The potential impact of climate change on Irish forestry[1]

Patrick M. Purser[a], Kenneth A. Byrne[b],
Edward P. Farrell[c] and John Sweeney[d]

Abstract
The Irish climate is projected to change over the next century. The long-term nature of forestry means that planning is essential if foresters are to practice sustainable forest management during and beyond this period of change. International models projecting the potential impact of climate change on forestry have improved significantly over the last decade, but are still a long way short of accurately modelling the complexities of forest ecosystems. Although it is generally accepted that rising temperatures and CO_2 concentrations will promote increased growth rates, it is uncertain to what extent this growth will be limited by water and nutrient availability, greater difficulties in forest establishment and increased risk from pests, diseases and forest fire. Irish forests are predominantly commercial plantations established on sites deemed either unsuitable or marginal for agriculture. They may therefore respond differently to climate change than native or semi-natural forests. The current programme for the expansion of Irish forestry may require adjustment to account for the prospect of climate change. Research programmes should also be initiated to investigate how climate change may affect the productive and ecological functions of Irish forests.

Introduction
The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) has reported a global average surface temperature increase of about 0.6°C since the start of the 20th century. The report also claims that it is very likely that the 1990s was the warmest decade and 1998 the warmest year in the instrumental record since 1861. The IPCC has projected that the scale and rate of climate change for the 21st century will exceed the changes observed during the 20th century. Confidence in the ability of models to predict future climate has increased. There is broad scientific consensus that anthropogenic influences will continue to affect atmospheric composition and climate throughout the 21st century and that these changes will persist for many centuries.

Sweeney and Fealy (2001) used high-resolution statistical downscaling techniques in forecasting future climate scenarios for Ireland. Milder winters and warmer summers are

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[a] Purser Tarleton Russell Ltd., Forest Industry Consultancy, Management & Research (ptr@eircom.net).

[b] Centre for Hydrology, Micrometeorology & Climate Change, Department of Civil and Environmental Engineering, University College Cork, Ireland.

[c] Forest Ecosystem Research Group, Department of Environmental Resource Management, University College Dublin, Belfield, Dublin 4, Ireland (ted.farrell@ucd.ie).

[d] Department of Geography, National University of Ireland, Maynooth, Co Kildare, Ireland (john.sweeney@may.ie).

forecasted with general temperature increases of 2 to 3°C expected by mid-century (Figure 1). With the exception of low lying areas in the north-east, east and south-east, winter precipitation is expected to increase by up to 25 mm per winter month. Summer precipitation is expected to decrease on 1961-1990 levels along a north-west to south-east gradient (Figure 2), with little change in the north-west but potential drought problems in the east and south-east. However, there is less reliance on forecast data for precipitation. In the projections of future climate change made by the IPCC (IPCC 2001), increased frequency of strong wind and storm events are forecasted for the North-East Atlantic and Western Europe. The (Irish) National Climate Change Strategy (Department of the Environment and Local Government 2000) projects an increase of approximately 12.5% of CO_2 equivalent greenhouse gas emissions over a 10-year period in Ireland.

The growth of trees and forests is highly influenced by climate. Indigenous forest ecosystems evolve in response to changing biogeochemical conditions. Because they are adapted to local climates, changed conditions are likely to impact on their future growth and wood output (Joyce and Nungesser 2000). In many regions where native species are used in the establishment of plantations, great care is taken in the selection of seed source, in order to match it to local climatic conditions. In countries such as Ireland, where exotic species are widely used, foresters pay close attention to site suitability, focusing on soil type and the prevailing micro-climate, both of which are heavily influenced by overriding climatic conditions. Their decisions are also influenced by potential markets into which they hope to sell products.

Because of the longevity of trees and forests, questions have been asked as to whether there will be enough evolutionary response time for forest ecosystems to adapt to severe climatic change (Andrasko 1990). In planning for the future, foresters should select species that will perform optimally over a full rotation. Currently, this embraces a period of 40 to 50 years, but it is doubtful if this is an ecological optimum, and the possibility that rotations may be increased in the future must also be considered. It is therefore essential for foresters to know what the likely changes in climate will be and what potential impact these changes will have on trees and forests.

Forest managers are increasingly responsible for the sustainable management of the forest ecosystem as a whole (Farrell et al. 2000). This is a considerably more complex task than fulfilling a single objective of sustainable wood production. Similarly, modelling forest ecosystems as a whole is far more complex than modelling wood production. Most authors dealing with the subject of climate change and its potential effects on forestry emphasise the limitations associated with their research. However, there are definite trends in the body of research carried out to date and there is broad agreement on many of the conclusions drawn so far.

Modelling forest growth

Forest planning, whether it is based on silviculture or economics or whether it is carried out on a local, regional or national basis, is dependent on being able to forecast or model forest growth at stand level. Obviously, from a forest planning point of view, it would be useful to accurately model future changes to the forest ecosystem as a result of changing environmental and specifically climatic conditions. Currently in Ireland, forest growth is modelled in one of two ways, which are best described by García (1988) as static or dynamic.

Static growth models attempt to predict changes over time in key production parameters, such as mean volume and mean diameter at breast height, based on reference to similar stands closely studied over extended periods. Historically in Ireland such tables, in the form of the Forestry Commission Management Tables (Johnston and Bradley 1963), have been used by foresters. These models are dependent on the maintenance of a *status quo* with regard to the macro environment in which the forests grow and the management regime applied. In the context of climate change they may therefore not be reliable in forecasting future productivity of Irish forests.

For many reasons, including those outlined, the Irish forestry sector has recently developed dynamic growth models for the important commercial species. Dynamic growth models account for changing management practice and environmental conditions over a forest rotation. Dynamic models currently used in Ireland do not use direct measurements of changes in the environment itself. Nor do they measure or directly take account of changes to the forest ecosystem (e.g. available soil nitrogen, available moisture, soil pH, etc.), which greatly influence the productive potential of the timber crop. However, the effect of a changing environment is reflected in measurements taken of the wood production variables over time. Unlike static models, dynamic models allow for current measurements of such variables to form the baseline from which future growth is projected; there is no requirement to fit data to static tabulated values. In this way the rate and effect of environmental change is implicitly taken into account. Hence, these models are a step in the right direction in recognising the need for a dynamic approach to growth modelling.

Unfortunately, none of the growth models currently used by Irish foresters attempt to model aspects of the forest ecosystem other than critical forest production variables such as height, volume and diameter. There are however many uncertainties associated with the modelling of a whole ecosystem and its vulnerability to climate change. Work is proceeding on models based on ecosystem processes (termed process-based models) in several countries, although they are still in the early stage of development. An initial attempt has been made in the application of a process-based model to forest growth in Ireland (Goodale et al. 1998), but no developmental work is currently being conducted here.

Potential primary effects of climate change

Potential primary effects are those changes in variables such as carbon dioxide (CO_2) enrichment, higher temperatures, stronger winds or lower rainfall, that may have an effect on tree or forest growth.

Increased CO_2 level

There is well-documented evidence of rising atmospheric concentrations of greenhouse gases, notably CO_2 (the dominant anthropogenic greenhouse gas) over the last century (IPCC 2001). On a global scale, the IPCC reports an average rate of increase of atmospheric CO_2 concentrations of 0.4% per year (IPCC 2001); these are projected to double over the next 100 years. The National Climate Change Strategy (Department of the Environment and Local Government 2000) projects a 12.5% increase in greenhouse gas emissions over a 10-year period from 2000 to 2010.

As CO_2 is the carbon source for photosynthesis, plant growth is highly influenced by CO_2 levels in the atmosphere. Rising CO_2 concentrations, in addition to influencing other climatic factors, are therefore likely to have a direct effect on tree growth. CO_2 is limiting to the rate of photosynthesis in C_3 species[2] (Breymeyer et al. 1996). This is thought to be particularly the case in a mature forest environment, where tree canopies are tightly bunched and air circulation is restricted (Daniel et al. 1979). Increased CO_2 concentrations would therefore be expected to stimulate tree growth, through what has become known as CO_2 fertilisation, and this has been proven in experiments such as those on oak (Broadmeadow 2000) and across a range of woody plants (Ceulemans and Mousseau 1994). In a review of current knowledge of tree and forest functioning in an enriched CO_2 atmosphere, Saxe et al. (1998) report that a number of recent studies indicate the potential for a persistent enhancement of tree growth over several years.

However, Joyce and Nungesser (2000) and Saxe et al. (1998) both point out that most experimentation has been carried out using seedlings or juvenile trees. It may be too early therefore to say whether increased growth due to CO_2 fertilisation is sustained over a full rotation or in a mature forest environment. Indeed, the capacity of ecosystems for additional carbon uptake may be limited by availability of nutrients and other biophysical factors (IPCC 2001). Difficulties arise in some scenarios in attributing growth responses to single parameters. This is a point underlined by Andrasko (1990) who claims that, because very little work has been done in situ on forest or other natural communities over extended time frames, the net effect of CO_2 enrichment, combined with forest decline from climate change and air pollution, remains uncertain. Despite this, recent studies by Spiecker et al. (1996) found that growth rates in European forests have increased and this has been partly attributed to climate change and nitrogen deposition.

Most research conducted on the impact of elevated CO_2 on water-use efficiency concludes that stomatal conductance from leaves will be reduced and that this will lead to diminished transpiration rates, thus leading to greater water use efficiency (Saxe et al. 1998). The stomata of conifers tend to respond less to elevated atmospheric CO_2 than those of broadleaves (Jarvis 1989, cited in Breymeyer et al. 1996). Despite this, Townsend (1993) reported a doubling of water use efficiency in Sitka spruce (*Picea sitchensis*) seedlings when CO_2 concentrations were doubled. This may be offset by increased leaf area associated with CO_2 fertilisation (Saxe et al. 1998).

Increased temperature

The IPCC report in their Third Assessment Report that global average surface temperature has increased by 0.6 ± 0.2°C since the late 19th century (IPCC 2001). The

[2] C_3 species are those in which the first product of photosynthetic CO_2 assimilation is a 3-carbon compound, phosphoglycerate (PGA) (Breymeyer et al. 1996).

report further states that it is 'likely that the rate and duration of the warming of the 20th century is larger than any other time during the last 1,000 years. The 1990s are likely to have been the warmest decade of the millennium in the Northern Hemisphere, and 1998 is likely to have been the warmest year.' In addition, it is expected that increased concentrations of CO_2 and other greenhouse gases may lead to further significant temperature rises in the medium term (Houghton et al. 1994). In an examination of future climate scenarios for Ireland using high-resolution statistical downscaling techniques, Sweeney and Fealy (2001) suggest mean temperature increases of 2-3°C by the middle of the 21st century in both summer and winter in Ireland. Figure 1 illustrates these projections.

Apart from influencing other climatic factors such as rainfall, humidity and wind speed (Broadmeadow 2000), a warmer climate will have a direct impact on tree and forest growth. Virtually all chemical and biological processes in plants and soils speed up with warmer temperatures, and photosynthesis and respiration in trees are no exception (Saxe et al. 2001). The same authors conclude from a comprehensive literature review that, depending on N mineralization and availability, increased temperatures will lead to an increase in net primary production of forests in temperate and boreal (northern) regions, including Ireland.

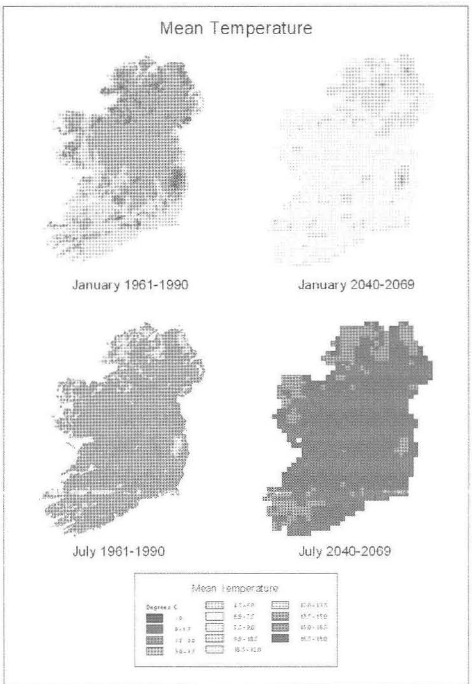

Figure 1. *Mean temperatures 1961-90 (baseline) and 2040-69 (downscaled) (Sweeney and Fealy 2001).*

The potential site productivity of Irish forests is assessed using an index called yield class, which is an estimate of the maximum mean annual increment of merchantable stem volume per hectare per annum (Edwards and Christie 1981). Yield class was found by Worrell (1987) to be closely correlated with both site temperature (estimated mean annual accumulated temperature above 5.6°C) and windiness. Analysis based on measurements from 142 sample plots found that these two climatic variables accounted for 78% of the variation in yield class. A multiple regression model developed by Worrell (op. cit.) would clearly indicate a rise in yield class with rising temperature, all other variables being equal.

Bud phenology (the periodicity of leafing, flowering and fruiting) is closely associated with temperature (Saxe et al. 1998). It is to be expected that, on lowland sites, an increase in average winter temperatures will result in later bud flushing of certain species including Sitka spruce, Norway spruce (*Picea abies*), ash (*Fraxinus excelsior*), beech (*Fagus sylvatica*) and sessile oak (*Quercus petraea*). This is because they require a certain number of chilling hours before bud flushing can take place in the spring (Cannell and Smith 1983, Thompson 1998). Later bud flushing in these species will result in a lower risk of damage from late spring frosts but may also mean a shorter growing season, potentially affecting production. However, Cannell and Smith (1983) argue that this effect would be lesser on upland sites where there would be more chilling hours through the winter than on lowland sites. In such situations, where sufficient chilling hours have occurred, earlier bud break may be expected and, hence, a longer growing season, as long as tender shoots are not damaged by late frost. For most species, the dominant trigger for shoot and bud growth cessation in autumn is night-length and not temperature (Saxe et al. 2001). Although shoot and bud growth may cease, it is possible that girth and volume growth will continue in warmer autumns.

Late spring frosts have caused considerable damage to early season growth of Irish forest crops, in particular Sitka spruce and ash planted on flat sites with low levels of air movement. Given that both winter and summer temperatures are expected to increase (Sweeney and Fealy 2001), it is reasonable to assume that frosts will be less frequent, particularly early autumn and late spring frosts. It is therefore likely that, because of their elevated locations, most Irish forest crops will commence growth earlier in the spring than at present. Also, species such as southern beech (*Nothofagus* spp.) and Monterey pine (*Pinus radiata*), previously thought of as unsuitable because of, among other factors, potential frost damage, may be reconsidered.

Increased storm frequency

In the projections of future climate change made by the IPCC (2001), increased frequency of strong wind and storm events are forecasted for the North-East Atlantic and Western Europe. The location of Irish forests, generally on exposed, windy sites with poor drainage renders them inherently vulnerable to wind damage. Irish forestry has recently suffered large losses to such events. In 1997, 1998 and 1999 Coillte, the Irish Forestry Board, reported about 0.5, 0.85 and 1.6 million m^3 respectively of roundwood being windthrown (Coillte 1997, 1998 and 1999). Britain suffers such events to a similar extent; it has been estimated by Quine et al. (1995) that, not counting extreme storm events, windthrow accounts for approximately 15% of the annual output of roundwood of Britain's forests. Up to 30% of the annual harvest in Ireland can comprise windthrown material (Forest Service 2000).

Ní Dhubháin (1998) suggests that, for existing forests planted on relatively exposed, ploughed sites and now reaching critical heights in relation to windthrow, the level of damage may increase. However, the same author suggests that younger forests, established on lower altitude, freer draining sites with improved cultivation and thinning techniques, should be more wind firm than those currently at risk.

Decreased rainfall

Figure 2 presents baseline (1961-1990) and a downscaled forecast (2040-2069) of summer and winter precipitation for Ireland (Sweeney and Fealy 2001). Potentially wetter winters for many parts of the west and midlands, and drier winters for the east and southeast are predicted. It is in the summer, however, that the most significant changes are forecasted with considerably less rainfall in all areas, with the exception of the northwest.

Soil moisture deficits are rarely encountered in plantation forestry in Ireland (Keane 1986). In general terms, reduced water availability, resulting from increases in potential evapo-transpiration and reductions in summer rainfall, may lead to loss of vigour on

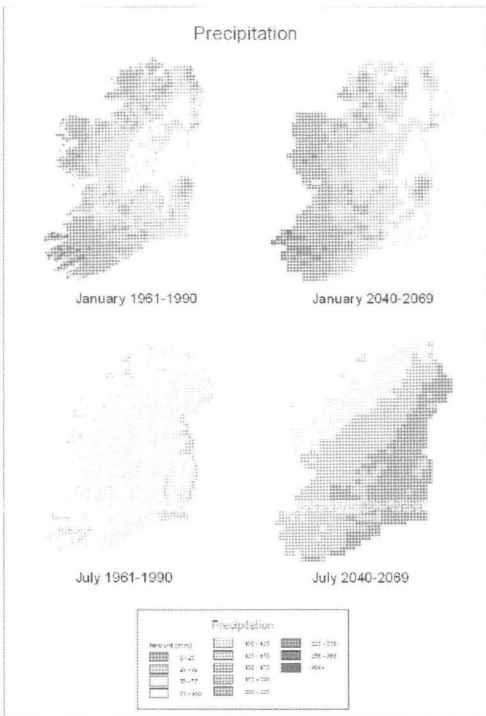

Figure 2. *Precipitation 1961-90 (baseline) and 2040-69 (downscaled) (Sweeney and Fealy 2001).*

some sites, particularly drier ones. However, this is very dependent on site type and species. A large proportion of commercial forests in Ireland are established on land considered marginal for agricultural use. Almost by definition, these sites are associated with high water holding capacities.

Periods of summer drought cause particular difficulties in the establishment of forests when roots have not yet fully developed and adjusted to their new environment. This has implications for current forest nursery practice and renewed research into the use of containerised stock or other methods of reducing planting shock may be worthwhile.

Potential secondary effects

Potential secondary effects are those indirect effects that may impact on tree or forest growth as a result of their primary effect on the forest ecosystem. A number of potential secondary effects are discussed in the context of the climate change projections and those potential primary effects discussed above.

Increased nutrient mineralisation

A key component of vegetation functioning is the maintenance of a nutritional balance. Given this, it is likely that responses to increased CO_2 levels will be limited by nutrient availability (Rastetter et al. 1992, Comins and McMurtrie 1993). Nonetheless, the responses of vegetation are also linked to the ability of vegetation to acclimatise to increased CO_2 concentration by making greater efforts to acquire limiting soil nutrients or by decreasing nutrient concentrations in biomass.

Thornley and Cannell (1996) suggest that, with regard to tree and forest growth, the crucial processes in climate change are those which affect the nitrogen (N) cycle. Forest productivity is strongly affected by N availability, since it is required in greater amounts than any other mineral nutrient (Saxe et al. 2001). In Ireland, N availability is most frequently affected by lack of drainage or the presence of competing vegetation.

Results from field and laboratory experiments show that elevated temperature will increase rates of organic matter decomposition and therefore nutrient availability (Saxe et al. 2001). However, overall soil warming effects on nutrient mineralisation may be no greater than the effects of continued nitrogen deposition, changes in vegetation, and natural and anthropogenic disturbance.

Forest pests and diseases

Elevated CO_2 is expected to alter foliar C levels, mineral nutrients and secondary metabolites. This is expected to have the effect of modifying insect and tree interactions (Saxe et al. 1998). In general terms, although each species has its own optimal temperature range, insect populations increase with increasing temperature. Insect populations will also exploit situations where trees are stressed because of, for example, drought, storm damage or flooding. There are a number of insects that either currently, or may potentially inflict damage on Irish forests because of climate change. Some of the more important ones are described below.

Green spruce aphid (*Elatobium abietinum*)
The green spruce aphid is present in Ireland and defoliates Sitka spruce, affecting all but the current year's growth. It rarely kills trees but can reduce productivity significantly, as has been experienced in a number of locations in Ireland over the last decade. Temperatures of below -7°C are required to kill off the aphid. Milder winters, particularly in drier areas, could result in large population increases and serious loss of growth on a regular basis.

Large pine weevil (*Hylobius abietis*)
The large pine weevil breeds in stumps and feeds on the vascular tissue of young trees during the establishment phase. It is one of the more serious insect pests in Irish forests, particularly on reforestation sites where breeding sites abound. A rise in average temperatures could result in greater pine weevil activity, particularly in combination with the effect of recent legislation banning the use of the pesticide lindane.

Great spruce bark beetle (*Dendroctonus micans*)
This species does not occur in Ireland but causes considerable economic loss in Norway spruce forests across Europe. Ireland, with large areas of spruce monoculture may well become vulnerable to this species, particularly in areas such as the east and southeast, where drought-induced stress may become significant and predispose the trees to attack.

The potential effects of climate change on a number of diseases that currently or could potentially afflict Irish forests are outlined below.

Fomes (*Heterobasidion annosum*)
Fomes, a root and butt rot, is currently the most economically damaging disease affecting Irish forestry. It spreads in a number of ways, such as through root contact and mycelial growth, but most importantly through the infection of freshly cut stumps by spores. The optimum temperature for its growth is 22.5°C (Rishbeth 1951). Fructifications are relatively resistant to both drought and moderate frost. This suggests that fomes may become more of a threat in a warmer and drier climate.

Phytophthora disease of alder
This fungus invades the stem and roots of alder and spreads to the connecting tissue of the bark causing die-back and death. It has only recently been identified as present in Ireland; it is possible that its recent expansion is an indication of environmental change.

Honey fungus (*Armillaria mellea*)
Honey fungus is one of the most widespread of all root and butt rot disease fungi. Its mycelia and rhizomorphs grow optimally at between 20 and 25°C, while fruit body formation is optimal at 25°C. Drought conditions have often been considered to render trees more liable to infection (Phillips and Burdekin 1982). It would therefore seem reasonable to suggest that climate change as forecasted will provide more favourable conditions for its spread.

Injurious mammals

Broadmeadow (2000) suggests that both deer and grey squirrel populations may respond positively to warmer winters in Britain. The population and range of both is increasing in Ireland. Environmental change resulting from higher temperatures and other factors could result in them posing an even more serious threat to economic forestry.

Forest fire

Forest fire in Ireland is relatively infrequent compared with other countries. About 450 ha are lost each year, mainly in the period from February to September, with the vast majority of outbreaks occurring in March, April and May. Rainfall, humidity, wind and temperature influence the flammability of competing vegetation, the tree crop and, on peat sites, the soil itself.

Warmer and drier conditions, particularly in the spring and early summer, can only serve to increase the risk of fire in Irish forestry. However, Keane (1993) points out, that as most forest fires in Ireland start outside the forest, it is more important to assess how climate change will affect other vegetation types before predicting whether forests themselves will be impacted.

Interaction of climate factors

In the previous sections the potential impact of changes in individual climate factors has been reviewed. However, it is clearly the interaction of different factors and their potential combined effects on forest growth that is of real interest and concern to forest owners and managers. Breymeyer et al. (1996) warn that failure to take account of the interaction of climate factors can lead to errors in the prediction of their overall potential impact.

There are a number of models which attempt to project the potential impact of climate change on forest ecosystems. As discussed earlier, this is a highly complex task, and results are generally as much a function of model design as they are of model inputs. Despite this, huge progress has been made in modelling the potential impact of climate change on forests.

Thornley and Cannell's (1996) work on temperate forest responses to CO_2, temperature and nitrogen changes is perhaps the most interesting from an Irish forestry perspective. This work involved the simulation of responses in a managed conifer plantation in upland Britain, a scenario typical of Irish forestry. It found that rising temperature, along with rising CO_2, may either increase or decrease forest productivity on such sites, depending on the rate of supply of N and changes in water stress. The particular model used analysed the potential impacts based on projected increases from 350 to 550 $\mu mol\ mol^{-1}$ CO_2 and 7.5 to 9.5°C (mean annual temperature)[3]. Goodale et al. (1998) drew similar conclusions, stating, 'Site specific conditions and management practices result in a range of forest productivity that is much greater than any likely to be induced by climate change or CO_2 enrichment'. Further evidence to suggest that soil fertility limits carbon sequestration by forest ecosystems in a CO_2 enriched atmosphere

[3] The ITE Edinburgh Forest Model (Thornley 1991).

is provided by Oren et al. (2001). They point out that forests are usually relegated to sites of moderate fertility where tree growth is often limited by nutrient supply, in particular nitrogen.

Joyce and Nungesser (2000) suggest that forest productivity may increase under elevated CO_2, but that the local conditions of both moisture stress and nutrient availability will strongly temper any response. Thornley and Cannell (1996) suggest that, because water use efficiency is expected to improve in an elevated CO_2 environment, temperate forests may be protected from the predicted water stress resulting from increased temperatures.

Many of Ireland's commercial forests are located on poor quality land drained specifically for the purpose of afforestation. Without the addition of P and/or N fertiliser, many of these forests might never have successfully established and grown. On such sites it is therefore possible that limitations in the supply of N and P will temper any potential for increased biomass production due to CO_2 fertilization or increased rates of photosynthesis. Further application of N and/or P fertiliser is possible but this has economic implications. However, much of the more recent planting has been on better sites where nutrient availability should not be limiting. These forests, along with older forests established on good sites, may have increased productivity in a CO_2 enriched and warmer climate, as long as water availability does not become limiting during the growing season.

Breymeyer et al. (1996), while acknowledging that nutrient limitation may negate the CO_2 fertilisation effect, maintain that C_3 plants will actually behave more efficiently in their use of nutrients in an elevated CO_2 environment. This agrees with the conclusions of Thornley and Cannell (1996) who state that, as a result of increased CO_2 levels, N acquisition (where available) and N-use efficiency will both increase, giving rise to increased ecosystem productivity and carbon storage. Cannell et al. (1998) tested this theory by using both the ITE Edinburgh Forest Model and the Hybrid Model (Friend et al. 1997). Both of these models associated historical increases in Net Primary Productivity (NPP) and yield class with increased CO_2 levels, temperature and N deposition. Significantly, however, they also both predict that the current rate of increase in productivity will continue until the end of the 21st century, with an increase in average yield class of about 5 m^3 ha^{-1} $year^{-1}$ and an increase in NPP of between 24 and 34% between 1990 and 2050.

Although increased CO_2 levels in the atmosphere are expected to increase water-use efficiency within trees, it is not necessarily correct to conclude that this will result in greater drought tolerance (Tschaplinski et al. 1995, quoted in Saxe et al. 1998). The increased water-use efficiency may be offset by increased leaf production (Broadmeadow 2000) and increased leaf area associated with increased N availability (Thornley and Cannell 1996), both resulting from elevated CO_2.

Forecasted increases in wind speed and the frequency of severe gales suggest that Irish forestry will continue to suffer from wind damage, and to a greater extent than in the past. However, as pointed out by Ní Dhubháin (1998), the increased afforestation of lower lying sheltered farm sites may mean that a higher percentage of Irish forests will be less vulnerable in the future. Shallow rooting and poor anchoring of trees as a result of impeded drainage and root alignment along plough ribbons are often the cause of windthrow in Irish forest crops. In a decreased rainfall scenario which may result in a lowering of the water table on some sites, it is conceivable that windthrow risk will be reduced. However, wind damage is not limited to windthrow. Wind snap can result in greater economic damage than windthrow as it renders the stem unusable for structural purposes because of splitting and shattering, whereas sawlog is commonly salvaged from wind thrown crops. The risk of wind snap would appear to be greater in the future, assuming improved root anchorage and increased leaf area and thus canopy resistance to wind.

It is generally accepted that trees and forests exhibiting vigorous growth are less susceptible and quicker to recover from damage by pests and diseases. It is therefore difficult to predict what might happen to Irish forests in a situation where growth is stimulated by CO_2 fertilisation and increased temperature, while at the sane time climatic conditions favour a dramatic rise in the populations of damaging pests and diseases.

Tree species have different optimal conditions for flowering and the production of seed. Generally these are weather and climate related. For both broadleaves conifers, conditions at the time of pollination determine the number of normally developed seeds that are formed. Dry, sunny and windy weather at this time will result in greater numbers of full seeds than dull, wet and still weather (Gordon 1992).

Forest management and policy implications of climate change

A mild and moist maritime climate is the single overriding factor that gives Ireland its competitive advantage in forest productivity over other European countries. For this reason, any implications of climate change are of great importance to the Irish forestry sector. This section discusses some potential implications for foresters and policy makers.

Species and provenance selection

The Irish forest industry is heavily reliant on exotic coniferous species. These have been selected by foresters as suitable for growth in the prevailing Irish climate and on existing Irish site types. Coniferous crops are generally grown over rotations of between 35 and 60 years. Unlike agriculture, there is no opportunity, without undertaking a premature felling, to replace species with one that is more suitable until the prescribed rotation is complete. Therefore, foresters planting forests now must make species selection decisions in the context of potential climate change. A decision taken today means a commitment of 35 years or more to a particular species and provenance. From the point of view of matching species to climate and site, it is reasonable to expect that a gradual climate change, although affecting growth in ways discussed earlier, can probably be accommodated, through suitable species and/or provenance selection, without it resulting in serious losses. However, a climate 'flip', such as suggested by Fleming (1998), may have more serious consequences.

Sitka spruce has a natural distribution that follows the wet coastal region of north-west America. It has a high moisture requirement; MacDonald (1952) reports that, in Britain, it is rarely seen at its best in areas of less than 1000 mm $year^{-1}$. This suggests that, apart from in mountainous areas, it may become less favourable a species along the east coast and in the south-east of Ireland, particularly if defoliating green spruce aphid populations take advantage of crops exhibiting water stress. However, apart from the frost tenderness of new growth, the growth of Sitka spruce appears to be relatively independent of temperature variations (MacDonald op. cit.) There is therefore no apparent reason, apart from in the areas discussed above, to suggest that this species will not continue to be the mainstay of commercial forestry in Ireland.

Current Irish forest policy is to diversify the range of coniferous species planted. The main alternatives to Sitka spruce are Norway spruce, Douglas fir and Japanese larch. Norway spruce is a species associated with a continental climate and is thus more tolerant than Sitka spruce of drier summers on drier sites. Douglas fir has an extensive natural range from coastal British Columbia in Canada to coastal California, inland as far as Colorado, with pockets extending into Arizona and Mexico. Coastal provenances from Washington are currently used in Irish forestry but there is evidently good potential for other provenances of this species to be used if climate change occurs as forecasted. However, Douglas fir is intolerant of flooding and this may limit its use if wetter winters result in flooded forest sites. In contrast, Japanese larch has a very small natural range and a consequently limited provenance range. It grows extremely vigorously in its early years, often resulting in poor stem form. Even more vigorous growth caused by warmer conditions and CO_2 fertilisation may exacerbate this problem and reduce log value. Western red cedar is a valuable timber species but is little used in Irish forestry, with only 40 ha of new forest being established each year (Forest Service 2001). It thrives under wet and mild conditions and on heavy soils with a high water-holding capacity. The inland part of its natural range is characterised by relatively dry summers. This species should be investigated further as one with serious potential for use in a climate change scenario. Keane (1993) suggests some other species that might be considered for future use, such as eucalyptus, southern beech (*Nothofagus* spp) and Monterey pine.

Thompson (1998) points out that genetic traits associated with adaptability to local conditions exist not just at species level, but also at provenance, family and individual level. Saxe et al. (1998), in a review of current knowledge on tree and forest functioning in an enriched CO_2 atmosphere, reference various studies that have shown different responses to CO_2 enrichment between species, hybrids of the same species and even between different families within species. Bazzaz et al. (1995) suggest that future CO_2 levels would lead to increased intensity of natural selection. There is considerable genetic variation within coniferous species used in Ireland, and seed sources, although of a specific provenance, are essentially wild and unlike agricultural crops, with little selection for optimisation of traits for Irish climatic, site and market conditions. This is supported by COFORD (1994) which indicates that although there are tree breeding programmes in place for most species, there is little genetically improved seed used in Irish forestry. It follows that, in a climate change scenario, there is good potential for continued use of existing species, with increased selection for traits that will accommodate the predicted environmental changes.

Forest site location

In the past, forestry has generally been located on land that was not economically viable in agricultural use. This is still the case, although to a lesser extent, particularly with the availability of grants and premiums for afforestation. The potential impact of climate change on Irish agriculture is therefore of critical importance to Irish forestry, as it may have a bearing on where and how afforestation will occur in the future. However, it is likely that it will continue mostly on wet land that is marginal for agriculture. There is nothing to suggest that these sites will ever become unsuitable for forestry. However, the importance of matching species to site has never been more important and it should no longer be assumed that the site will not alter significantly during the course of the rotation.

Forest establishment and management

Current forest establishment practice in Ireland involves cultivation and drainage, and protection using fencing and vegetation control. Other operations such as fertilising and the creation and maintenance of firebreaks also take place to a limited extent. Tree planting is carried out in the dormant winter season, although the use of cold-stored plants means that the planting season can be extended into late spring. In a potentially milder climate, the timing of a number of these operations may become more critical. On some sites, the use of machinery in cultivation and drainage is currently restricted by wet winter conditions. In a scenario where winters become generally wetter, it may become necessary to complete all drainage and cultivation work in the summer or autumn prior to planting rather than in conjunction with planting, as is currently practised. Competing vegetation will probably benefit from an extended growing season and increased growth rates; its control may therefore require earlier and more frequent interventions. Similarly, depending on species, the dormancy period may be affected, with a resulting effect on optimal planting dates. Post-planting care may also become more critical, particularly in areas experiencing warmer, drier summers which are often the cause of tree mortality in newly planted areas. The use of container-grown transplants, used in some countries to extend the growing season and reduce planting shock, may therefore become more favoured. Fire management is likely to become increasingly relevant with warmer and drier summers; extra resources may be required in order to militate against the risk of economic loss due to fire.

Harvesting and transport

The principal forms of forest harvesting undertaken in Irish forests are thinning and clearfelling. These are carried out using heavy machinery which may, as part of a harvesting plan, be seasonally restricted as a result of wet weather or waterlogged sites. For this reason, certain sites are considered as ‘summer sites’, as they are best harvested during the drier summer months. If Ireland is to experience wetter winters and drier summers as a result of climate change, there may be increased pressure to harvest on a greater number of sites in summer. This may cause logistic problems for the harvesting sector to supply sufficient quantities of roundwood during the winter.

Silvicultural systems

Conventional practice within the Irish forest industry is to operate a silvicultural system using even-aged crops of generally not more than two species grown over an optimal financial rotation, followed by clearfelling and reforestation. There are many alternative silvicultural systems to clearfelling, and the prospect of climate change provides an appropriate opportunity to consider their relative merits vis-à-vis their potential ability to cope with a changing climate.

The clearfell system offers the forester the opportunity to begin with a new species and management regime that match the prevailing site and climatic conditions. Alternative systems do not afford this opportunity to the same extent. However, the bare establishment site is a relatively harsh environment for young trees, exposed to wind, drought, attack from pests and vigorous competing vegetation. Group and continuous cover silvicultural systems offer the newly planted or naturally regenerated tree a more protected environment in which to establish. These alternative silvicultural systems also appear to be less susceptible to wind damage, leaving fewer exposed edges than clearfelling and providing a diverse stand height structure that, in addition to providing mutual crown support, effectively filters wind rather than behaving as a resistive barrier. From a purely economic viewpoint, the economies of scale associated with clearfelling cannot be matched by alternative silvicultural systems. However, it is still perhaps too soon to economically assess the sustainability of production from clearfelling and alternative systems.

Forest health and protection

Predicted downscaled climate change scenarios for Ireland (Sweeney and Fealy 2001) show warmer and drier summers over the period 2040-2069, particularly in the southeast and east of the country. Forests in these areas are likely to suffer from increased frequency and severity of insect and disease damage as a result of drought induced stress. These warmer, drier conditions will also make Irish forests more vulnerable to the introduction of pests such as the great spruce bark beetle. Current policies on preventing entry will require regular review. Most timber shipped to Ireland from Europe arrives at ports in the east and southeast, which adds to the risk of pest introduction.

Measures currently in place to limit the spread of fomes include a legal requirement to treat all freshly cut stumps with a urea solution which renders them inhospitable to colonisation. It is unlikely that any further measures would be cost-effective in controlling the spread of this or other diseases.

Forecasted climate change scenarios would suggest a more favourable habitat for already damaging mammals such as deer and grey squirrel. Regional management plans will be necessary for the control of these species, as they cannot be effectively managed on an individual site basis.

Carbon sequestration

The ability of forests to sequester atmospheric CO_2 is well documented. The ability of Irish forests to function as carbon sinks in a changed climate remains uncertain. While the combined effects of stimulated photosynthesis and reduced respiration result in increased rates of carbon sequestration, there is evidence that soil warming may increase C losses from soil by accelerating microbial respiration and dissolved organic carbon leaching (Mac Donald et al. 1999). In a study of the impacts of terrestrial ecosystem warming in tundra, grassland and forest, Rustad et al. (2001) found that soil warming increased soil respiration, nitrogen mineralisation and plant productivity. In contrast to these findings, Liski et al. (1999) found that the amount of carbon in Finnish soils of both high and low productivity forest types actually increased with temperature. Given the scientific uncertainty which exists, it is clear that in order to understand the possible effects of climate change on the carbon cycle in Irish forests, studies of the importance of specific factors such as moisture, temperature, soil type, land use history, etc. at different spatial and temporal scales will be required. Any future changes in the carbon balance of our forests will have implications for national strategies to reduce greenhouse gas emissions.

The use of woody biomass as a renewable energy resource may also become an important tool in the Government's Climate Change Strategy. The use of woody biomass is already an important component of the renewable energy sectors of other European countries. It is likely that the Irish forestry sector will be charged with the responsibility of creating and managing such a resource in the future.

Research and development

It is evident that climate change as forecasted both internationally by the IPCC and nationally through research such as that of Sweeney and Fealy (2001) will impact on Irish forestry.

Research areas identified by COFORD (1994) as being of strategic importance such as forest genetics and tree breeding, forest health and vitality, silviculture, nursery research and development, are all potentially affected by climate change. It is important that all such research acknowledges and accounts for potential changes in the Irish climate. A number of specific areas requiring further research have been identified and are summarised as follows:

- Recent advances have been made with the introduction of dynamic yield models. These should be regarded as a stepping stone to more holistic forest ecosystem or process-based models. Through simulating ecosystem processes, these should ultimately predict the development of the ecosystem over time and in response to changing environmental conditions. The output of models will encompass not only forest production, but also the wider issue of sustainability of the forest ecosystem.
- Long-term research is required into the potential impact of climate change on organic matter turnover and N mineralisation.
- There is a need to continue to assess different provenances and species in long-term research trials. It is recommended that particular attention be paid to alternative provenances of Douglas fir and western red cedar.
- The national tree breeding programme should be reassessed in the light of current knowledge on potential climate change and with a view to the selection of traits that will accommodate and capitalise on these changes.
- The potential for the production and transplanting of containerised nursery stock

should be reassessed.

- Climate change scenarios should be included in the Forest Inventory and Planning System operated by the Forest Service in the Department Agriculture and Food.

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