

# Climate change impacts and adaptive strategies

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## Abstract

Forecasted changes in Ireland's climate will have a significant influence on the productivity of managed forests and woodlands. Given the long-term nature of forestry, the selection of suitable provenances or genotypes and adaptable management practices under future climate change scenarios are essential for sustainable forestry in Ireland. In this paper we assess potential impacts of climate change on forest productivity in order to identify and provide adaptation measures. We argue that the impacts of climate change on forest productivity are not as well characterised as expected. Despite these shortcomings, we present an ecological site classification framework to describe species responses to climatic drivers in an effort to develop adaptive strategies to address these problems.

## Keywords

Climate change, impacts, adaptation

## Introduction

Global forests contribute substantially to atmospheric greenhouse gas emissions, but they also offer the potential to reduce emissions. Future climate change policies and actions need to consider the interaction between the impacts of climate change, adaptation for sustainable forestry and mitigation options, such a carbon sequestration through afforestation activities (Black et al. 2009a). For example, if no mitigation or adaptation actions are implemented, forests may be more vulnerable to a future climate change and this will be exacerbated by further global climate change. On the other hand, if mitigation policy directs the afforestation of areas planted with forest species not suitable to future climates, the advantage of these actions will not be realised unless suitable species are selected. Although national climate change mitigation issues are discussed in a separate paper in this issue (Byrne, 2010), these policies should not be considered in isolation.

Forecasted changes in Ireland's climate (McGrath et al. 2005) will have a significant influence on the productivity of managed forests and woodlands. Given the long-term nature of forestry, the selection of suitable provenances or genotypes and adaptable management practices under future climate change scenarios are essential for sustainable forestry in Ireland. In this paper we discuss the development of support tools to guide a strategic adaptive climate change policy to maintain a robust and sustainable forest resource in Ireland. However, national implementation of adaptive climate change strategies is dependent on a sound knowledge of the impacts of climate change at a local level. This aspect of climate change research represents a significant

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knowledge gap in an Irish context. Here we review numerous climate change impact approaches including ecological site classification (ESC), process based physiological models and medium to long term research data to assess changes in species suitability and yield, resulting from historic, current and future climate change scenarios. We also attempt to highlight some key unresolved research issues, which the climate change scientific community needs to address before the impact of climate change on forest health and productivity are understood and robust adaptive strategies can be implemented.

### **Observed impacts**

In this section we consider both observed historic trends in response to changing climatic variables and review literature from experimental and modelling studies. We also briefly describe an ecological site classification system developed for Irish forestry, which characterises species suitability for specific site and climatic conditions.

#### *Species distribution*

##### *a) Historic trends*

In order to understand how species distribution is influenced by climate, it is important to consider ways in which trees have responded to climate change in the recent past. There is some evidence of some climatically driven shifts in species distribution until humans first began to have an influence on forests in Neolithic times, ca. 5500 years before present (BP). Tree species started to spread to north-western Europe in the early Holocene following the contraction of the polar ice pack after the last ice age, 11,000 to 13,000 BP (Moore et al. 1996). From about 8,000 BP much of the Irish landscape was dominated by oak (*Quercus* spp.) and elm (*Ulmus* spp.) with some yew (*Taxus baccata* L.) ash and hazel (*Corylus* spp.) in the underscrub (Mitchell and Ryan, 1997). Scots pine (*Pinus sylvestris* L.) occurred in drier sites and at higher elevations with alder in wetter areas. Pine became more prominent as the climate became wetter in about 7,000 BP and elm disappeared about 5,700 BP possibly due to disease. However, since the Bronze Age, Irish forests have suffered relentless deforestation to a level less than 1.4% of the total land area by 1905 (McEvoy 1954).

##### *b) Current trends*

There is little evidence of climatically driven alterations in tree species distribution over the past 100 years. Trees growing at the limits of their ecological tolerance would be more sensitive to climate change. Most commonly occurring trees in Ireland, with the exception of non-forest species (e.g. *Arbutus*), are not at the extreme of their range and, therefore, may not show any distribution shifts related to climatic change. This lack of any apparent climatically driven association with species distribution in Ireland may also be due to a limited geographical range and climatic gradient. The small area of remaining natural forest and large areas of plantation forestry means that species distribution is primarily a result of silvicultural management, where species selection (and hence distribution) is determined by site type (Horgan et al. 2004, Ray et al in press) rather than climate. For example, much of the peatland forestry is comprised

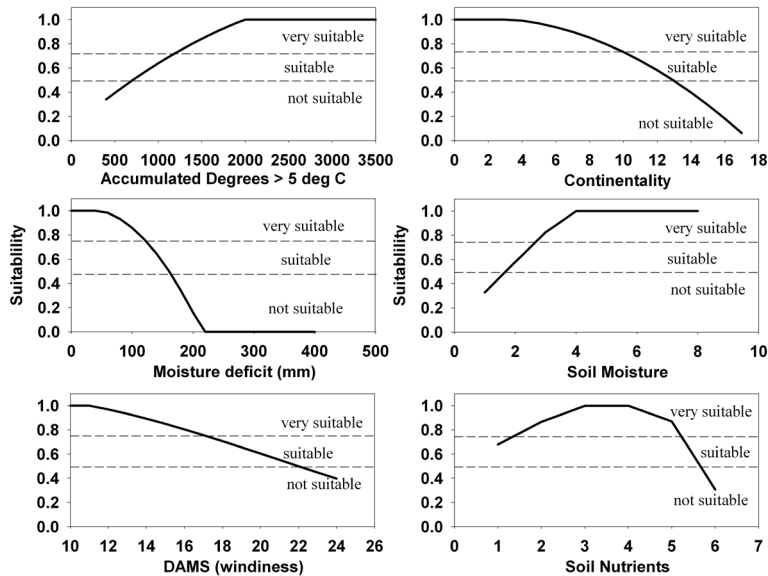
of lodgepole pine (*Pinus contorta* Loud.) and Sitka spruce (*Picea sitchensis* (Bong.) Carr.). Small areas of other conifers, such as Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco.), are found on the well drained brown earths, or Scots pine on podsolic soils.

The only evidence of recent species distribution shifts are successional changes associated with land-use change or management. For example, encroachments of hazel scrub on the Burren landscape (characterized by limestone pavements and lithosols) due to a reduction in livestock grazing in these areas or birch (*Betula* spp.) and alder (*Alnus* spp.) on abandoned cutaway peatlands (Black et al. 2009b) have been observed.

### *Species suitability*

Since the establishment of plantation forestry in Ireland in the early 1900s, the silvicultural interest, from a climate perspective, was species selection for the correct site type. Forest growth, function and productivity are influenced not only by climate, but by the interaction of climate, soil type and site specific factors (Horgan et al. 2004). These complex interactions between climate and edaphic factors make it difficult to understand and predict species suitability in response to current or future climate. However, predictive models can provide some insight into how species may respond to different climates. Site classification systems, which have been used in Scandinavia (Cajander 1926) and central Europe (Ellenberg 1988) to describe forest cover of regions, use biophysical variables describing site and climatic characteristics. An ecological site classification system (ESC) has been developed for Ireland (for review see Ray et al. 2009), based on a similar GIS system for the UK (Clare and Ray 2001, Ray et al. 2003). This system has since been used to assess the impacts of projected climate change scenarios on species suitability. Multi-factor forest site classification systems, by definition, separate the effects of climate and edaphic factors on tree species or forest type suitability (Figure 1). The ESC approach describes the response of all major forest species in Ireland and the UK to four climatic factors: warmth (AT), drought (i.e. moisture deficit (MD)), wind exposure (measured using the detailed aspect method of scoring, DAMS, see Ray et al. 2009), and continentality, based on Delphi models (see Pyatt et al 2001 for definitions). The suitability class (Very Suitable, Suitable, or Unsuitable) of different tree species was linked to each of the climatic factors, and to two soil quality factors representing soil wetness (soil moisture regime – SMR) and soil fertility (soil nutrient regime – SNR). GIS data describing these variables and Delphi characterisation of current and potential forestry tree species have been compiled, so we are now able to produce suitability maps for 26 tree species (for example see Sitka spruce suitability map, Figure 5). These maps have, however, not been finalised because a recent statistical validation exercise suggest that some edaphic factors such as SMR need to be modified.

The delivery of a web-based application for species suitability under current and most likely future climate scenarios is the major objective of this study (CLIMADAPT, Ray et al. 2009) and is the primary climate adaptation issue facing sustainable Irish forestry in the future.



**Figure 1:** The suitability of Sitka spruce according to a) AT – (day degrees above 5°C) and b) MD (mm), DAMS or windiness, SMR-soil moisture regime and SNR- soil nutrient regime. Suitability is classified on a scale from 0 to 1, where limiting factor (  $f$  ) values  $\geq 0.75$  are very suitable (GYC > 20),  $\geq 0.5$  are suitable (GYC 10 to 20) and  $< 0.5$  are unsuitable (GYC < 10).

#### *Phenology and dormancy*

The International Phenological Gardens (IPG) network was established in 1957 with the aim of collecting phenological data from 50 sites across Europe (Chmielewski and Rötzer 2001). Clones of tree and shrub varieties were planted at each site to account for localised genotypic variations in response to environmental conditions. Analysis of Irish data collected between 1970 and 2000 (Donnelly et al. 2004), suggest that over 50% of the broadleaved species investigated showed significant changes in the timing of leaf unfolding (early growth season (EGS) initiation) and leaf fall (i.e. end of growth season). For many species the length of the growing season (LGS) increased due to both an earlier start to the growing season and a delay in the date on which leaf fall occurred. The greatest increase in LGS was observed in the south-west of the country. In Ireland, along with an increase in mean spring and mean annual temperature, the timing of phenological events has advanced in the case of EGS and delayed in the case of leaf fall over the last 30 years. However, the spring phenological response could not be explained simply by average spring temperature alone, indicating an influence of other environmental factors on phenology (Donnelly et al. 2004).

There is currently no information on changes in phenological development for the major conifer species in Ireland. Difficulties in interpreting any climatically induced changes in conifer species phenology is exacerbated by the introduction of more

productive provenances of Sitka spruce such as from Oregon and Washington, in recent years, which show a later onset of dormancy (Thompson 1998, Black unpublished data).

### *Forest productivity*

Previous dendrochronology studies for Irish oak, extending back 7000 years (Baillie and Brown 1995) show notable downturns in growth relating to catastrophic environmental events (Baillie 1999). The effect of recent increases in temperature on growth is not clearly evident in the oak chronology study. This is consistent with preliminary results from a more recent dendroclimatology study, conducted on Sitka spruce in Avoca, which shows no significant temperature related increase in growth over a 70-year chronology (Tene et al. 2009). However, the results of that study showed that where large reductions in radial growth were recorded, these were associated with large MDs above 180 mm (the limiting MD level for Sitka spruce as defined using ESC models; see Figure 1). The study by Tene et al (2009) also shows that radial growth responses to MD were consistent with natural carbon and oxygen isotopic signals of cellulose, extracted from cores. These observations are consistent with the current hypothesis that the increased frequency of stomatal closure in response to moisture stress may be limiting carbon assimilation, resulting in a decrease in tree growth (Barbour et al. 2002).

Since the initial afforestation initiatives were introduced in the 1940s, the average productivity of Sitka spruce has increased by up to 5% (see Horgan et al. 2004). This may be associated with a change in silvicultural practice, the introduction of genetically superior seed sources and the increased availability of better quality site types. For example, over the past decade there has been a shift away from afforestation of blanket peats with conifers, in the west of Ireland in the 1950-60s, to more productive sites characterised by fertile soils such as brown earth and gley soils (Black et al. 2009). These factors, together with the relatively short history of forest research in Ireland, make it difficult to discern any past impact of changing climate on forest growth or health. This is confounded by the lack of sustained or long term climate change mitigation, impact or adaptation research activities before the ICP monitoring network was established in Ireland and the Irish Council for Forest Research and Development (COFORD) climate change programme was initiated in 2002.

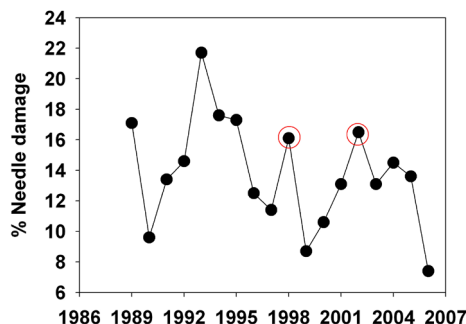
Based on the evidence presented above, or lack thereof, the only way to quantify and characterise any impacts of climate change on forest productivity is by process based modelling (Goodale et al. 1998, Black et al. 2006), analysis of large scale international experimental or monitoring data. The international literature shows that forest productivity has been increasing across Europe for some time. Although some of the increased productivity is thought to have resulted from improved silviculture and genetic improvement (Worrell and Malcolm 1990), the main cause is now considered to be nitrogen fertilisation from atmospheric pollution (Goodale et al. 1998, Magnani et al. 2007) in combination with a warming climate. Long term ICP forest monitoring trends, for Ireland, suggest there is an increase in N-deposition in the eastern half of the country (Neville pers. comm.). The extent to which N deposition may influence

the productivity of forests does, however, depend on the stage of N saturation and nutrient status of forest soils (see Aber et al. 1998)

### *Pests and diseases*

In most cases, historical trends in the epidemiology of insects and diseases in Irish forests are a direct result of forest management or afforestation history. For example, the increased outbreak of the large pine weevil in reforested stands during the re-establishment phase is associated with an increase in the area of forest clearfelled in recent decades and changed control practices, due to restrictions of pesticide use.

- a) Green spruce aphid (*Elatobium abietinum*): Information from Level I ICP monitoring plots, suggest periodic peaks in needle damage may be related to aphid outbreaks (Figure 2). Aphid outbreaks occur on a 3-6 year cycle resulting in a delayed reduction in volume productivity of ca. 10% (Day 2002). Other studies, suggest a larger yield reduction of 24% in the year following an aphid outbreak (Straw et al. 2002). The population size and structure of the green spruce aphid is related to the pattern of change and the phenology of bud burst, which signifies a change in needle sap quality. Therefore, yearly differences in the winter temperature regime may affect the duration of the population growth phase and peak numbers attained in late spring (Day 2002). A combination of the population density in the summer and the number of severe cold periods below  $-7^{\circ}\text{C}$  in the winter months, determine the size of the population the following year. An aphid outbreak results in significant losses of two and three year old needles during the following growing season and thus a reduction in productivity the year after peak infestation. Based on long term ecosystem flux studies in a Sitka spruce stand in the midlands, it is suggested that stand productivity is possibly associated with a 'knock-on effect' of aphid outbreaks (Straw et al. 2002, Black et al. 2007). High population densities of spruce aphid in 2002 were associated with browning and a subsequent loss of foliage, resulting in an 80 to 90% increase in litterfall in 2003 and 2004 compared to previous years (Tobin et al. 2006). Whilst a reduction in net ecosystem productivity in 2004 (18 to 23%) may have been exacerbated by the 2003 drought and self thinning, following canopy closure; these results highlight the importance of the indirect influences of climate change, such as insect outbreaks, on potential forest productivity in the future.



**Figure 2:** The annual trends in % needle damage in Level 1 ICP plots. The red circles highlight where the occurrence of needle damage was associated with aphid outbreaks in 1998 and 2002 (Neville et al. unpublished data).

- b) Large pine weevil (*Hylobius abietis*): As mentioned, this is a particular problem in reforested stands, replanted 1 to 2 years after clearfell in warmer regions in the south and south east of the country. An increase in summer temperatures could result in greater weevil activity, particularly in combination with drought events and recent legislative policy banning the use of the insecticide Lindane (Purser et al. 2004).
- c) Great spruce bark beetle (*Dendroctonus micans*): Not present in Ireland, but large areas of spruce monoculture may become vulnerable to bark beetle outbreaks, particularly in the south and south east of the country (Purser et al. 2004), where drought-induced stress may become significant (Ray et al. 2007).
- d) *Phytophthora* disease of alder and larch: This species has only recently been identified in Ireland; it is possible that its expansion may be an indication of an increased planting of alder species or environmental changes (Purser et al. 2004).
- e) Fomes (*Heterobasidion annosum*): Root and butt rot fungus is the most economically damaging disease affecting Irish forestry. It is suggested that fructifications are resistant to drought and moderate frost implicating a greater threat in a warmer and drier climates (Purser et al. 2004)
- f) Red band needle blight (*Dothistroma septosporum*) is currently expanding its range across Europe. The disease affects many species of pine and can be transferred to other species including European larch (*Larix decidua* Mill.), Douglas fir and Sitka spruce. The fungus requires high humidity and warm spring temperatures (12-18°C) (Brown et al. 2003). However, the predicted warmer and drier spring weather in Ireland may not provide ideal conditions for the spread of this pathogen in the future.

### *Extreme events*

Extreme climatic events, such as drought and storms, pose the greatest climatic threat to forest productivity. Disturbances and recent extreme events in Ireland include: drought (1976 and 1995) and windstorms (1982, 1987, 1990 and 1999). Fire outbreaks are rare in Ireland, but an average of 400 ha affected by wild fires annually (NIR 2007). The largest areas burned by natural fire occurred in 2003, where numerous fire outbreaks affected some 1030 ha of plantation forests.

The location of many Irish forest plantations on exposed, windy sites with poor drainage renders them vulnerable to wind damage. In 1997, 1998 and 1998 Coillte reported 0.5, 0.85 and 1.6 M m<sup>3</sup> respectively of roundwood being windthrown (Purser et al. 2004). Ní Dhubháin (1998) suggests that forests on relatively exposed, ploughed sites are reaching critical heights in relation to windthrow risk and this level of damage may increase. Pre-mature felling (age of maximum mean annual increment less 20%, i.e. commercial rotation or at top heights of 18, 21 or 24 m) in high windthrow risk sites is a common practice resulting in lower site productivity and this may have a profound influence on timber sustainability or a decline in the sequestration potential of the national forest plantations, if national harvest levels are not adjusted accordingly.

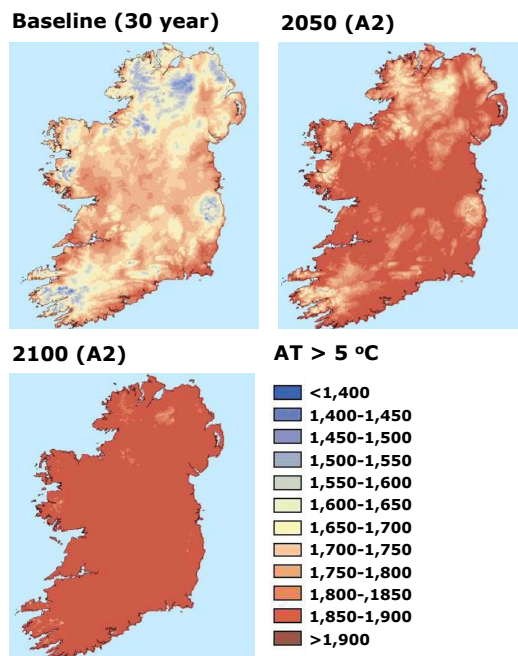
### **Climate change projections**

Regional climatic model scenarios (IPCC - A2 and B1) for Ireland have been derived using a dynamic downscaling method, published by the Community Climate Change Consortium for Ireland (C4i), and validated using back-casting techniques (McGrath et al. 2005). The simulated daily mean temperatures, daily rainfall, and daily evaporation have been compiled into mean monthly and annual values for 30-year periods. Tree physiological response to temperature may be better defined using accumulated temperature (AT), which is an index of climatic warmth, with a threshold set at 5°C, above which both plant respiration and growth occur. AT and climatic MD (i.e. rainfall minus evapotranspiration) were calculated for the growing season (March to October, see Ray et al. 2002).

Based on the medium-high IPCC scenario (A2), the Irish climate is predicted to warm by 1.3°C by mid century, increasing to 3.4°C by 2100. In Ireland the mean increase in AT above 5°C is predicted to be about 200-300 day degrees by 2100 (a 15% increase, Figure 3).

The future predictions of MD, show large increases of 40-60 mm in the south and east of the country, when compared to the climatic 30-year mean for the baseline period (Figure 4). This is partly due to predicted warmer summers and a shift in the seasonality of rainfall, with less in summer months (up to 15% decrease) and more in winter months (20% increase).



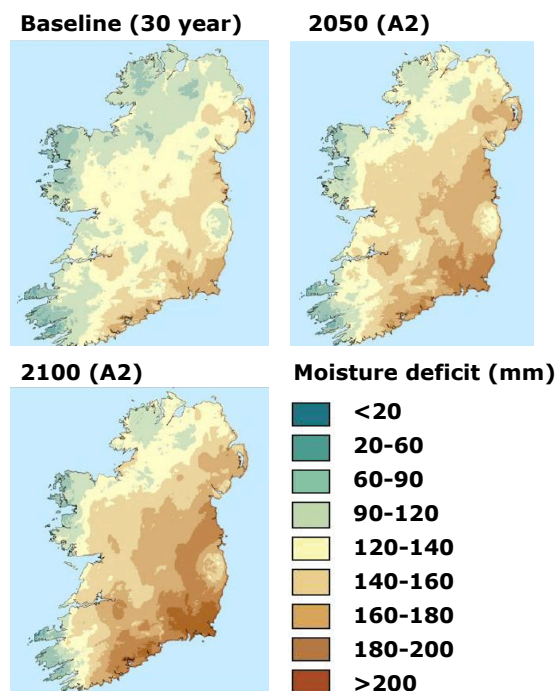


**Figure 3:** Changes in warmth index for forest growth, based on accumulated day degrees above 5°C, over the next century. The current baseline data in the top left panel is the 30-year mean for 1960-1990. The projected data are means from simulations for the 30-year periods 2020-2050 (top right) and 2070-2100 (bottom) using the A2 medium-high green house gas emissions scenario.

A frost risk assessment map has also been developed based on five topographic variables including elevation, slope, aspect, curvature and distance from the sea. Each variable was classified in three risk categories; low, medium and high based on expert knowledge and literature. Whilst it could be speculated that less hardy species could be planted in existing high frost risk areas as the climate warms, the occurrence of frost is determined by microclimatic factors. The production of frost risk maps in ESC could assist with species selection (Ray et al. 2009), particularly if a warmer future climate might tempt foresters to plant less hardy species.

Projections suggest that the climate will become more variable. Therefore, it is likely that there will be an increase in the incidence of extreme events such as dry and hot summers and intense rainfall events leading to flooding episodes in both summer and winter. One example links the projected frequency of dry summers to areas of Ireland providing a mechanism to assess the risk of drought damage to sensitive species caused by frequent dry summers. These data suggest that the frequency of water deficits above 180 mm will increase from 2 years per decade to 7 years per decade by 2080 in eastern parts of the country (Ray et al. 2008). A major scientific challenge facing the climate change modelling community is the characterisation of

extreme events. Traditionally, climate change is expressed on the basis of a change in the mean over long periods. However, these projections assume no change in the statistical distribution of variables at both the spatial and temporal scale. Recent studies by Schär et al. (2004), show that in addition to a change in mean temperature, there is larger shift in the statistical distribution of higher temperatures than was previously thought. Whilst this is consistent with suggestions that the frequency of extreme events will increase, it also highlights the importance of assessing the probability distribution functions (pdf) of climate change variables. Advances in this area are primarily limited due to spatial resolution of GIS datasets. However, even if these pdfs could be generated on a fine spatial scale, there is at present no clear understanding of the relationship between the frequency and magnitude of extreme events and forest productivity. For example, we do not know how an increased frequency of drought would influence species distribution.



**Figure 4:** Changes in average MD (mm) over the next century. The current baseline data in the top left panel is the 30-year mean for 1960-1990. The projected data are means from simulations for the 30-year periods 2020-2050 (top right) and 2070-2100 (bottom) using the A2 medium-high green house gas emissions scenario for the current baseline period.

### Potential impacts

Expected impacts are primarily determined using process based and ESC models, which describe forest processes as a function of mean changes in climatic drivers. In some cases, the models are not detailed enough to characterise the potential impacts of climate change due to a lack of scientific knowledge. In these cases, we provide a broad synopsis of the literature to infer expected impacts in Ireland.

#### *Vegetation phenology*

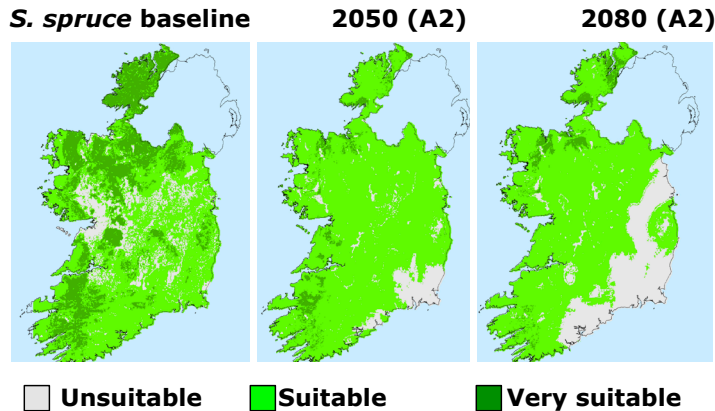
Based on the Irish IPG network data (see previous section), an increase of 1°C in annual average temperature may result in a 5 to 14 day extension to the length of the growing season (Donnelly et al. 2004). Assuming a linear trend in changes of phenology and temperature, these changes would translate to a 7 to 18 day increase in the length of the growing season (i.e. extended time between bud burst and leaf fall) by 2050, increasing to 17 to 48 days by 2100. However, this could potentially make some species more susceptible to early or late frost, but the occurrence of frost may be less frequent.

It is also expected that warmer temperatures during the late autumn-early winter periods could result in later bud dormancy initiation of certain species, such as ash, Sitka spruce, Norway spruce (*Picea abies* Karst.), and beech (*Fagus sylvatica* L.). These species require a certain number of chilling hours before initiation of bud set.

#### *Species suitability*

Together with the use of GIS, soil maps and future climate projections, an ESC system for Ireland has produced some predictions of future species suitability and distribution. However, the influence of potential drivers, such as CO<sub>2</sub> fertilisation, elevated ozone and nitrogen deposition, are not considered due to a lack of knowledge on how these variables interact with main ESC factors.

Preliminary CLIMADAPT-ESC analyses suggest that the predicted warmer and drier climate may offer the possibility of extending the range of species that are currently less common in Ireland. The warmer climate will be more suitable for southern beech (*Nothofagus nervosa* (Phil.) Krasser), Monterey pine (*Pinus radiata* D. Don), Maritime pine (*Pinus pinaster* Loud.), walnut (*Juglans regia* L. and *Juglans nigra* L.) (Anon 2000a), and more southerly provenances of conifers from the Pacific North West (D. Thompson pers. comm.). However, the increased mean MD (> 180 mm) will severely affect the suitability of a number of species on drier well drained soils. In particular, Sitka spruce, Norway spruce, Japanese larch (*Larix kaempferi* (Fortune ex Gord.)) and European beech are likely to become less suitable in a drier climate (Broadmeadow and Ray, 2005; Figure 5), and in addition downy birch (*Betula pubescens* Ehrh.), common alder (*Alnus glutinosa* L.), pendunculate oak (*Quercus robur* L.), and common ash (*Fraxinus excelsior* L.) will become less suitable on shallow freely draining soils (Pyatt et al. 2001) in the drier areas of the south and east of Ireland.



**Figure 5:** Ecological site classification GIS maps showing the suitability of Sitka spruce to the current (left panel) and projected climates for 2050 (middle panel) and 2080 (right panel) assuming the IPCC A2 medium-high green house gas emission scenario. Suitability is classified on a scale from 0 to 1, where limiting factor ( $f$ ) values  $\geq 0.75$  are very suitable ( $GYC > 20$ ),  $\geq 0.5$  are suitable ( $GYC$  10 to 20) and  $< 0.5$  are unsuitable ( $GYC < 10$ ).

Strategies to introduce or replace new species, such as Monterey pine, should however, first consider suitable provenances, risks of introducing new pests or diseases, site suitability and best silvicultural practice.

It should be highlighted that there is no complete soil map for Ireland. Therefore, a GIS indicative soil map, based on satellite and vegetation models (Fealy et al. 2006), was used to characterise ESC-site variables such as SNR and SMR. The final web-based ESC system for Ireland, does, however, include a function where the soil type is determined by the end-user following a site inspection and soil classification exercise (Ray et al. 2009). It is evident that the predicted over estimation of suitability classes for Sitka spruce, particularly in areas of Donegal (see Figure 5), may be associated with either misclassification of the soil type, based on the GIS model, or poor definition of ESC soil variables, such as rooting depth and SNR, in these regions. Similarly, indication of unsuitable areas for Sitka spruce in east Galway and Westmeath (Figure 5, base-line map), may be associated with poor characterisation of soil variables or the inability of the current ESC model to deal with interactions (Xenakis et al. in review). Recent analysis using Bayesian inference and Monte Carlo Markov Chains (Xenakis et al. 2008) has provided a multi-factorial calibration framework for the ESC model, which potentially could improve yield class estimates (Xenakis et al. in review).

#### *Productivity and timber quality*

A modelling sensitivity study on Sitka spruce in Ireland, conducted by Goodale et al. (1998), indicated that site-specific conditions and management practices influence productivity to a greater extent, compared to those likely to be induced by climate change or elevated  $CO_2$ . These authors suggest the effect of climate change and  $CO_2$  fertilization is strongly dependent on N availability. A potential 10% increase in net

primary productivity (NPP) was estimated under high N inputs. This is, however, somewhat lower than recent estimates from combined free-air CO<sub>2</sub> enrichment (FACE) experiments (Ainsworth and Long 2005).

Where other factors important for growth are not limiting, the warmer climatic conditions will tend to increase forest productivity. However, the extent of the temperature related increase in yield is less certain. Estimates suggest that a general yield class (YC) increase of 2 to 4 m<sup>3</sup> ha<sup>-1</sup>yr<sup>-1</sup> may result from an increase in mean temperature of 1°C (Cannell 2002). Recent modelling exercise, based on ecosystem flux measurements on Sitka spruce, suggests that increases in gross primary productivity are not significant following a 1.3 °C increase in temperature (Black et al. 2006). This is consistent with a lack of any apparent relationship between temperature and radial growth in a 70 year Sitka spruce dendroclimatology study (Tene et al. 2009).

In addition to influencing species distribution, it is plausible that an increase in the frequency and magnitude of MD events could reduce productivity in some species, such as Sitka spruce. Evidence from long-term eddy covariance studies suggest that a delayed reduction in productivity of Sitka spruce in response to water deficits is driven predominantly by increased needle turn-over rather than physiological factors in the shorter term. We hypothesise that this ‘knock-on or lag’ response to water deficits and interactions with insect infestations may be more important than short-term physiological factors under present and future climates (Black et al. 2007). This hypothesis is currently being tested using dendroclimatology and natural isotope abundance studies across a climatic and drought gradient (Tene et al. 2009).

The fast growth rate of Sitka spruce, under current climatic conditions, results in poor timber quality, when compared to that of species growing at slower rates. However, there are opportunities to select material (including alternative provenances) to improve timber quality for a warmer climate in a breeding programme, such that micro-fibril angle and density remain optimal. In contrast, the pines, larches and Douglas fir will grow faster without a reduction in wood density (Ray et al. 2008). The timber quality of hardwood species varies in response to increased growth in a warmer climate. Ring porous species such as oak, ash, and elm produce harder and stronger timber when grown at a faster rate. Diffuse porous species such as sycamore and birch do not respond in this way. Chestnut and beech are intermediate in response (Ray et al. 2008).

### *CO<sub>2</sub> fertilisation?*

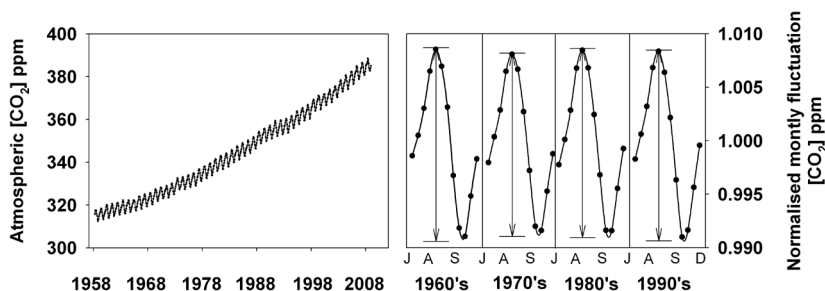
Despite a large body of experimental evidence suggesting that elevated CO<sub>2</sub> levels (from 280 ppm pre-industrialisation to 385 ppm at present) enhance photosynthesis at the leaf level, there is less evidence that it has a positive effect on global forest productivity. Historical trends suggest that the effects of CO<sub>2</sub> fertilisation (i.e. increase photosynthetic response to elevated CO<sub>2</sub>) may be reduced due to acclimation processes, such as a relative decrease in tree leaf stomatal density since the pre-industrial era (Woodward 1987). This notion is supported by the results from a meta-analysis of mean monthly concentrations of CO<sub>2</sub> at the atmospheric recording station Mauna Loa in Hawaii (see Figure 6, Keeling et al. 1995). Records show considerable variation in monthly atmospheric CO<sub>2</sub> levels associated with a draw down of CO<sub>2</sub> during the period

of most rapid growth and activity over the summer months in northern temperate and boreal forests. However, there is no suggestion<sup>1</sup> of an increased photosynthetic draw down of CO<sub>2</sub> from the atmosphere due to elevated CO<sub>2</sub> levels. The amplitude of the fluctuations in mean monthly CO<sub>2</sub> levels has not increased over the last 5 decades (Figure 6, Moore et al. 1996). This provides evidence from a global observation perspective, which is apparently sensitive to fluctuations in forest productivity, that the effects of elevated CO<sub>2</sub> on forest productivity are not as great as previously hypothesised. Therefore, projections of CO<sub>2</sub> fertilisation effects should be treated with caution because of current limitations in our understanding of the factors controlling CO<sub>2</sub> uptake with respect to acclimation processes, climatic constraints and feedbacks from interactive processes (for review see Ainsworth and Long 2005, Hyvonen et al. 2007). These reviews provide evidence suggesting that the projected increase in forest productivity as a function of elevated CO<sub>2</sub> may not be as large as expected due to:

- a) *Physiological acclimation* such as the decrease in Rubisco activity and regeneration, stomatal density changes (Woodward 1987) and evidence of decreased N and chlorophyll content in long term FACE experiments (Ainsworth and Long 2005)
- b) *Scaling errors*. In many cases, the expected magnitude of photosynthetic enhancement does not translate into a similar increase in growth due to increased maintenance respiration as temperature increases, for example.
- c) *Co-limitation*. A lower CO<sub>2</sub> fertilisation effect may occur during non-drought years or under N limiting conditions (Norby et al. 2005, Ainsworth and Long 2004, Hyvonen et al. 2007), so the extent of any enhanced productivity would depend on the availability of other growth-limiting resources. Indeed, resources may become more limiting due to acclimation responses to elevated CO<sub>2</sub> (e.g. enhanced N limitation). In other cases, increases in stand productivity have been associated with an increase in leaf area index (LAI) under elevated CO<sub>2</sub>. However, this effect is reduced after canopy closure (Norby et al. 2005, Ainsworth and Long 2005). Plantation forestry in Ireland is characterised by high LAI and co-limitation by light and CO<sub>2</sub> is the major limiting factor under N rich conditions (Wang and Jarvis 1993, Black et al. 2006). Therefore, the effect of elevated CO<sub>2</sub> in these forest types may be lower than expected.
- d) *Poor experimental design*. Experiments using step-change increases in carbon dioxide concentration may cause unrealistic ecological responses. Attempts to understand ecological effects of increasing atmospheric CO<sub>2</sub> concentration usually involve exposing ecosystems to elevated CO<sub>2</sub> concentrations imposed with a one-time step-change increase of 200 ppm or more. An assumption underlying this approach is that exposing ecosystems to a single-step increase in CO<sub>2</sub> concentration will cause similar ecological responses, when compared to those of a gradual increase over several decades.

<sup>1</sup> The seasonal amplitude of CO<sub>2</sub> in the atmosphere in relation to the carbon cycle of northern temperate and boreal forests could be masked by seasonal changes in sea temperatures, which would act in opposition to the vegetation cycle and hence dampen these oscillations (see Moore et al. 1996).

Klironomos et al. (2005) tested this assumption on a mycorrhizal fungal community over a period of 6 years. The authors suggested that “studies may overestimate some community responses to increasing CO<sub>2</sub> because biota may be sensitive to ecosystem changes that occur as a result of abrupt increases”.



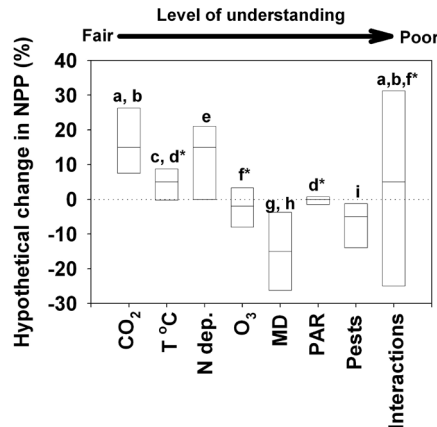
**Figure 6:** Mean monthly atmospheric CO<sub>2</sub> levels measured at the Mauna Loa observatory since 1958 (modified from Keeling et al. 1995). The right hand side panel shows the mean decadal amplitude of the CO<sub>2</sub> draw-down (i.e. decrease in normalised monthly CO<sub>2</sub>, as indicated by arrows) associated with photosynthesis in temperate and boreal forests during the northern hemisphere summers (generally from May to September).

Source of data: <http://www.cdiac.esd.ornl.gov/fip/trends/co2/maunaloa.co2>

### Interactions

The magnitude of the change in forest NPP in response to changing global environmental factors depends on forest type, geographical region, degree of co-limitation of growth resources, extent of saturation of limiting resources and experimental assumptions used in deriving the data. Therefore, there is a large degree of uncertainty when assessing the impacts of individual climate change drivers on forest productivity. Meta-analysis of published data, shown in Figure 7, shows the degree of uncertainty increases and the level of understanding decreases when interactive effects of climate change are considered, when compared to simple cause and effect studies. For example, much existing evidence from long-term and large-scale (FACE) experiments does not include interactive effects of other pollutants or climatic variables. A FACE experiment with elevated CO<sub>2</sub> and O<sub>3</sub>, suggest that the CO<sub>2</sub> fertilisation effect in *Populus tremula* L. is negated by the presence of O<sub>3</sub> at predicted future levels (King et al. 2005). This result reinforces the need to consider multiple factors in global-change ecosystem experiments because it can be misleading to simply “add” results from single-factor experiments.





**Figure 7:** Hypothetical changes in NPP of forest ecosystems in response to elevated atmospheric CO<sub>2</sub>, temperature (T °C), nitrogen deposition (N dep.), elevated atmospheric O<sub>3</sub>, MDs (MD), global dimming, or reduced photosynthetically active radiation (PAR), pests and interactions of different environmental changes. The arrow indicates a reduction in the level of understanding and certainty of the magnitude of the hypothetical changes in NPP. The box plots represent a mean, minimum and maximum change based on a meta-analysis of published literature. <sup>a</sup>Ainsworth and Long 2005, <sup>b</sup>Hyvonen et al. 2007, <sup>c</sup>Cannell 2002, <sup>d</sup>Black et al. 2006, <sup>e</sup>Aber et al. 1998, <sup>f</sup>King et al. 2005, <sup>g</sup>Chapin et al. 2002, <sup>h</sup>Reichstein et al. 2007, <sup>i</sup>Day 2002 and Black et al. 2007. The references noted with an asterisk refer to changes in gross primary productivity. These values were converted to NPP using a GPP to NPP ratio of 0.6.

### Adaptive strategies

Newly developed computer-based spatial site classification systems can be used to as a guide for in the development of robust species choice decision tools and improved silvicultural systems to minimise the negative effects of climate change to forests, forest ecosystems, as well as other services that forests provide to society.

Some major guidelines include:

- Selection of new provenances or species for warmer climates (see section on ESC). However, species replacement options should also consider indirect consequences, such as the introduction of new diseases (e.g. red band needle blight associated with many pine species). Timber quality should also be considered in this context.
- Planting policies need to take water availability into account. It has been shown that the establishment of Sitka spruce (Tene et al. 2009, Black et al. 2007, Ray et al. 2008), under current climatic conditions, is susceptible to water deficits.
- Silvicultural practices may need to be altered to adapt to future climate change threats. For example, planting density may need to be reduced to minimise root competition for water under MD conditions.
- Rotation length may need to be reduced to take higher growth rates into account.



- Windthrow risk models have been developed for Irish forestry (Ní Dhubháin 1998), based on probability of windthrow risk using a number of stand and site variables. However these models need to be linked to future climate change scenarios to account for the higher frequency of cyclones and increased wind speed on stand stability in the future.
- Adaptive management strategies, such as reducing deadwood (i.e. fuel) load in older stands or preventative management should be considered because it is likely that fire risk would increase as the climate gets warmer. However, a shift away from the historic trend of afforesting upland peats to planting of low level marginal farm land, with vegetation which is less prone to wild fires, may reduce the occurrence of fires.
- An assessment of the effects of climate change of carbon cycling and sequestration potential of our national forest estate is also required.

### **Conclusions**

Overall, understanding the potential impact of future climate change is key to developing adaptation and mitigation strategies. Despite much research over the past two decades, there is still a poor understanding of the potential impacts of climate change on forest growth and productivity. Whilst the ESC system for Ireland does provide recommendations on climate change adaptation, more work is required to include multi-factorial analysis and a move away from Delphi-based models to empirical and process-based approaches using ESC factors as the spatial framework for this work. The inclusion of more process-based drivers, such as elevated CO<sub>2</sub> or N deposition levels in these models, is also required, but only if interactive relationships are well defined and modelling over-simplifications are avoided.

Extreme climatic events such as storms and severe drought offer the greatest threat to forest sustainability in the future. There is a need for the climate change research community to move away from assessing long-term means for the characterisation of the statistical probabilities of extreme climatic events, and their influences on forest ecosystem function. Furthermore, risk assessments and management plans are required to provide guidelines on how these events should be managed effectively to reduce the potential negative impacts on forest productivity.

Finally, an integrated mitigation, impact and adaptation management policy is required to take advantage of opportunities arising from, and reduce risks associated with, global climate change.

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