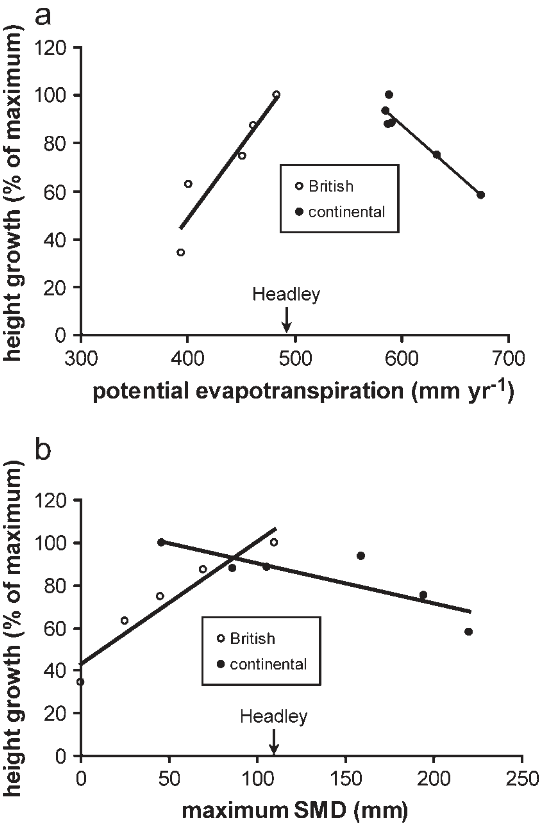

Figure 8. Relationship between seedling vigour and (a) origin potential evaporation or (b) origin maximum soil moisture deficit for 11 provenances of ash (*Fraxinus excelsior*). UK and continental provenances are treated separately, with relationships fitted by linear regression. (a) UK provenances: $R^2 = 0.87$, $P = 0.02$; continental provenances: $R^2 = 0.92$, $P \leq 0.01$. (b) UK provenances: $R^2 = 0.92$, $P \leq 0.01$; continental provenances: $R^2 = 0.71$, $P = 0.035$.

seems likely that, initially, climate change is likely to benefit broadleaf timber productivity across the majority of the UK. Under the more extreme climate change scenarios – either through the progression of time or if global greenhouse emissions are not controlled – broadleaf timber production is predicted to be adversely affected by the effects of drought overriding the beneficial effects of rising CO$_2$ levels, longer growing seasons and increased solar radiation inputs. The model outputs from ESC on which these conclusions are based assume that both species and provenance selection are unchanged. However, when predicted climates for the southern UK are matched to current climates in continental Europe, it becomes apparent that, except under the most extreme scenarios (2080s High-emissions scenario), ash, sycamore and beech are currently grown for timber in those regions, although in many cases with lower yield. The current policy for planting local provenances acknowledges an adaptation to local climate, and this is confirmed by the observed relationships between seedling vigour, and both SMD and PET of the site of origin in this study. However, it has been argued by Brown (1997) that local adaptation is dynamic and that a static definition of native species or genetic origin is artificial, particularly in a changing environment. Provenance selection thus presents an opportunity to adapt to predicted climate change, and could be considered for both native woodland and forests managed primarily for timber production. Billington and Pelham (1991) conclude that native birch woodland may be unsuited to the prevailing climatic conditions of the future, while Peterken and Mountford (1996) have demonstrated the scale of impact that a single dry year can have on native woodland communities. Adaptation to climate change should therefore consider all forms of woodland, although it must first be ascertained that a selected provenance performs well under the current climate of the UK. The provenances selected in the trials described here would not be suitable on the evidence of the climate-matching analysis carriedout in this study, demonstrating a clear need for ongoing research to identify suitable material for future planting. The climate at origin of these provenances should reflect the oceanic character of the climate of the UK, with rainfall higher in winter than summer, and low diurnal and annual temperature ranges in comparison with more continental regions of Europe.

Alongside suitable provenance selection, species chosen on the basis of an assessment of suitability to both current and future climates will provide woodland which is likely to be more robust in the light of the climate change predictions. Mixed species stands will also provide some insurance against uncertainty in the response of woodland to climate change, and in the predictions of climate change itself. In the south and east, pedunculate oak would be expected to be more resilient against drought than sessile oak, while for both beech and, under the more extreme scenarios, ash, much of southern England is predicted to become unsuitable for timber production. Caution must be applied to interpreting the suitability maps generated by ESC, particularly since soil type will be a key determinant of the ability to withstand increasingly severe and frequent summer droughts. Site-based assessments are thus essential.

An alternative approach would be to plant non-native species in advance of climate change. Although sycamore is initially predicted to benefit from climate change in southern England, its growth will be limited by moisture availability in the latter half of this century, as is confirmed by its limited range of high productivity in France. An alternative is sweet chestnut, which has been successfully grown in southern England, although largely managed as coppice. This species is predicted by ESC to perform better than other broadleaf species, and should be considered on sites on which other species are thought likely to perform poorly. Other species, including *Robinia pseudoacacia*, *Nothofagus* spp. and *Quercus cerris* may also have potential, although their performance under the oceanic climate of the UK should be ascertained before their widespread planting is considered.

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