General paper

Climate change – the evidence so far and predictions for tree growth

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Summary
Atmospheric carbon dioxide concentrations will continue to rise for the foreseeable future at a rate dependent on human activity and the success of the emission control policies prescribed at the United Nations Convention on Climate Change. Evidence suggests that this and other 'greenhouse' gases have already influenced our climate and may have had an effect on forest productivity during the course of the twentieth century. Predictions of future climate are now available, and the influence of climate change on forest growth can already be modelled through an analysis of spatial clines in climatic variables such as temperature and rainfall. The direct effects of atmospheric carbon dioxide concentrations and interactions with a changing climate are, however, more difficult to model. For these purposes, physiological or process-based models are required, in which the response of individual physiological processes to changing carbon dioxide concentrations is determined in controlled environment facilities and then parameterised for input into the growth models. The individual processes of these models can be validated by comparison with whole canopy water vapour and carbon dioxide flux data, while the growth predictions can be partially validated using historic climate and yield data. Only when these models are finalised and validated can we reliably predict the impact of climate change on forest growth.

Climate change and prediction of future climate
The temperature of the earth's atmosphere and surface is maintained at values favourable to life through the balance of incoming and outgoing solar radiation. Much of the heat from incoming solar radiation is radiated back into space. The presence, however, of greenhouse gases in the atmosphere results in the absorption of outgoing heat, particularly in the infrared part of the electromagnetic spectrum. This 'greenhouse effect' is important in maintaining favourable temperatures, but if the concentrations of greenhouse gases increase in the atmosphere, the warming effect will be enhanced, resulting in anthropogenic climate change – global warming. Greenhouse gases are therefore those which absorb radiation in the infrared part of the electromagnetic spectrum and are present in the atmosphere. They include carbon dioxide, water vapour, methane, nitrous oxide, ozone and chlorofluorocarbons (CFCs). Of these gases, the concentrations of carbon dioxide (Keeling *et al.*, 1995; Figure 1), methane and CFCs have increased significantly in the atmosphere as a result of human activity.

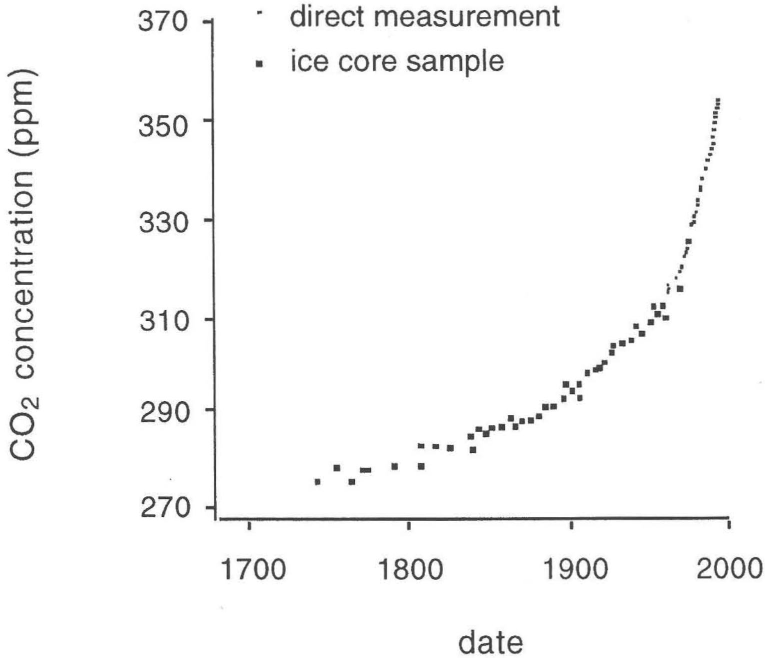

Figure 1. *Atmospheric CO_2 concentrations since 1850. Redrawn after Friedli* et al. *(1986) and Keeling* et al. *(1995).*

It is now widely accepted that anthropogenic climate change is occurring, and the UN Intergovernmental Panel on Climate Change (IPCC) has concluded that "the balance of evidence suggests a discernible human influence on global climate" (IPCC, 1995). Over a number of years, the evidence from average global surface temperatures has become increasingly clear, and 1997 was the hottest year on record to date. Average global temperatures have risen by 0.6°C in the last 130 years, and general circulation models (GCMs) are now able to predict the impact of increasing greenhouse gas concentrations on global temperatures.

In order to understand the potential impacts of climate change, it is essential to have accurate predictions of future climate at the regional scale. Internationally, predictions or scenarios have been provided by the IPCC. Within the UK, these have been provided by the Meteorological Office at the Hadley Centre for Climate Prediction and Research, at a spatial resolution of 10 minutes (i.e. 10 km grid squares). Predictions at this scale are clearly very useful for predicting impacts on vegetation. Mean winter temperatures and average precipitation in millimetres per day are available for the 1961-90 baseline period and for the years 2025, 2050 and 2100. This work forms the basis of the scenario which the Climate Change Impacts Review Group (CCIRG) of the UK's Department of the Environment, Transport and the Regions (DETR) has assessed since 1995. The relatively small changes in temperature and rainfall (Table 1) will lead to much larger changes in potential evapo-transpiration, while the annual distribution of rainfall and the occurrence of storm events may also change. Projected temperature increases should therefore not be viewed in isolation.

Table 1. *Predicted changes to the climate of south-east and north-west UK for 2050, representing the UK Climate Change Impacts Review Group scenario (CCIRG, 1996).*

	South-east		*North-west*	
	Summer	*Winter*	*Summer*	*Winter*
Temperature	+1.8°C	+1.8°C	+1.2°C	+1°C
Rainfall	-9%	+10%	+5%	+3%
Potential evapo-transpiration	+30%	+100%	0%	-25%
Mean windspeed	+2%	+6%	+2%	+2%
CO_2	+57% (525 ppm)			

Impacts on forestry

The changes predicted in the scenario outlined in Table 1 would have very important implications for forestry. The occurrence of late spring frost is already a problem for forestry in parts of the UK, restricting the use of some tree species and provenances (Murray *et al.*, 1994). Similarly, increased windiness, particularly storms, could have devastating effects, as exemplified by the 1987 storm in southern England. One important feature of UK forestry relevant to these impacts is that a number of introduced species are used widely as they grow rapidly over short rotation lengths. A second important feature is that the native species have ranges which span considerable climatic differences. For the introduced species, seed origins (provenance) are used to select for the most appropriate genotype to maximise growth potential. Therefore, a shift of seed origin is a possible proactive response to climate change. For example, for Sitka spruce (*Picea sitchensis* (Bong.) Carr.), it is possible that more Oregon or Washington provenances should be planted in place of the Queen Charlotte Island provenance. In the case of native species, the majority do grow over a wide range of climatic conditions. This wide genetic base should therefore allow for adaptation to a changing environment. Natural selection may, however, not keep pace with the rate of environmental change, and the selection of non-native provenances should be considered.

Cannell *et al.* (1989) have listed tree species which are currently not widely planted but which might show enhanced growth under a warmer UK climate (Table 2). These include *Eucalyptus* spp. and *Nothofagus* spp. which are native to regions with a warmer climate than that currently experienced in the UK. These authors have also listed species which are currently used but which may perform better or worse should the predicted changes occur. Those which might grow better are species such as beech (*Fagus sylvatica* L.) and small-leafed lime (*Tilia cordata* Mill.), for which the northern limit for growth is determined by temperature and passes across the UK. Species which may grow less well include grey alder (*Alnus incana* (L.) Moench), bird cherry (*Prunus padus* L.) and willow (*Salix* spp.), which will suffer from higher soil moisture deficits. In addition to temperature and extreme events (late spring frost and storms), there are a number of other environmental factors which are changing and which may influence tree growth and forest productivity. These include UV-B, air pollutants (particularly nitrogen and ozone in the lower atmosphere) and drought, and the interactions of these factors with forest insects and pathogens.

Table 2. *Potential impact of predicted climate change on the growth of existing forest species, and new species for consideration under such conditions (Cannell* et al., *1989).*

Species which may grow better	*Species which may grow less well*	*New species to consider*
Fagus sylvatica L.	*Alnus incana* (L.) Moench	*Acer* spp.
Ilex aquifolium L.	*Prunus padus* L.	*Eucalyptus* spp.
Nothofagus spp.	*Salix pentandra* L.	*Fagus orientalis* Lipsky
Populus alba L.	*Sorbus aucuparia* L.	*Ficus carica* L.
Quercus rubra L.		*Juglans nigra* L.
Robinia pseudoacacia L.		*Platanus orientalis* L.
Tilia cordata Mill.		*Populus* spp.
Tilia platyphyllos Scop.		*Prunus dulcis* D.A. Webb
		Prunus serotina Ehrh.
		Quercus ilex L.

Direct effects of elevated CO_2 and interactions in the effects of CO_2 and other factors

While the increase in the concentration of carbon dioxide in the atmosphere is probably the primary driving force for the greenhouse effect and changing climate, the concentration of CO_2 also has direct effects on plant growth, since it is the plant's source of carbon. These direct effects of elevated CO_2 also impinge upon the response of tree growth to some of the other environmental factors listed above. It is important to be able to predict the magnitude of these responses, and this can be investigated directly through experimental research. The Forestry Commission has set in place a research programme using open-top chambers at upland and lowland sites, to investigate the response of tree growth to elevated CO_2 alone, and also, the interactions of these responses with ozone, drought and nutrition for several tree species. The experiments have shown that the growth response to CO_2 alone is species specific and highly dependant on the other factors included in the experiments (Ceulemans and Mousseau, 1994; Broadmeadow *et al.,* 1996). Figure 2 demonstrates that for sessile oak (*Quercus petraea (*Mattuschka) Liebl.), there is a large positive growth response to elevated CO_2, which also ameliorates the detrimental effect of elevated ozone pollution. Both Scots pine (*Pinus sylvestris* L.) and common ash (*Fraxinus excelsior* L.) showed little response to ozone, while the CO_2 enhancement of growth was minimal in common ash and small in Scots pine, relative to sessile oak.

These observed responses of growth to elevated CO_2 represent the integrated effects of a number of physiological processes. The direct enhancement of photosynthesis in elevated CO_2 is evident (Figure 3). If these measurements are made at saturating CO_2 concentrations representing potential photosynthetic capacity (Figure 4), complex interactions between ozone pollution, water supply and CO_2 are observed. Ozone severely reduces photosynthetic capacity, an effect which is completely reversed by elevated CO_2 under conditions of drought, but not irrigation. This is likely to be a result of stomatal closure in response to increased internal CO_2 concentrations (Stitt, 1991) reducing the effective ozone dose, a response diminished by irrigation. A combination of direct CO_2 enhancement of photosynthesis and reduced stomatal conductance generally leads to increases in water use efficiency (Guehl *et al.,* 1994), as shown in Figure 5, which may counteract the predicted reductions in water availability. Under conditions of poor soil

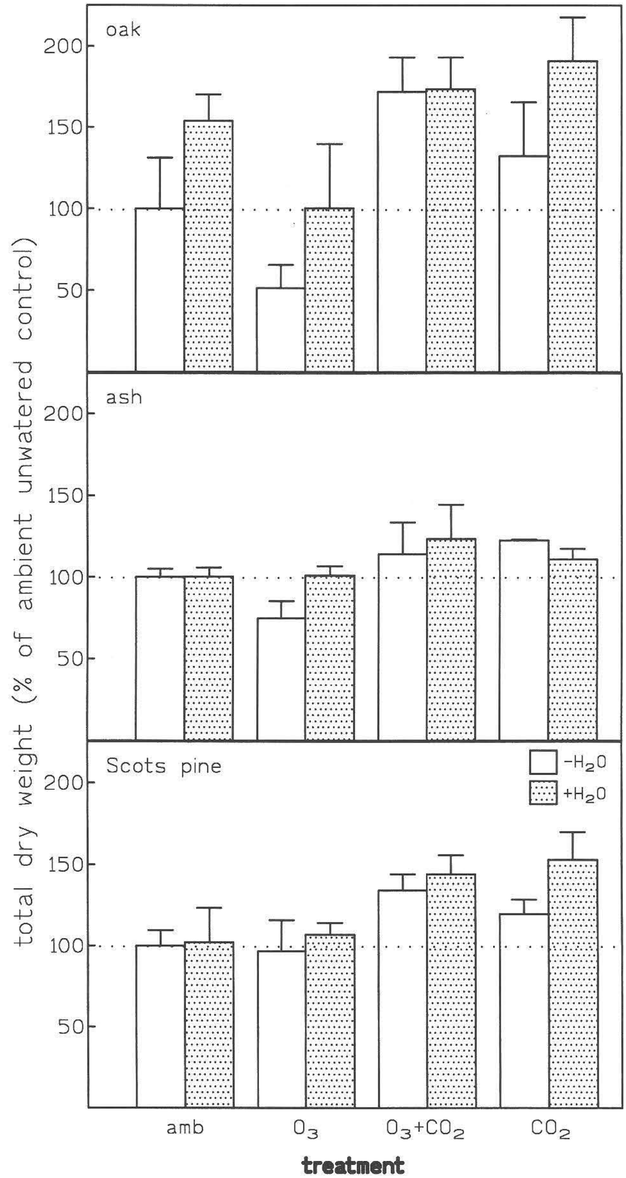

Figure 2. *Growth responses of sessile oak* (Quercus petraea *(Mattuschka) Liebl.*), *common ash* (Fraxinus excelsior *L.*) *and Scots pine* (Pinus sylvestris *L.*) *to treatments of elevated CO_2, ozone and irrigation. Trees were exposed for 3 years to factorial treatments of ambient (350 ppm) or elevated (700 ppm) CO_2, ambient or elevated (20 ppb overnight rising to 100 ppb for 4 hours/day during the growing season) ozone, and 10% or 20% volumetric soil moisture. Values are expressed as a percentage of the unwatered ambient control (100%), with error bars representing half the difference between duplicate chambers.*

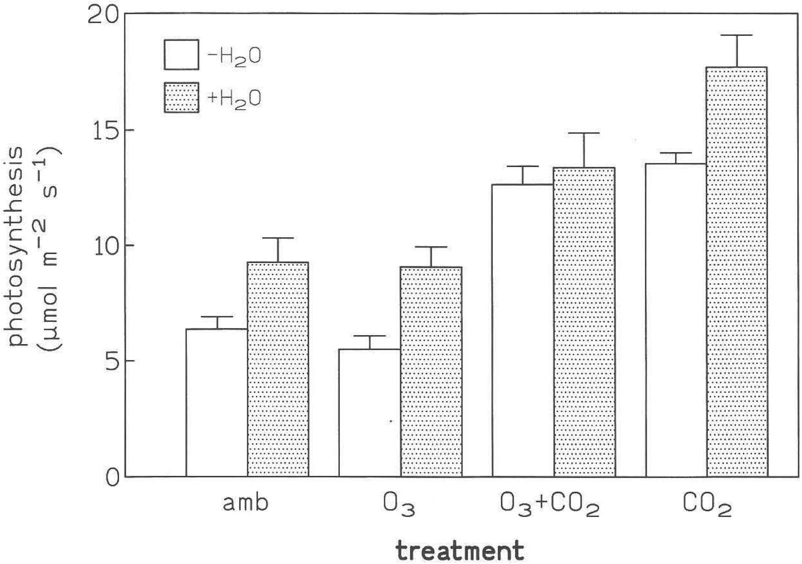

Figure 3. *Photosynthesis of oak exposed to elevated CO_2, O_3 and irrigation as described in Figure 2. Measurements were made using a LCA-3 gas exchange analysis system (ADC Ltd., Hoddesdon, Herts, UK). Values represent the mean (+/- 1 standard error of the mean) of 7 days' analyses during the 1995 growing season, with 10 measurements made per treatment per day.*

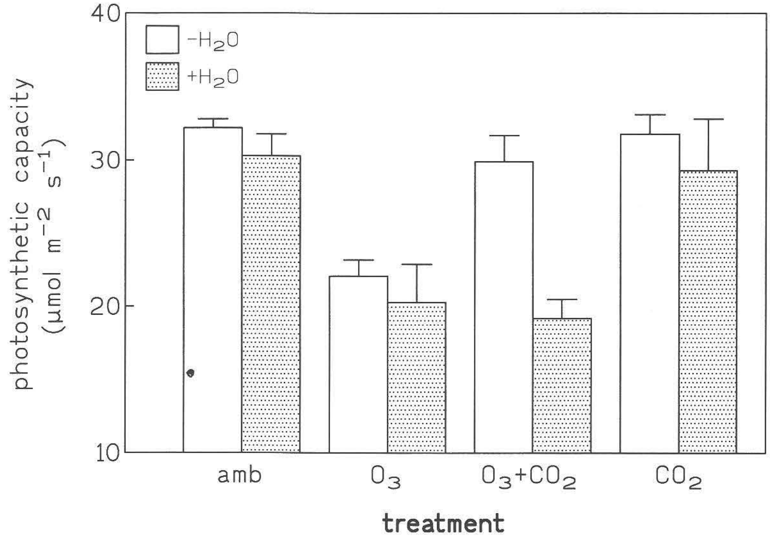

Figure 4. *Light and CO_2 saturated rates of photosynthesis in oak. Measurements were made at 1600 ppm CO_2 on 4 days during the 1995 growing season. Values are the mean of the 4 days' analyses (+/- 1 standard error of the mean), with 10 analyses per treatment per day.*

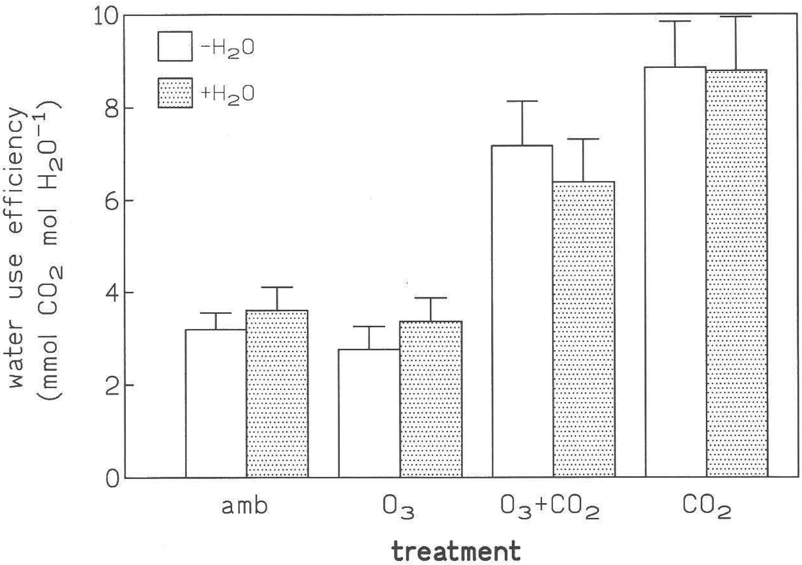

Figure 5. *Water use efficiency in oak, expressed as mmol CO_2 assimilated per mol H_2O transpired. Measurements were made concurrently with those of photosynthesis shown in Figure 3.*

nutrition, increased growth rates have often been shown to lead to nitrogen deficiency and a reduction in photosynthetic capacity (Eamus and Jarvis, 1989; Ceulemans and Mousseau, 1994). This reported 'down-regulation' of the photosynthetic apparatus may, however, be a function of experimental conditions, since much of the early work was carried out on potted trees with restricted rooting volumes.

Modelling growth responses to climate change

These complex responses of growth to increasing atmospheric CO_2 and environmental change cannot be modelled using traditional mensuration techniques, since there is minimal spatial variation in ambient CO_2 concentrations. There are data which suggest that site productivity has increased this century (Spiecker *et al.*, 1996), but changes in forest management and many other factors affect the conclusions that can be drawn. Physiological or process-based models can, however, be used to predict the effects of environmental change on forest growth. These models require large numbers of parameters to be obtained from both experiments, such as those described above, and from mature forest stands. The models can then be validated and calibrated with whole canopy water and CO_2 flux data using techniques such as Eddy Correlation, for which an increasing number of sites are available under EU-funded projects such as EUROFLUX and ECOCRAFT.

Interactions between forests and the environment

The interactions which may be of most relevance to forestry are water-use, nutrition and windthrow. Firstly, the predicted combination of increased evapo-transpiration and less rainfall in some areas will mean that water resources may become more scarce. The increased use of water by trees as compared to other forms of natural vegetation could become an argument against increasing woodland and forest cover (UK Environment Agency, 1998). The evidence and predictions are complicated in this area, and although an experimental research programme has been established in the UK, it is too early to draw conclusions. Secondly, 'CO_2 fertilisation' and falling nitrogen deposition may lead to nitrogen deficiencies on some sites, thereby limiting any beneficial effects of environmental change on forest growth. Nitrogen budget studies need to be carried out alongside the modelling activities described above, to identify whether nitrogen deficiencies are likely to become more commonplace in forestry. Finally, elevated CO_2 generally leads to an increase in leaf area, and therefore, to enhanced windthrow susceptibility. This may, however, be counteracted by reduced water availability and nutrition, leading to a change in the balance of allocation to root growth. Predictions of the effects of climate change on susceptibility to wind damage are therefore difficult to make, although suitable windthrow models do exist (Quine *et al.*, 1995).

International agreements and their implications for forestry

Following the Climate Change Convention, the 1997 Kyoto agreement had two important outcomes which influence the position of forestry in climate change response strategies. Firstly, the total agreed decreases of CO_2 emissions were rather small, indicating that the direct effects of elevated CO_2 concentrations, and the secondary effects through climate change, will not be quickly overcome through abatement. Secondly, the idea of increasing carbon sinks, particularly through tree planting, has remained part of the Convention and is included as a possible option in the Kyoto agreement. The sequestration of CO_2 through tree growth therefore remains an important issue, and the quantification of sequestration is currently high on the scientific agenda. There is no doubt that carbon accumulates in the above-ground part of tree crops while they are growing. Whether or not this carbon sequestration is of any long-term benefit depends on the way in which the timber is used after harvest (Matthews *et al.*, 1996).

Forests as carbon sinks

In the UK lowlands, where mineral soils of low organic matter content predominate, carbon accumulates in soil during the growth of a woodland, and there may be a continuous removal of approximately 1.0 t of carbon/ha/yr from the atmosphere. Undisturbed peat accumulates carbon at a rate of approximately 0.7 t/ha/yr, but also emits methane (Cannell and Milne, 1995). The ploughing and drainage of peat for tree planting may, however, result in between 2.0 and 7.0 t/ha/yr loss of carbon. Huge amounts of carbon are stored in peat soils in the UK, with upland peat bogs containing 200 times as much carbon as all UK vegetation (Harrison *et al.*, 1995). It is therefore essential that soil-atmosphere carbon exchange budgets are modelled adequately. It is estimated that European forests remove 85 to 120 million tonnes of carbon from the atmosphere annually (Cannell *et al.*, 1992). This is approximately 5% of the carbon emitted in European fossil fuel burning. About 70-115 million tonnes of this storage results from increased standing volume, and 15 million tonnes from the build up of forest products. The increase in standing volume is primarily because only 70% of the annual increment is harvested. Therefore, standing wood volumes are increasing, although the recently reported enhancement of European forest growth rates may also contribute (Spiecker *et al.*, 1996).

Table 3. *Summary of beneficial and detrimental effects associated with environmental and climate change relating to forestry.*

Factor	*Beneficial effects*	*Detrimental effects*
Resistance to windthrow	Increased allocation to roots in conditions of water or nutrient deficiency.	Increased leaf area and thus, canopy resistance to wind. Increase in occurrence of storm events and mean wind speed.
Water use and availability	Reduced water use as a result of stomatal closure in response to elevated CO_2.	Increased water use as a result of increases in leaf area. Reduced water availability as a result of increases in potential evapo-transpiration and reductions in summer rainfall.
Nutrient availability		Nutrient dilution in response to increased growth. Restriction in availability as soil water content decreases.
Physiology	Budburst accelerated by warmer temperatures. Growing season lengthened by warmer temperatures.	Budburst delayed by unsatisfied chilling requirement. Tissue damage resulting from late spring frosts.
Pathology		Pest populations not reduced during mild winters. Movement of pests and diseases to new regions. Changing disease and pest epidemiology.
Pollution	Reduced acid deposition. Reduced ozone dose as a result of reduced stomatal conductance.	Reductions in sulphur and nitrogen deposition.
Carbon uptake	CO_2 fertilisation effect. Reduced photo-respiration. Increased photosynthesis in response to higher air temperatures.	Increased respiration rates in response to higher temperatures. Reduced carbon uptake in response to summer drought.

Conclusion

These authors cannot subscribe to the idea which has been publicised recently, at least in the UK, that climate change is likely to have an overall beneficial effect in forestry (CCIRG, 1996). This assessment may be an over-simplistic view which cannot be justified by a detailed consideration of the evidence (Table 3). Direct effects of elevated CO_2 are only likely to be beneficial if other environmental requirements are met. Foremost is the availability of water and plant nutrients. The impacts of extreme events and of interactions with entomological and fungal pathogens could also be of major importance and have not been thoroughly investigated. Species and provenance choice may have to be altered, and there is an urgent need for information on which to base such decisions. The provision of suitably scaled predictions of climate and of research into the impacts of these predictions in forestry should continue to be viewed as critical areas of study.

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REFERENCES

Broadmeadow, M.S.J., Ludlow, A.R. and Randle, T.J. 1996. Modelling the effects of global change on European forests. *In:* Report on Forest Research 1996. Forestry Commission, Edinburgh. pp. 34-37.

Cannell, M.G.R., Grace, J. and Booth, A. 1989. Possible impacts of climatic warming on trees and forests in the UK: A review. *Forestry* 62(4):337-364.

Cannell, M.G.R. and Milne, R. 1995. Carbon pools and sequestration in forest ecosystems in Britain. *Forestry* 68:361-379.

Cannell, M.G.R., Dewar, R.C. and Thornley, J.H.M. 1992. Carbon flow and storage in European forests. *In:* Responses of Forest Ecosystems to Environmental Changes. Edited by Teller, A. and Jeffers, J.N.R. Elsevier, London and New York. pp. 256-271.

CCIRG. 1996. Review of the Potential Effects of Climate Change in the United Kingdom. HMSO, London.

Ceulemans, R. and Mousseau, M. 1994. Tansley Review No. 71. Effects of elevated atmospheric CO_2 on woody plants. *New Phytologist* 127:425-446.

Eamus, D. and Jarvis, P.G. 1989. The direct effects of increase in the global atmospheric CO_2 concentration on the natural and commercial trees and forests. *Advances in Ecological Research* 19:1-55.

Friedli, H., Lotscher, H., Oeschger, H., Siegenthaler, U. and Stauffer, B. 1986. Ice core record of the $^{13}C/^{12}C$ ratio of atmospheric CO_2 in the past two centuries. *Nature* 324:237-238.

Guehl, J.M., Picon, C., Aussenac, G. and Gross, P. 1994. Interactive effects of elevated CO_2 and soil drought on growth and transpiration efficiency and its determinants in two European tree species. *Tree Physiology* 14:707-724.

Harrison, A.F., Howard, P.J.A., Howard, D.M. and Hornung, M. 1995. Carbon storage in forest soils. *Forestry* 68(4):335-348.

IPCC. 1995. Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the

IPCC IS92 Emission Scenarios. Edited by Houghton, J.T., Meira Filho, L.G., Bruce, J., Lee, H., Callander, B.A., Haites, E., Harris, N. and Maskell, K. Cambridge University Press, Cambridge, UK.

Keeling, C.D., Whorf, T.P., Wahlen, M. and van der Plicht, J. 1995. Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980. *Nature* 375:666-670.

Matthews, R.W., Nabuurs, C.-J., Alexeyev, V., Birdsey, R.A., Fischlin, A., MacLaren, J.P., Marland, G. and Price, D.T. 1996. WG3 summary: Evaluating the role of forest management and forest products in the carbon cycle. *In:* Forest Ecosystems, Forest Management and the Global Carbon Cycle. Edited by Apps, M.J. and Price, D.T. Proceedings of the NATO Advanced Research Workshop held in Banff, Canada, 12-16 September 1994. Springer-Verlag, Berlin. pp. 293-301.

Murray, M.B., Smith, R.I., Leith, I.D., Fowler, D., Lee, H.S.J., Friend, A.D. and Jarvis, P.G. 1994. Effects of elevated CO_2, nutrition and climatic warming on bud phenology in Sitka spruce (*Picea sitchensis*) and their impact on the risk of frost damage. *Tree Physiology* 14:691-706.

Quine, C.P., Coutts, M.P., Gardiner, B.A. and Pyatt, D.G. 1995. Forests and Wind: Management to Minimise Damage. Forestry Commission Bulletin 114. HMSO, London.

Spiecker, H., Mielikainen, K., Kohl, M. and Skovsgaard, J. 1996. Growth Trends in European Forests. Springer-Verlag, Berlin.

Stitt, M. 1991. Rising CO_2 levels and their potential significance for carbon flow in photosynthetic cells. *Plant, Cell and Environment* 14:741-762.

UK Environment Agency. 1998. Broadleaf Woodlands: The Implications for Water Quantity and Quality. The Stationary Office, London.