Forestry Commission England


Pedunculate oak

Research Note

Climate change: impacts and adaptation in England's woodlands

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The changing climate presents a challenge for forest planning and forest management in England because the projected increases in temperature, changes in the seasonality of rainfall, and an increased frequency of extreme events add complexity to species selection and silvicultural practice. By actively adjusting forest management now, to anticipate future changes, we can hope to increase resilience by reducing exposure to risks in forestry and in the goods and services that woodlands provide for society. Tree growth will increase in some areas and decline in others, and the effects will vary with species. Some relatively less known species will become more suitable – including some from other continents and current climates more similar to those projected for England. New approaches to woodland management will be required to address the threats of drought and increased risk of damage from pests, diseases, wind and fire. There are many uncertainties associated with climate change, and the likely impact on trees, silviculture and forest operations. This uncertainty should not prevent adaptation but, instead, should direct woodland managers to implement measures that increase resilience whatever climate change brings, or that are likely to reap the greatest rewards in the future. A key concept in managing risk is diversification: from broadening the choice of genetic material and mixing tree species in different ways, to varying management systems and the timing of operations.

Introduction

Climate change is one of the greatest global challenges, and research continues to identify impacts on the environment, including on trees and woodland ecosystems (Box 1). Woods planted now and in the future must be resilient and suited to both current conditions and to the changing climate through the rest of the 21st century, and even further ahead for species with longer rotations. Forestry makes a positive contribution to the reduction of atmospheric CO_2 concentrations, and has an important function in mitigating greenhouse gas (GHG) emissions. It is vital that the management of forests and woodlands incorporates climate change adaptation principles, to ensure effective mitigation, and to help maintain the important benefits forests provide for society.

An overarching aim of forestry in England is to ensure that woodlands are resilient to the impacts of climate change and are able to contribute to the way in which society, biodiversity and natural resources adjust to a changing climate. Such adaptation is also necessary to ensure that forestry can continue to make its important contribution to a future low-carbon society through active management providing woodfuel and timber products. This Research Note provides some guidance on how to fulfil these aspirations, by providing the context for the adaptation of forests and woodlands in England, and by giving pointers to where woodland managers and forest planners can access more detailed information to guide those decisions.

Observed change

In England there is compelling evidence that the climate has changed considerably over the past 50 years and this is consistent with what is known about the effect of increasing atmospheric GHG concentrations on global temperatures. For example, 10 of the 12 warmest years in the 350-year Central England Temperature record have occurred in the last 20 years, and winters are becoming wetter and summers slightly drier (Jenkins *et al*., 2007). Other evidence comes from the way that living systems are responding, in some cases, rapidly.

Biological observations

The annual cycle of many events in the lifecycle of plants and animals shows clear relationships with climate, particularly temperature. The longest continuous record of the timing of these natural events (phenology) was begun by Robert Marsham in Norfolk in 1736. Many phenological records focus on the date on which the leafing and the flowering of specific plants occur, while others assess the dates of insect activity and bird migration.

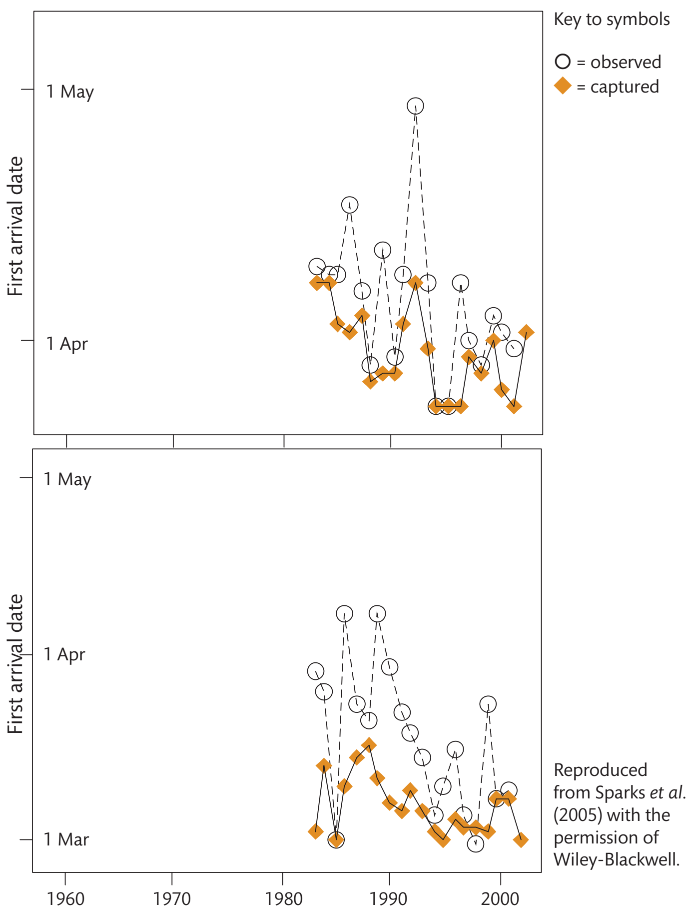
Box 1 – Summary of the main climate change impacts.

- Current projections suggest that areas of south, central and eastern England will have drier and warmer summers, resulting in increasingly severe soil moisture deficits which will reduce tree growth – particularly on shallow, south facing slopes, and sandy-textured, freely-draining soils.
- Warmer growing seasons and rising CO_2 concentrations will stimulate productivity and timber production where soil water and nutrient availability allows. Increases of 2–4 $m^3\ ha^{-1}\ yr^{-1}$ in upland conifer forests of the north and west of England may result. Improved growth may also occur, initially, in more southerly regions, although species will need to be matched carefully to site conditions.
- Changes in the seasonality of rainfall have occurred gradually over the past century, and this trend is projected to continue and to strengthen in the future. The resulting wetter autumn and winter periods will cause greater water table fluctuations, limit rooting depth, and reduce tree stability on exposed sites.
- Changes in the wind climate are highly uncertain but, with reduced anchorage on wet sites, the risk of windthrow will increase.
- The incidence and severity of tree disease and pest outbreaks will increase. A warmer climate and, particularly, warmer winters will allow tree pests and pathogens to extend their range.
- Drier and warmer summers will heighten the risk of fire (Figure 1).
- Climate change presents new opportunities for the forestry sector, particularly the planting of new woodlands to sequester carbon and provide wood fibre and timber products for future generations; but these new woodlands must also be resilient to the impacts of climate change.

Figure 1 Wildfire in a young pine stand.

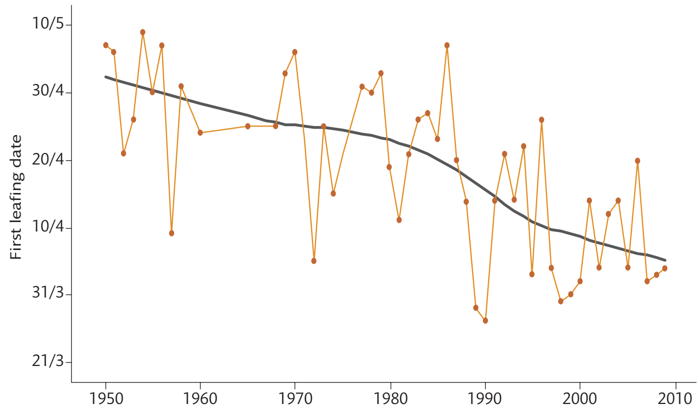
Two examples of phenological change that illustrate the alterations that are already happening to woodland ecosystems in England are the arrival of migratory woodland birds and the leafing date of pedunculate oak (*Quercus robur*). The timing of bird migration has changed over recent decades. Analysis of mean arrival date shows a trend of earlier arrival of two woodland birds, the chiffchaff (*Phylloscopus collybita*) and the willow warbler (*Phylloscopus trochilus*), at Dungeness over recent decades (Figure 2a, Sparks *et al*., 2005), which has correlated with warmer temperatures. A recent study has shown links between the abundance and frequency of some woodland species and recent climate change, recorded over the past thirty years (Kirby, 2005). In the case of pedunculate oak, the records begun by Jean Combes in 1947 in Surrey show how sensitive the date of first leafing is to mean spring temperature. Leafing has advanced by approximately 6 days for every 1°C increase in spring temperature and is now about 25 days earlier than in the 1950s (Figure 2b). Many tree species respond similarly, although some are less sensitive to temperature and, instead, respond to day length. However, there is little convincing evidence of trends in tree growth in the UK – either positive or negative – in part because of the complex range of contributory factors. This contrasts with much of continental Europe, where increases in forest productivity have been reported.

Figure 2a Patterns in first arrival date of the willow warbler and chiffchaff at Dungeness in Kent.



Reproduced from Sparks *et al.* (2005) with the permission of Wiley-Blackwell.

Figure 2b Trend in first leafing date of pedunculate oak trees (*Quercus robur*) in Surrey.



Data courtesy of Jean Combes and Tim Sparks.

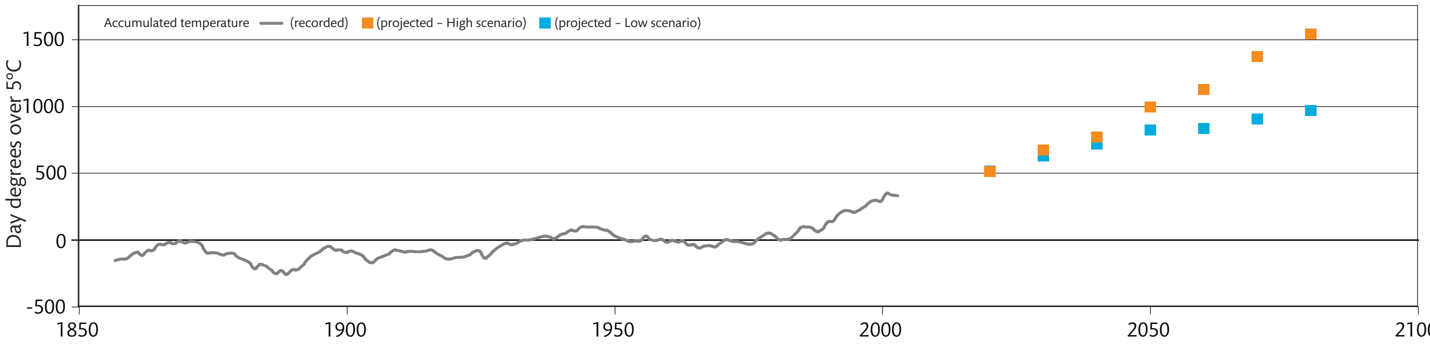
Climate observations

One of the key observed climate trends is the 'Central England Temperature' (CET), which is a carefully compiled dataset from several sites. The CET mean annual temperature has risen by about 1°C since the 1970s, with 2006 being the warmest year in the 350 year record; 1.3°C warmer than the 1961–90 average. Records from individual stations in different regions of England show similar patterns. For some biological processes, including tree growth, annual accumulated temperature above 5°C (AT) is a better indicator of growing season warmth than mean annual temperature. An example is shown in Figure 3 for Oxford (other locations are included as online resources), demonstrating the steady increase in AT since the beginning of the 20th century together with projections of a continuing trend (see below; UKCIP, 2009).

Annual mean precipitation over England has not changed significantly since records began in 1766 but, although seasonal rainfall patterns are highly variable, rainfall appears to have decreased in summer and increased in winter as shown for Oxford in Figure 4. The trend of increasing winter rainfall and decreasing summer rainfall is projected to strengthen. These two examples of annual temperature and rainfall emphasise that the observed changes to date have been small in comparison with likely changes in the future.

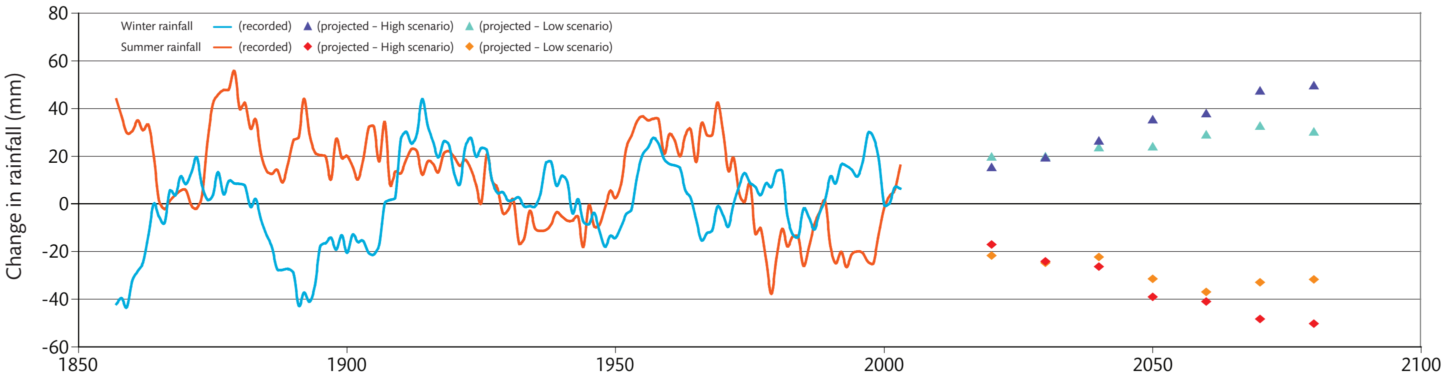
It is also important to consider the difference between weather and climate. Recent relatively cold winters (2008/9 and 2009/10) and wet summers (2008 and 2009) do not mean that the trends shown in Figures 3 and 4 are not realistic; indeed, while January 2010 was the coldest January since 1963 in the UK, globally it was the warmest January on record. The variability in UK weather over recent years is to be expected within the overall trend of rising temperatures and declining summer rainfall.

Figure 3 Accumulated temperature (day degrees over 5°C) anomaly of past and future projected values compared with the mean for 1961–1990 for observations from the Oxford climatological station (presented as the ten-year running mean) and UKCP09 climate projections.



Data courtesy of UK Meteorological Office and UKCIP.

Figure 4 Summer and winter seasonal rainfall anomaly of past and future projected values compared with the mean for 1961–1990 for observations from the Oxford climatological station (presented as the ten-year running mean) and UKCP09 climate projections.



Data courtesy of UK Meteorological Office and UKCIP.

Projected change in climate

Evaluating the likely impacts of future climate change involves calculating the effects of increasing concentrations of GHGs in the atmosphere through the use of global circulation models and regional climate models. When these are used with scenarios of future population growth, economic growth, and fossil fuel consumption, the different GHG emissions (estimated for each future scenario) provide a range of climate projections from the models. They are not forecasts, but represent likely conditions, given the assumptions in the scenarios, and can be compared with recent conditions – the 'baseline climate' (usually 1961–1990). The A1FI (High emissions) scenario represents a fossil fuel intensive world of rapid economic growth and increasing population; the B1 (Low emissions) scenario represents a world with convergent sustainable economic development globally, and a declining population after the middle of the century. Climate projections using these GHG emissions scenarios have been published by UKCIP (www.ukcip.org.uk). It should be noted that global GHG emissions continue to track the 'High' scenario and it is unlikely that they will drop to the Low emissions projections for the 2020s and the 2050s. Planning should therefore embrace the High emissions projections as a distinct possibility.

UKCIP02

UKCIP02 climate projections have been used to calculate the key climate factors of accumulated temperature (AT – an index of climatic warmth) and moisture deficit (MD – an index of climatic dryness). The warmth index is very sensitive to changes at the beginning and end of the growing season, and the large changes shown in Figure 5 reflect the longer growing season as well as the increased warmth that climate change will bring.

Moisture deficit (MD) is calculated as the monthly excess of evaporation over rainfall accumulated through the summer months and averaged over the 30-year climate period. Projected MD values increase in the south and east of England from baseline climate values of 180 mm to values in excess of 240 mm by 2050 for the High emissions scenario, and up to 220–240 mm by 2050 for the Low emissions scenario (Figure 6). As some forest soils hold only 150–180 mm of water accessible to plants, woodlands in central and southern England, on such soils, are likely to experience more frequent and increasingly severe summer drought.

Figure 5 Accumulated temperature (AT) for the baseline period (1961–1990) and projected for the 30-year periods 2041–2070 and 2071–2100 for the UKCIP02 Low (B1) and High (A1FI) emissions scenarios (Hulme *et al*., 2002).

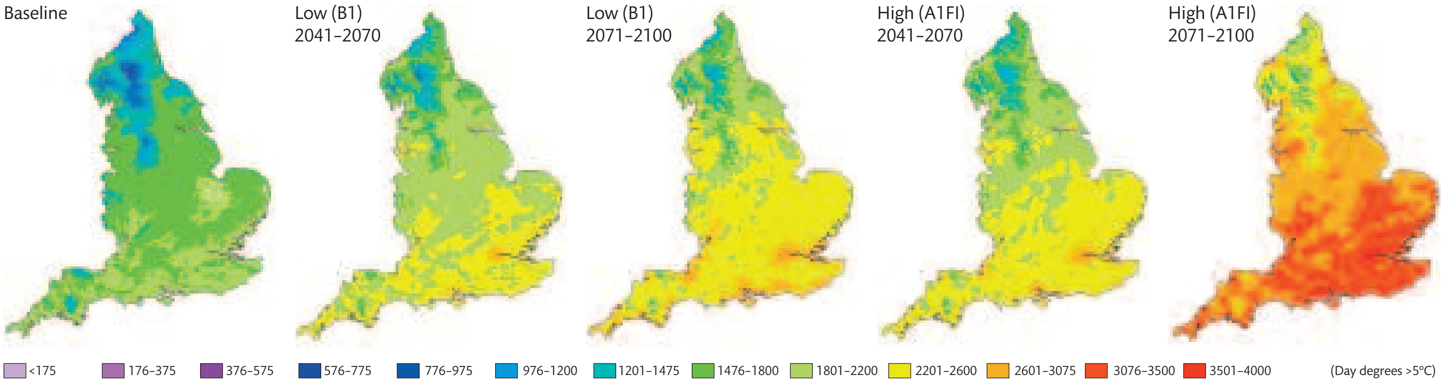
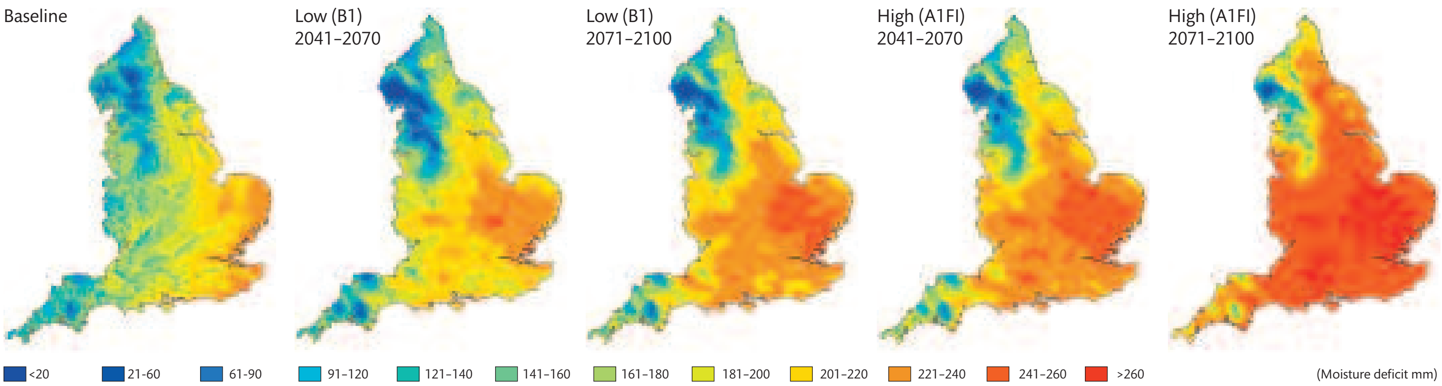


Figure 6 Moisture deficit (MD) for the baseline period (1961–1990) and projected for the 30-year periods 2041–2070 and 2071–2100 for the UKCIP02 Low (B1) and High (A1FI) emissions scenarios (Hulme *et al*., 2002).



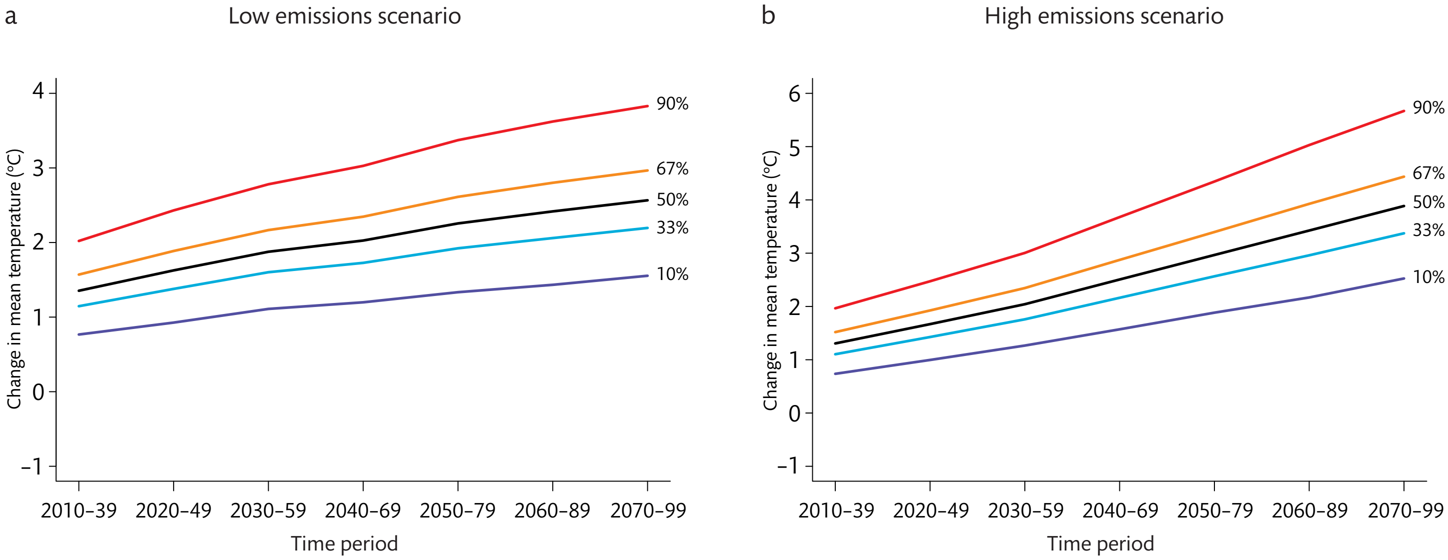
UKCP09

New climate projections were published in 2009 (UKCP09, Murphy *et al*., 2009). The projections are broadly similar to the UKCIP02 climate scenarios, although the projected reduction in summer rainfall in southeast England is less severe in UKCP09. The UKCP09 projections are substantially more developed, and allow ready access to information (www.ukcip.org.uk and http://ukclimateprojections.defra.gov.uk). The information is available at three levels: key findings; pre-prepared maps and graphs; a user interface in which specific database queries of future changes can be made and which includes a 'Weather Generator'.

A new development in UKCP09 is the provision of probability statistics for the climate projections, made possible through multiple 'runs' of different climate models to assess uncertainty, rather than the single simulation with one climate model used in the UKCIP02 scenarios. They are important for forest management in gauging vulnerability and risk and assessing appropriate and timely action to implement adaptation measures. Evaluation of the impact of extreme events should form the critical thinking behind developing contingency plans and adaptation plans for forestry. Example analyses of extreme events from the Weather Generator are available as on-line resources (www.forestry.gov.uk/fr/climatechangeengland).

An example of the type of information that is available from the UKCP09 website is a probabilistic 'plume' plot (Figure 7). In this example the change in annual temperature at decadal time steps through the century is shown for northwest England for the Low and High emissions scenarios. Each plume plot shows the change that is as-likely-as-not (50% probability or the 'median'), and two sets of probabilities about that median. The probability ranges are: unlikely to be less than (33%), unlikely to be more than (67%), very unlikely to be less than (10%) and very unlikely to be more than (90%). This provides some measure of the change and uncertainty relative to the baseline climate for each decade through the century.

Figure 7 Projected change in mean annual temperature in northwest England through the 21st century (compared to the baseline period of 1961–1990), a) Low emissions scenario b) High emissions scenario. The 50% line indicates the median probability increase, and lines for other probabilities represent the range of uncertainty. (Data courtesy of UKCIP).



Impacts on forestry

The likely impacts of climate change on species choice have been assessed using the Ecological Site Classification (ESC) decision support site matching tool. Underlying knowledge-based models in ESC link six site related factors using a suitability class (unsuitable, marginal, suitable, very suitable) to different tree species. The term suitability is a measure of relative productivity, indicating how well a tree species is matched to site conditions. Four of the site factors are climatic: accumulated temperature – AT (climatic warmth); moisture deficit – MD (climatic dryness); wind exposure – DAMS; continentality – Conrad index (distance from the sea); and two factors are edaphic: soil moisture regime – SMR (soil wetness); and soil nutrient regime – SNR (soil fertility). It should be noted that the ESC suitability models do not take any account of the effects of pests and pathogens, or increasing CO_2 concentrations on tree productivity. The UKCIP climate projections have been used to develop AT and MD projections for future emissions scenarios for an assessment of changes in species suitability, using ESC (see Figures 5 and 6).

Productive woodland

Warmer summer temperatures, a longer growing season and rising CO_2 levels in the future will increase potential stand productivity. However, water availability in the summer months is likely to be a limiting factor to growth. This will certainly be the case on sandy-textured, freely-draining, and thinner soils in the southeast and east of England. The impact of drier summers is shown by the declining trend of suitability for conifer and broadleaf tree species in both regions, estimated by ESC, particularly for the High emissions scenario in both the 2050s and 2080s. Table 1 summarises changes in species suitability by region. The change in projected suitability for individual species over any time period can be mapped, as exemplified in Figure 8 for Douglas fir (*Pseudotsuga menziesii*). Maps for a range of other species showing changing suitability across England can be accessed and downloaded at www.forestry.gov.uk/fr/climatechangeengland.

Native woodland

Climate change is expected to have many impacts on ancient and native woodland, as outlined in Table 2. Changes in tree species composition are likely and some of these are noted in the Table. Ash wood communities may expand along major rivers that have headwater tributaries in the west of the country, and ash could become more dominant in wet woodlands. There is likely to be a range shift for beech and yew woodlands. Beech is already a regenerating component of many oak woods in north and west England, where its suitability will increase further (see Table 1). Large changes are likely in the vegetation community structure because of altered plant competition as a result of changes in light from increased leaf area and earlier leafing, changes in the growing season temperature, and drier soil conditions in many woodlands during the summer months. The age structure of stands will be affected by an increased frequency of natural disturbance events, and the risk of fire damage may increase in woodlands that are heavily visited. It will therefore be important to consider climate change in the management of ancient and native woodland and to develop management and contingency plans to deal with impacts.

Table 1 Changes in tree species suitability in five regions of England for Low and High emissions scenarios (UKCIP02; Hulme *et al*., 2002) based on projected yield from Ecological Site Classification.

Tree species	Southeast England				Southwest England				East England				Northwest England				Yorkshire & the Humber			
Broadleaves	Baseline	2050 (L)	2050 (H)	2080 (H)	Baseline	2050 (L)	2050 (H)	2080 (H)	Baseline	2050 (L)	2050 (H)	2080 (H)	Baseline	2050 (L)	2050 (H)	2080 (H)	Baseline	2050 (L)	2050 (H)	2080 (H)
Alder	Suitable	Suitable	Unsuitable	Unsuitable	Marginal	Suitable	Marginal	Unsuitable	Suitable	Suitable	Unsuitable	Unsuitable	Marginal	Suitable	Unsuitable	Unsuitable	Suitable	Suitable	Unsuitable	Unsuitable
Ash	Suitable	Suitable	Suitable	Marginal	Suitable	Suitable	Suitable	Marginal	Suitable	Suitable	Marginal	Marginal	Marginal	Suitable	Marginal	Marginal	Marginal	Suitable	Marginal	Marginal
Beech	Suitable	Suitable	Marginal	Unsuitable	Very suitable	Suitable	Suitable	Unsuitable	Suitable	Suitable	Marginal	Unsuitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Marginal
Downy birch	Marginal	Marginal	Unsuitable	Unsuitable	Marginal	Marginal	Unsuitable	Unsuitable	Marginal	Unsuitable	Unsuitable	Unsuitable	Suitable	Suitable	Unsuitable	Unsuitable	Suitable	Marginal	Unsuitable	Unsuitable
Pendunculate oak	Suitable	Suitable	Suitable	Marginal	Suitable	Suitable	Suitable	Marginal	Suitable	Suitable	Suitable	Marginal	Marginal	Marginal	Marginal	Marginal	Marginal	Suitable	Marginal	Marginal
Poplar	Suitable	Suitable	Marginal	Unsuitable	Suitable	Suitable	Marginal	Unsuitable	Suitable	Suitable	Marginal	Unsuitable	Marginal	Suitable	Marginal	Unsuitable	Suitable	Suitable	Marginal	Unsuitable
Rauli	Marginal	Marginal	Unsuitable	Unsuitable	Marginal	Marginal	Marginal	Unsuitable	Marginal	Marginal	Unsuitable	Unsuitable	Unsuitable	Marginal	Unsuitable	Unsuitable	Marginal	Marginal	Unsuitable	Unsuitable
Roble	Suitable	Suitable	Marginal	Unsuitable	Suitable	Suitable	Marginal	Unsuitable	Suitable	Very suitable	Unsuitable	Unsuitable	Marginal	Marginal	Marginal	Unsuitable	Marginal	Suitable	Unsuitable	Unsuitable
Silver birch	Suitable	Suitable	Marginal	Marginal	Suitable	Suitable	Marginal	Marginal	Suitable	Suitable	Marginal	Marginal	Marginal	Suitable	Marginal	Marginal	Marginal	Suitable	Marginal	Marginal
Sessile oak	Suitable	Suitable	Marginal	Unsuitable	Suitable	Suitable	Marginal	Marginal	Suitable	Suitable	Marginal	Unsuitable	Marginal	Suitable	Marginal	Marginal	Marginal	Suitable	Marginal	Marginal
Sweet chestnut	Marginal	Suitable	Suitable	Suitable	Marginal	Suitable	Suitable	Suitable	Marginal	Suitable	Suitable	Suitable	Unsuitable	Marginal	Marginal	Marginal	Marginal	Marginal	Marginal	Suitable
Sycamore	Suitable	Suitable	Marginal	Unsuitable	Suitable	Suitable	Marginal	Unsuitable	Suitable	Marginal	Marginal	Unsuitable	Suitable	Suitable	Marginal	Marginal	Suitable	Suitable	Marginal	Marginal
Wild cherry	Very suitable	Very suitable	Suitable	Unsuitable	Suitable	Suitable	Suitable	Marginal	Very suitable	Very suitable	Suitable	Marginal	Suitable	Suitable	Suitable	Marginal	Suitable	Suitable	Suitable	Marginal
Aspen	Suitable	Suitable	Marginal	Marginal	Suitable	Suitable	Suitable	Marginal	Suitable	Suitable	Marginal	Marginal	Suitable	Suitable	Marginal	Marginal	Suitable	Suitable	Marginal	Marginal
Norway maple	Suitable	Very suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Very suitable	Suitable	Suitable	Marginal	Suitable	Marginal	Suitable	Suitable	Suitable	Marginal	Suitable
Wych elm	Suitable	Marginal	Unsuitable	Unsuitable	Suitable	Marginal	Marginal	Unsuitable	Marginal	Marginal	Unsuitable	Unsuitable	Suitable	Suitable	Marginal	Unsuitable	Suitable	Suitable	Marginal	Unsuitable
Conifers	Baseline	2050 (L)	2050 (H)	2080 (H)	Baseline	2050 (L)	2050 (H)	2080 (H)	Baseline	2050 (L)	2050 (H)	2080 (H)	Baseline	2050 (L)	2050 (H)	2080 (H)	Baseline	2050 (L)	2050 (H)	2080 (H)
Corsican pine	Very suitable	Very suitable	Very suitable	Suitable	Very suitable	Very suitable	Very suitable	Suitable	Very suitable	Very suitable	Very suitable	Suitable	Marginal	Suitable	Suitable	Very suitable	Suitable	Suitable	Very suitable	Very suitable
Douglas fir	Suitable	Suitable	Suitable	Unsuitable	Suitable	Suitable	Suitable	Marginal	Suitable	Suitable	Suitable	Marginal	Marginal	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Marginal
European larch	Suitable	Suitable	Unsuitable	Unsuitable	Suitable	Suitable	Marginal	Unsuitable	Marginal	Marginal	Unsuitable	Unsuitable	Suitable	Suitable	Marginal	Marginal	Suitable	Suitable	Marginal	Unsuitable
Japanese larch	Unsuitable	Unsuitable	Unsuitable	Unsuitable	Suitable	Marginal	Marginal	Unsuitable	Unsuitable	Unsuitable	Unsuitable	Unsuitable	Suitable	Suitable	Suitable	Unsuitable	Marginal	Marginal	Marginal	Unsuitable
Norway spruce	Suitable	Suitable	Unsuitable	Unsuitable	Very suitable	Suitable	Marginal	Unsuitable	Marginal	Marginal	Unsuitable	Unsuitable	Suitable	Suitable	Suitable	Marginal	Suitable	Suitable	Marginal	Unsuitable
Scots pine	Suitable	Suitable	Marginal	Marginal	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Marginal	Marginal	Suitable	Suitable	Suitable	Marginal	Suitable	Suitable	Suitable	Suitable
Sitka spruce	Marginal	Marginal	Unsuitable	Unsuitable	Suitable	Marginal	Marginal	Unsuitable	Unsuitable	Unsuitable	Unsuitable	Unsuitable	Suitable	Suitable	Suitable	Marginal	Marginal	Marginal	Marginal	Unsuitable
Western hemlock	Suitable	Marginal	Marginal	Unsuitable	Suitable	Marginal	Unsuitable	Unsuitable	Marginal	Marginal	Unsuitable	Unsuitable	Suitable	Suitable	Unsuitable	Marginal	Suitable	Suitable	Unsuitable	Unsuitable
Grand fir	Unsuitable	Unsuitable	Unsuitable	Unsuitable	Marginal	Marginal	Unsuitable	Unsuitable	Unsuitable	Unsuitable	Unsuitable	Unsuitable	Marginal	Marginal	Unsuitable	Unsuitable	Marginal	Marginal	Unsuitable	Unsuitable
Lodgepole pine	Suitable	Suitable	Suitable	Unsuitable	Suitable	Suitable	Suitable	Unsuitable	Suitable	Suitable	Suitable	Unsuitable	Very suitable	Suitable	Suitable	Suitable	Very suitable	Very suitable	Suitable	Marginal
Noble fir	Suitable	Suitable	Unsuitable	Unsuitable	Suitable	Suitable	Suitable	Unsuitable	Suitable	Suitable	Unsuitable	Unsuitable	Suitable	Suitable	Suitable	Marginal	Suitable	Suitable	Unsuitable	Unsuitable
Red cedar	Marginal	Unsuitable	Unsuitable	Unsuitable	Suitable	Marginal	Unsuitable	Unsuitable	Unsuitable	Unsuitable	Unsuitable	Unsuitable	Suitable	Suitable	Marginal	Unsuitable	Marginal	Marginal	Unsuitable	Unsuitable

Very suitable Suitable Marginal Unsuitable

Figure 8 Projected change in Douglas fir suitability from the baseline period to 2050 in the B1 Low (a) and the A1FI High (b) emissions scenarios.

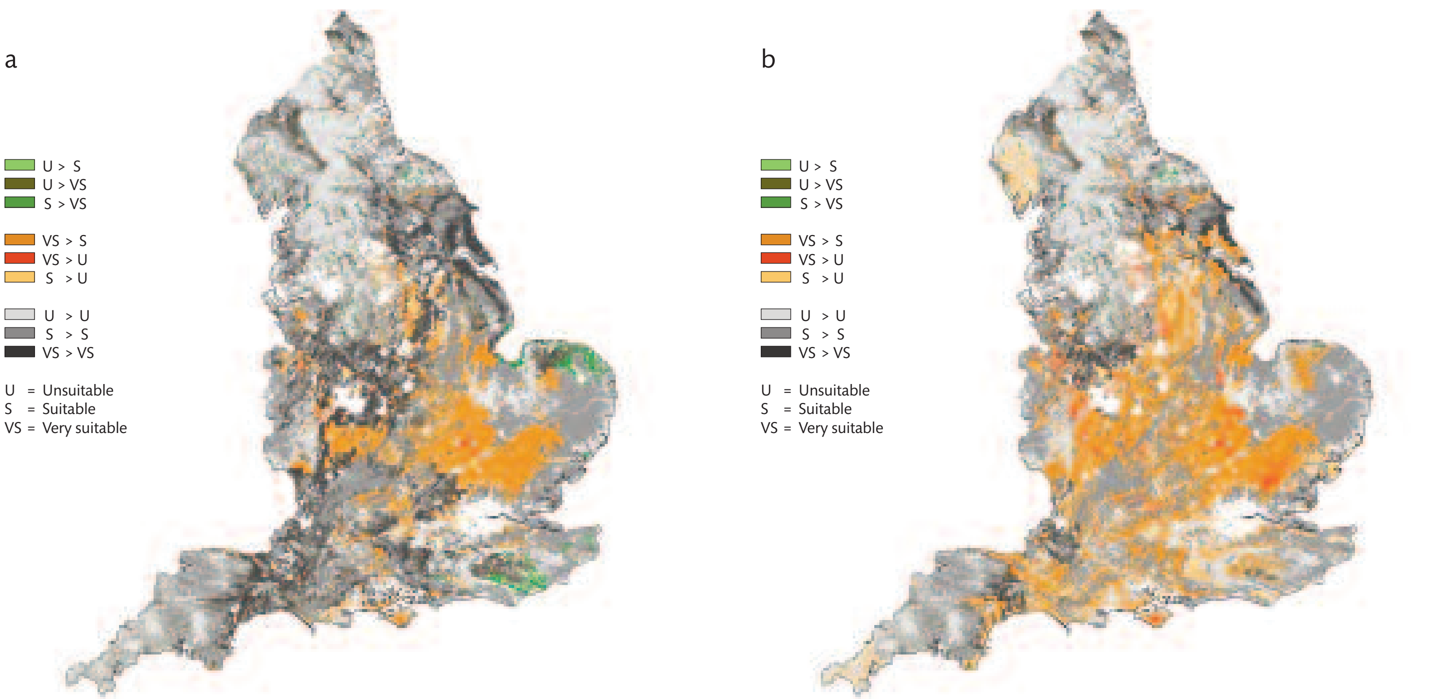


Table 2 Impacts of different combinations of climatic driver on the types of ancient and native woodland found in England.

Likely change	Lowland mixed broadleaved woodland	Lowland beech and yew woodlands	Upland oakwoods	Upland mixed ashwoods	Wet woodlands
Woodland community expansion/ range shift	Range possibly restricted on more drought prone soils with conversion to semi-arid scrub communities. **Drier summers**	Spread to north and west. **Milder winters, springs and summers** Habitat restricted to deeper soils and north-facing slopes. **Drier summers**	Range restricted to wetter regions and replaced by communities more typical of lowland broadleaved and mixed woodland. **Warmer and drier summers**	Colonisation of wet woodland sites along river tributaries that arise in lowland areas. **Drier summers**	Colonisation of open ground habitat in lower reaches of catchments fed by upland headwater tributaries. **Wetter winters**
Composition of woodland vegetation	Increased colonisation by beech (*Fagus sylvatica*) and increased growth rates of sycamore (*Acer pseudoplatanus*) over ash (*Fraxinus excelsior*), oak (*Quercus robur*) and elm (*Ulmus glabra*). **Milder winters, springs and summers** Increased growth and fruiting of lime (*Tilia cordata*), hornbeam (*Carpinus betulus*) and other warm-temperate species. **Warmer summers** Localised dominance by young ash (*Fraxinus excelsior*) in areas damaged by wind and drought. **Increased frequency of winter gales and summer drought** Localised change in ground flora and under-storey composition. **Increased frequency of fire**	Replacement by pedunculate oak (*Quercus robur*) on heavier soils as older beech trees (*Fagus sylvatica*) die due to increased levels of fungal disease, root die-back and windblow. **Drier summers and wetter winters** Localised change in ground flora and understorey composition. **Increased frequency of fire**	Beech (*Fagus sylvatica*) encroachment where climate is warmer and wetter. **Milder winters, springs and summers** Rowan and birch increase in dominance in areas affected by windblow. **Increased frequency of winter gales** Change in composition of epiphytic lichen and bryophyte communities. **Warmer and drier summers** Localised change in ground flora and understorey composition. **Increased frequency of fire**	Rowan (*Sorbus aucuparia*), downy birch (*Betula pubescens*) and silver birch (*Betula pendula*) increase in dominance in areas affected by windblow. **Increased frequency of winter gales** Change in composition of epiphytic lichen and bryophyte communities. **Warmer and drier summers**	Reduction in alder (*Alnus glutinosa*) dominance due to *Phytophthora* spp. **Milder and wetter winters**
Change in woodland age and/or growth structure	Woodland reduced to scrub in extreme cases; in milder cases, mortality of older trees and levels of deadwood increase. **Warmer and drier summers plus increased frequency of winter gales** Localised loss of seedling regeneration and established saplings. **Drier summers and an increased frequency of fire**	Woodlands with scrubbier growth as older beech trees (*Fagus sylvatica*) die due to increased levels of fungal disease, root dieback and windblow. **Drier summers and wetter winters**	Localised loss of seedling regeneration and established saplings. **Drier summers and an increased frequency of fire**	Even aged, young stands of ash (*Fraxinus excelsior*) in areas affected by windblow. **Increased frequency of winter gales**	Mortality of older trees and development of scrubby stands due to increased damaging floods. **Increased winter rainfall** Localised change in ground flora and understorey composition. **Increased winter rainfall**

Note: climate change drivers are shown in bold, green type.

Resilient woodlands

The extent and timing of changes to the climate are uncertain and it is not possible to predict the future climate with a high level of confidence, nor the precise impacts on trees and woodlands. However, the analyses and projections presented in preceding sections make it clear that the future climate will be different from the recent 'norm' and, moreover, continually changing – at least over the next century. We therefore need to adapt forests and their management to this changing future. The uncertainty over changes in climate is compounded by other influences on management. Some of these, including global timber prices, land use change and recreational use, are also affected by climate change. For these reasons, there cannot be a blueprint for adaptation, and it is essential to use an adaptive management approach. As an example, this might involve recognising sensitive sites within forests or regions and trialling adaptation methods, with detailed documentation of: the species used and the silvicultural systems applied; careful monitoring of outcomes; and thorough review to identify the more successful approaches. It should also be noted that conflicting adaptation measures may be required to address different aspects of climate change and that the selection of measures will therefore be site dependent. It is not intended that this Research Note should provide the template for adaptation actions. However, it provides ideas that can be explored within different regions of England, and used to build adaptive capacity in forest management.

A general point for adapting to uncertain and/or unpredictable events is to ensure that contingency plans are in place to deal with, for example, damaging drought, wind, fire and pest and disease outbreaks. Similarly, plans may need to be made for intense rainfall events that might cause soil erosion, slope failure, and damage to forest infrastructure. Some further approaches to adaptation are outlined in Table 3, and are

Table 3 Summary of the main impacts of climate change and potential adaptation strategies in England's woodlands and forests, identified through expert panel discussions and the synthesis of peer reviewed work[1].

Factor	Impact	Adaptation measure
Longer growing season	Earlier bud burst, later bud set, more lammas growth.	Select planting stock with an origin up to 2° latitude south of site, and up to 5° south as a small component of mixed provenance stock in species of low frost sensitivity.
Warmer growing season increased CO_2 concentration	Increased growth rates, improved yield.	Choose conifer and broadleaf species that will produce better quality timber grown in a warmer climate, but beware of frost sensitive species on frost prone sites.
Fewer frost days – milder winters	Reduced hardening, later dormancy, increased risk of autumn frost damage to sensitive species with extended growing season.	Change to less frost sensitive species/provenances; change to species requiring less cold to harden, and increase genetic diversity.
Reduced summer rainfall	More frequent and drier summers, reduced growth, increased drought stress, secondary pest/disease outbreaks[2] resulting from drought stress, increased fire frequency.	Change/mix species to drought tolerant types on sensitive sites. More thinning to reduce moisture demand in open stands. Increase public awareness and vigilence. Contingency plan and regular training for fighting fire.
Increased winter rainfall	Increased waterlogging and anaerobiosis, increased wind damage, increased soil erosion and slope failure, increased Phytophthora infection[2].	Shorter rotation, switch to species tolerant of wet soil on sensitive sites, smaller coupes, self-thinning mixtures, forest operations controls.
Longer growing season	More generations of insect pests per year (increased voltinism)[2].	Increase tree species diversity; enhanced monitoring and intervention where possible or appropriate.
Milder winters, warmer growing season, increased CO_2 concentration	Increased productivity; increase in woodland mammal populations, insect pests and tree diseases[2] and colonisation by alien invasive species.	Increase deer and squirrel management effort; enhanced pest and disease monitoring and intervention where appropriate. Increase tree species diversity.
Increased windiness	Increased wind damage and resultant bark beetle outbreaks and increased bluestain fungus infection[2].	Reduce risk through shorter rotations, species diversification and early thinning, and self-thinning mixtures.

Notes
[1] Citations have been removed from the table to save space but a full version of the table is available at www.forestry.gov.uk/fr/climatechangeengland.
[2] Two tables summarising the effect of climate change on forest insect pests and forest pathogens, published in the Read Report (2009) are reproduced in the web resources www.forestry.gov.uk/fr/climatechangeengland with accompanying notes.

related to the causal change and the potential impact that may warrant an adaptation response. The timing of a response is important – not 'too-little-too-late' and not 'too-much-too-soon' – as both are inefficient and, potentially, expensive. The Read Report, *Combating Climate Change: a Role for UK Forests* provides a thorough treatment of the various impacts, and summary information from the publication has been made available at www.forestry.gov.uk/climatechange.

Adapting silvicultural systems

A suitable adaptation approach to prepare for uncertain events is to spread the risk of the potential impacts through diversification. The key requirement is to have a good understanding of the interactions between site, species and climate. Table 3 suggests a range of adaptation measures: intimate mixtures; species diversification at stand and landscape scale; self-thinning mixtures; and genetic diversification. These will spread risk, reduce impacts, and increase the resilience of woodland ecosystems. Resilient woodlands will have an increased capacity to absorb perturbations caused by environmental or climate change. Diversification might be achieved in a number of ways. For example, in mixing species, it might be appropriate to have stands of intimate mixtures – planted, naturally regenerating, or within continuous cover forestry (CCF) systems where appropriate. In addition, a mix of species at a woodland block scale could be achieved with several different single-species stands.

Box 2 shows the key silvicultural approaches to adaptation, and for practising adaptive management through monitoring and review. Vulnerability tools to help managers understand climate risks and the impacts that might occur are being developed as on-line resources.

Adapting to drier summers

In the east and south of England the projected decrease in summer rainfall and increasing temperature will result in reduced soil water availability during the growing season, restricting tree growth on some sites. Warm, dry summers will occur more frequently in the region, and the impact will be greatest in woodlands on shallow, freely draining soils, particularly with a high proportion of sand or stones and on sites with restricted rooting depth. On these site types there may be increased mortality. Box 3 outlines particular issues relating to species choice on different site types.

Box 2 – Factors to consider in mixing species and amending silviculture to adapt to climate change.

- Aim to diversify age, structure, species composition, and genetic diversity at the forest level with species that are suited to site conditions now and in the future. A proportion could be planting stock from more southerly regions, even up to 5° of latitude in some circumstances; elevation of both site and planting stock origin should also be considered. Discuss species and provenance needs with a nursery at least two years in advance of planting.
- Identify sensitive soil types and consult guidance on species choice for individual sites. Review practice as further evidence becomes available. Consider aspect, topography and soil variability in assessments of species suitability.
- Consider the susceptibility of trees and woodlands to pests and pathogens and develop strategies to reduce risk.
- Consider alternatives to clearfell systems where suitable sites and species combinations allow. For example, continuous cover forestry (CCF) systems may offer advantages for regeneration and establishment , and the regeneration may provide enhanced evolutionary adaptation. Aim to establish a range of stand structures and silvicultural approaches over time. Consider augmenting natural regeneration through planting where species diversity and potential adaptability is likely to be limited.
- Consider non-conventional species choice if timber production is an important objective (further information given in on-line resource and the Read Report).
- In mixed species stands ensure that species are compatible in terms of growth rate and light requirement if intimately mixed.
- Review rotation lengths in response to changing productivity and wind risk. Consider self-thinning mixtures on sites that are, or will become, more susceptible to wind damage.
- Monitor and review species performance over time and use the evidence to modify forest plans. This is good adaptive management practice. Notes and records from monitoring must be systematically archived for future reference. Reviews should take place on a minimum of a 10-year cycle.
- Ensure that Forest Plans are sensitive to site conditions. Diversify the range of species (and genetic material) to meet management objectives wherever soil conditions and projected climate allow.
- Review planting seasons in response to changing conditions and establishment success and promote natural regeneration. Increased rainfall in autumn and winter and milder winters with shorter dormant periods may require novel approaches to restocking and new planting.
- Bring woodlands into management; following thinning of woodlands where species diversity is limited and considered at risk due to projected climate change, consider enriching species diversity through planting.

Box 3 – Factors to consider in assessing species suitability for potentially droughty sites.

- Most tree species that are currently well suited to the soil and current climatic conditions of sites, are likely to continue to be suitable up to the middle of the century. Species that are marginally suited to sites in the current climate, with moisture deficit the limiting factor, are very likely to become less suitable in the future. Many sites in England will show a reduction in productivity as a consequence of the projected drier summers, particularly in the east and south of England. However, this does not mean that these species will cease to be functional components of woodland ecosystems.
- Beech (*Fagus sylvatica*) is vulnerable to dry summers on shallow, freely draining soils, particularly when mature. Hornbeam (*Carpinus betulus*), roble beech (*Nothofagus obliqua*) and sweet chestnut (*Castanea sativa*) are drought tolerant alternative broadleaved species for sites considered too dry for beech in the future. On deeper, loamier textured soils beech will continue to be a suitable species across England.
- Douglas fir (*Pseudotsuga menziesii*) requires adequate moisture for good growth on freely draining soils. However, along with Scots pine (*Pinus sylvestris*), it is regarded as relatively drought tolerant and therefore a suitable species in eastern and southern England on fertile soils, with Scots pine preferable on less fertile soils.
- Pedunculate (*Quercus robur*) and sessile oak (*Q. petraea*) have different distributions, in part determined by soil moisture requirements. Pedunculate oak is found in central and eastern England where it is capable of very deep rooting and is tolerant of fluctuating water tables in both summer and winter. Sessile oak is found mainly in central and western England where it occurs on freely draining soils but requires adequate soil moisture conditions through the summer. Pedunculate oak may remain suitable on sites with fluctuating water tables, but it is likely to show a reduction in growth due to reduced water availability in drier summers.
- Ash (*Fraxinus excelsior*) requires adequate soil moisture throughout the growing season and, for high productivity, should be limited to very fertile sites with plentiful water supply. Sites on which it currently grows well may continue to be suitable, including those in the riparian zone. However, any prolonged dry periods will seriously affect ash where it has inadequate access to moisture.
- Sitka spruce (*Picea sitchensis*), Norway spruce (*P. abies*), Japanese larch* (*Larix kaempferi*), European larch (*L. decidua*) and hybrid larch (*Larix* x *eurolepsis*) are planted in the cooler wetter forests in the uplands of the north and west of England. These species are likely to continue to remain suitable on gleyed (in the case of spruce) and moist but freely-draining sites. A warmer climate is likely to increase productivity on suitable sites.
- Alternative more drought tolerant species should be considered for freely draining and shallow sites in central, eastern and the southern counties of England, or sites subject to fluctuating water tables between and within seasons (e.g. swelling clay soils, and soils on clay-with-flints). Dry, freely draining forest soils in the east of England (e.g. Thetford Forest in Norfolk) pose difficult species selection questions, as the choice of pine species is currently limited by red-band needle blight (RBNB). Woodlands on drought prone sites will need to be monitored and thinned regularly to reduce competition for water.

*Concerns over the current Phytophthora outbreak in southwest England and Wales should be noted and up-to-date information sought if considering planting larch.

Research is currently underway to identify species more tolerant of drier summers and a series of trials are being established across Europe. Our detailed knowledge of potential species is currently limited, but will improve over the coming decade. The limited experience of growing alternative drought tolerant species in the UK should not be used as an excuse for avoiding adaptation decisions on drought susceptible sites. Table 4 provides a list of drought tolerant species that might be considered in forest plans.

Table 4 Some moderately drought tolerant conifer and broadleaved species that might be suitable on specific sites in England.

Common name	Scientific name	Common name	Scientific name
Conifers		Broadleaves	
Scots pine	*Pinus sylvatica*	Wild service tree[2]	*Sorbus torminalis*
Douglas fir	*Pseudotsuga menziesii*	Service tree[2]	*Sorbus domestica*
Maritime pine[1]	*Pinus pinaster*	Sweet chestnut	*Castanea sativa*
Caucasian spruce	*Picea orientalis*	Roble beech	*Nothofagus obliqua*
Macedonian pine	*Pinus peuce*	Sessile oak	*Quercus petraea*
Atlantic cedar	*Cedrus atlantica*	Pedunculate oak	*Quercus robur*
Coast redwood	*Sequoia sempervirens*	Red oak	*Quercus rubra*
Japanese red cedar	*Cryptomeria japonica*	Rowan[2]	*Sorbus aucuparia*
Western red cedar	*Thuja plicata*	Italian alder	*Alnus cordata*
Lawson's cypress	*Chamaecyparis lawsoniana*	Robinia[3]	*Robinia pseudoacacia*

[1]Susceptibility to RBNB to be determined; [2]Only as a minor component; [3]Concern over future risk as an invasive species.

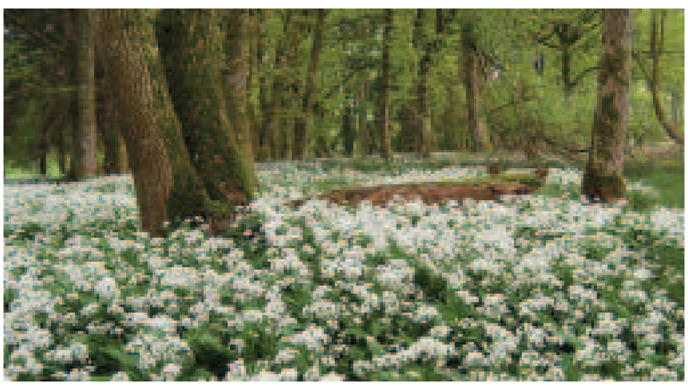
Management of native and ancient woodlands

Ancient woodlands are likely to be fairly resilient to climate change, due to inherently high species diversity, although there is likely to be a gradual adjustment of species composition. However, management to increase resilience in ancient woodland that has been managed for a particular market with a dominant tree species (e.g. beech, hazel coppice, sweet chestnut coppice) could be more challenging. It may require some intervention to change the age structure, and introductions by planting to increase the species diversity. Other drivers such as habitat fragmentation, impacts of surrounding land use, deer browsing, recreational pressure, nitrogen deposition, invasive species, and pests and disease will also affect ancient and native woodlands. It is therefore important that objectives are clear in woodland management plans and that an adaptive form of management to monitor and review progress is implemented.

Ancient semi-natural woodlands form an important 200 000 ha reserve of sequestered carbon in England. The long timescale of development of this woodland resource has resulted in the build up of large carbon pools in the trees, understorey, standing and fallen deadwood, humus, soil and roots. Ancient and native woodlands are also historically, aesthetically and culturally important, and recent resurgence in public interest and involvement in woodlands is centred on these woods. So for all these reasons (and more), ancient and native woodlands should be exemplars of sustainable management that considers and addresses the impacts of climate change.

The assemblages of plants that are used to characterise different priority woodland types are in a dynamic balance with climatic and other site factors. Even small changes in the climate will have an impact on plant communities, favouring some species over others. England has five Priority Woodland Habitats covered by the UK Biodiversity Action Plan; all will be affected by climate change in different ways. In addition to the factors to consider in managing woodland (Box 4), a list of the main issues is outlined in Table 3 together with example measures to reduce impacts.

Figure 9 Ramsons in ancient semi-natural Woodland (ASNW).



Box 4 – Factors to consider when managing ancient and native woodlands.

- In managing ancient woodland, or creating new native woodland, it is important to understand the local climate change pressures and constraints on component species.
- Select planting material that is locally native and well adapted to the planting site and consider supplementing this with a proportion of non-local native material to increase the resilience of the woodland to climate change.
- Increase the diversity of native species representative of the woodland type.
- In new native woodlands a small proportion of species from hotter drier parts of continental Europe may enhance the resilience of new woodlands in the long term. However, species choice should be restricted to regions and sites with a contemporary climate to that projected for England in the future, and also consider potential impacts on native biodiversity through competition and invasiveness. Take advice from JNCC (Joint Nature Conservation Committee) and/or Forest Research.
- It is important to manage woodlands with a mix of tree species that are well suited to the site. A large proportion (at least 80%) should be native, but a small proportion of non-native species may be beneficial if they are well suited to site conditions and not an invasive threat.
- Ensure that operations are carefully planned to avoid irreparable damage to the environmental, ecological, historical, and cultural features of the wood. Wetter winters in the future could exacerbate soil compaction, rutting and erosion and may place additional constraints on operations.
- Non-intervention is appropriate in some circumstances, particularly where a diverse structure has established. However, in many other ancient and native woodlands, management will promote natural regeneration and evolutionary adaptation.
- Warmer and longer growing seasons will promote productivity and provide more food for herbivores, both invertebrates and mammals. Deer and rabbit populations will tend to increase in response to food availability and milder winters, requiring robust control measures in the future, particularly where natural regeneration is a priority.
- Invasive species including boar, grey squirrel, edible dormouse, rhododendron, laurel, Japanese knotweed and Himalayan balsam should be monitored as a warmer climate will promote expansion of their range/population. Some non-native tree species may present a future risk of becoming invasive.
- Woodlands will become increasingly vulnerable to fire in dry spring and summer weather, particularly in woods that are frequently visited. Develop a fire risk assessment and employ greater vigilance during periods of high risk.
- Coppice can improve resilience to drought as stools have deeper roots than regenerating seedlings and planted material, and coppiced shoots tend to have a higher vigour than young plants.

Box 4 – continued

- Look for opportunities to expand and maintain ancient wood pasture and parkland, which will aid the dispersal of many woodland species. More open woodland for grazing will provide shade in warmer summers and shelter in wetter winters.
- Where site conditions are likely to become unsuitable for particular woodland types in part of their present range, safeguard areas that will remain suitable for a longer period from other environmental pressure, for example by focusing on the wetter and cooler part of the range of upland oakwood.
- Changing conditions will make a site less suitable for one woodland type and more suitable for another. Management response should plan for changes in distribution and promote colonisation, for example by managing adjacent woodland to provide opportunities for species colonisation.
- Natural regeneration is likely to be affected by climate change although this may vary from species to species. Information about the effect that climate change may have on pollen dispersal and seed germination processes is limited. It may therefore be necessary to get specialist advice, and also to consider planting material that is better suited to problem sites that suffer natural regeneration failure.
- Where the likelihood of increased colonisation of unwanted invasive species occurs, create buffer areas around core woodland where invasive species are absent, or remove small isolated patches of invasive species if already present at the site. However, it must be remembered that climate change is driving species range shifts, and attempts to prevent natural colonisation may exacerbate woodland fragmentation in the future.
- Avoid management that would result in a less wind-firm stand where frequent gales and wetter winters are likely to cause more damage.
- Where impacts affect age structure through the mortality of older trees, release smaller trees to promote rapid development of the next cohort.
- Long term change should be monitored, recorded and reviewed at regular (perhaps 10-year) intervals. Monitor the range of habitats, age range, vertical structure, deadwood, and field layer vegetation composition to provide evidence of long term change. Ancient woodland could also provide a long term, resilient, resource for monitoring climate change impacts and the diverse range of species in native woodlands may provide some evidence to guide adapted species choice in other types of woodland.

Fragmentation and connectivity

Fragmentation is caused by the partial or complete loss of woodland patches and by intensive management of land between patches (e.g. development, roads and agriculture, Figure 10). This increases the isolation of the remaining woodland fragments as the distance between patches increases. Habitat loss and isolation have a serious impact on biodiversity as the area of available habitat is reduced and the ability for species to move declines. This weakens the resilience of a woodland ecosystem – population viability is threatened, the opportunity for dispersal and colonisation is reduced and disturbance is more likely to cause local extinctions. Landscape planning which considers such factors (Box 5) can help dispersal between patches, absorb disturbance and support re-colonisation. It is important to appreciate that mobile animal species, and the seed of many plants, can disperse between patches that are not physically connected. Successful movement depends on species dispersal ability and the permeability of the landscape between habitat patches for the particular organisms in question.

Box 5 – Factors to consider in making landscapes more permeable for species movement.

- Small ancient woodland remnants should be enlarged to create larger core woodland areas. Avoid fragmenting existing priority open habitat and consider the impact of new woodland on the ecology of adjacent sites.
- Improve the connectivity of the landscape for woodland species by extending and targeting woodland expansion to link existing semi-natural habitat.
- Hedgerows and shelterbelts can help promote dispersal in agricultural landscapes. Create linkages between ancient woodlands.
- Widening riparian corridors and other linear semi-natural vegetation features can help reduce fragmentation.

Figure 10 Aerial photograph showing broadleaved woodland (dark green) within a highly-fragmented agricultural landscape.

Infrastructure

Climate change will affect the infrastructure of forests and Box 6 considers factors to reduce impacts. A major concern is the impact that wetter winters and more intense rainfall events will have on forest and woodland infrastructure as forest roads and accompanying roadside drains and culverts are particularly vulnerable to damage through erosion and washout. In addition, sloping buffer areas that receive water from roadside drains could slip or erode under intense storm flow. Increased fire risk in warmer, drier, springs and summers may require specific measures, such as fire ponds, or other water supply provision, and the creation of firebreaks.

Box 6 – Factors to consider in reducing damage to the woodland infrastructure in the future climate.

- Consider carefully the projected changes to seasonal rainfall when specifying culvert and road design.
- Manage woodland on steep slopes in a way to reduce the impact of heavy, intense or prolonged rainfall causing slope failure. High forest management systems on steep slopes in high rainfall areas could increase the risk of slope failure and damage to infrastructure. On difficult sites consider adapting forest management systems, e.g. native woodland, traditional coppice. Avoid draining or diverting water into channels on steep slopes.
- In locating new woodland, consider the potential benefits in relation to flood alleviation (Figure 11), improvement of water quality and other ecosystem services. There is evidence that woodland planted in valley bottoms prone to flooding can attenuate high peak flow discharge events downstream, and reduce flooding in towns and cities.

Figure 11 Storage of water by floodplain woodland in the New Forest.

Woodlands for people

Warmer (and drier summer) conditions are likely to encourage an outdoor lifestyle with greater numbers of people taking recreation and relaxation opportunities in forests and woodlands; Box 7 considers factors to consider in adaptation planning. This will influence the infrastructure requirements of woodlands. However, this could also be affected by a move to a low-carbon economy; promotion of 'local' tourism, reduced mobility, or the need for more public transport access. Trees and woodlands also have a role to play in adapting the urban environment to climate change, particularly in microclimate modification.

Box 7 – Factors to consider in managing woodlands for people.

- In urban situations, consider the potential benefits of woodland and trees in reducing the impacts of the climate change and contributing to sustainable urban drainage systems.
- Woodlands are increasingly being planned as part of the urban environment. Here they can help reduce stress, reduce noise, reduce air pollution, improve the visual quality of towns, provide shelter in the winter (reducing heating requirements), and reduce maximum summer temperatures (reducing air conditioning requirements).
- Street tree species selection poses some challenges because of the harsher (warmer and drier) urban environment, issues relating to public health (allergens), and the risk of trees causing subsidence and infrastructure damage. However, a wide range of species can be used in towns and cities and further information is available at www.right-trees.org.uk.
- More visitors to urban and community woodland increases the risk of fires during dry spring and summer weather. Take precautions to reduce the risk of fire in woodland.
- Communicate preventative information on animal disease risk to visitors, e.g. the risk of tick borne diseases such as Lyme disease will increase in the countryside with milder winters.
- Tree mortality is likely to increase as a result of climate change, requiring greater attention to monitoring of tree condition and safety (and subsequent action) along paths and in areas used for recreation.
- More visitors may require transport links, more or larger paths, car parks and other facilities that will also require consideration of climate change impacts in their design.

Adaptive management techniques

The long timescale of forestry makes the challenges and requirements for adaptation much more demanding than many other sectors, and some key factors are considered in Box 8. It is critically important to start implementing adaptation measures now as the continuing changes in climate through this century will affect existing and, particularly, new woodlands. In all cases, it is important to be aware of the climate projections locally, ensure that management and planning is tested against the worst case scenarios, and so better understand the risks associated with different options.

Box 8 – How to prepare for climate change adaptation in forest management.

- Training courses that develop and maintain field skills in plant identification and soil identification will help improve recognition of different forest sites types, and in particular the different climate change challenges associated with those sites.
- Forest Research and Forestry Commission England are jointly developing resources to help managers identify risks, design plans that take risk into account, and design systems to monitor and review systems and impacts.
- Climate change information is under continual review – and will change. Current information and guidance will be provided through online resources, and updated from time to time.
- Regionally based practical adaptation trials should be set up across England. Trials will involve climate impacts assessment and risk analysis, site survey, planning, monitoring, review, re-evaluation and dissemination of findings. Information from operational trials should be collated and evaluated (including between regions) alongside more formal research trials.

Conclusions

Climate change is a major issue for forestry, globally. In parts of England the climate will become warmer and drier, and so it is imperative that vulnerable sites are identified and targeted for adaptive action. The UKCP09 projections provide information from which risk analyses can be developed to show the timing, degree of exposure and risk of serious climate impacts.

The Forestry Commission is developing resources and tools using UKCP09 and other information to help forest managers assess the vulnerability of forests in England, and prioritise where and by when adaptation is required. To do nothing is not a sensible option. However, it is important that vulnerable sites are targeted first and that a careful assessment is made about the best time to intervene to prevent 'maladaptation'.

Adaptive management is an iterative process in which it is important to test new systems and ideas and judge how these perform under extreme climatic conditions. In some cases, these measures will push at the boundaries and carry a significant risk of failure – but represent considerable gains if successful. It is imperative that the iterative process includes a phase of dissemination and information exchange as findings emerge. This will allow information and experience to be tested efficiently in different regions of England. What works now in southern England might be appropriate for central or northern England in 20 years time.

Contingency planning for extreme events is an essential component of the adaptation of forestry to climate change. The process of thinking about responding to a catastrophic event is an important exercise in developing plans for worst-case scenarios, and will help forest managers, woodland staff, and the public anticipate the extreme effects of climate change.

The acceptance of change (or bearing of loss) should also be considered as an adaptation response. Examples of such change could be accepting alterations to the character of ancient and semi-natural woodland or that a species currently viewed as 'unsuitable' for timber production on a specific site because of low productivity might be viewed as 'suitable' in the future.

The measures identified in this Research Note show how the resilience of England's woodlands might be improved so that woodland ecosystems have more ability to absorb the impacts of climate change. Resilience is also at the core of maintaining and increasing the contribution of forests to the broad range of ecosystem services which benefit society. Indeed, woodland creation and management can make a real contribution to reducing emissions as part of a low carbon economy, but good decisions regarding species choice and management are the key to ensuring that new woodland is well adapted to future climate impacts and delivers a range of ecosystem services for future generations.

Uncertainty over the future climate and its impact on forests and woodland ecosystems must be acknowledged; however, it must not be used as an excuse for not acting but, rather, should direct woodland managers to implement measures that increase resilience. Such planned adaptation measures are likely to reap the greatest rewards in the future.

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