SECTION 8

Modelling the impact of climate change and nitrogen deposition on carbon sequestration of UK plantation forests

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Abstract

The dynamic process based model of forest growth, Edinburgh forest model (EFM) couples the carbon, nitrogen and water cycles both above and belowground. It has been used to explore the effects of changes in climate, nitrogen deposition and atmospheric CO_2 concentrations on future carbon sequestration rates of UK plantation forests. Two widely planted UK tree species were simulated; Sitka spruce (*Picea sitchensis*) and beech (*Fagus sylvatica*) for six sites across the UK (latitudes ranging from 56°45'N to 51°15'N). At each site information was obtained on atmospheric CO_2, N-deposition, weather and forest management. Meteorological data and appropriate future scenarios for these inputs, for 1900-2100, were obtained from the Climate Research Unit and the Hadley Centre's Global Climate Model (HadCM3) experimental results. Nitrogen deposition was taken from the STOCHEM model. EFM runs starting in 2000 were made for 60 or 90year rotation periods, for Sitka spruce and beech, respectively. Initial model runs were made using current and past data for nitrogen deposition, atmospheric CO_2 and weather. Subsequent scenario runs included singularly and in combination future predictions of environmental changes appropriate to each of the six sites. These simulations showed that not only will the increase in NPP vary across the UK and be species dependant but will also be affected differently according to site location by N deposition, climate and [CO_2]. On average NPP increased by 12 % with the largest and smallest increases found in beech (7 and 15 %, respectively). Changes in N deposition and [CO_2] both had a positive impact on forest NPP across the UK. However, future climate change scenarios are predicted to have a small negative impact on the NPP of both species growing in southern England.

Introduction

Recent reports on growth of European forests have suggested that over the 20th century growth rates have increased (Spiecker *et al*., 1996). This finding has highlighted not only the uncertainty as to which past environmental variable or group of variables have caused this stimulation in growth, but also our lack of ability to predict future changes without further investigation. As the ultimate goal of this study was to improve our understanding of long-term responses of UK forests to increasing atmospheric CO_2 concentration, climate change and future nitrogen deposition rates, interactions between these environmental resources are also critical to the analysis.

Because of the long life-span and complexity of forests, major experimental limitations restrict the study of the responses of trees and forests to elevated CO_2 so that the use of models to integrate individual responses and to extrapolate these responses to make predictions in time and space is indispensable. Numerous processes are involved in the responses of trees to elevated CO_2, climate change and N deposition rates, particularly at a forest scale. Because we are dealing with a complex system in which processes occur at different time scales and secondary effects lead to feedback mechanisms the need for a forest-based process model is essential. Furthermore, the use of such a model is useful to identify gaps in our understanding of these responses and to make further predictions in time and space. For the reasons outlined above the Edinburgh Forest model (EFM) was modified for use with both coniferous and deciduous plantation tree species and employed within this study.

Results from studies such as this one are important not only in identifying the key parameters responsible for both past and future forest growth? But also in addressing the growing issue of forest biome carbon balances. The importance of forests in alleviating climate change processes is a matter of both national and global concern. It is also a highly topical issue as carbon-trading quotas are close to implementation. The work reported here follows on from that presented in the last annual report (Murray and Thornley, 2002).

Methodology

Edinburgh Forest Model

The process-based Edinburgh Forest model (EFM) used in this study, describes the pools and fluxes of carbon, nitrogen and water in an even-aged, single species plantation of either *Picea sitchensis* (Sitka spruce) or *Fagus sylvatica* (beech) that is periodically harvested and replanted. A full and detailed description of the model can be found in Dewar (1991) last years annual report. Briefly, carbon fixation is represented by the ultimate increase in woody biomass (branches, stems and woody roots) and non-woody (foliage and fine roots) of tree parts. During the life of the stand the forest floor continuously receives carbon from trees in the form of dead foliage, branches, stems, woody roots, and fine roots, which subsequently decompose in the process of soil formation. In addition, a proportion of this biomass is transferred to the product pool following each rotation and thinning and ultimately decays to CO_2. The model also includes feedbacks between the carbon, water and nutrient cycles.

Observed yield class and carbon accumulation of both coniferous and broadleaf forests were simulated using the EFM in a managed plantation (thinned according to, species specific current management recommendations) free form natural disturbances, such as forest fires and insect damage, at six locations across the UK. Six environmental scenarios were used to simulate past and future climatic conditions and nitrogen deposition rates representative of the six chosen sites. Nitrogen deposition rates adopted in this study differ from previous reports and are described later.

In this study both coniferous and deciduous versions of the model simulated forest growth for the same six UK sites as previous reported ran the conifer version of the EFM at six different sites across the UK and the beech version for two (Table 1.).

Table 1. UK sites used in model simulations of both the conifer and beech versions of the EFM. With total nitrogen deposition rates applied at each site taken from NEGTAP report (1996).

1.	Central Grampians	56°45’N 4°14’W	12 Kg N ha^{-1} y^{-1}
2.	Scottish Borders	55°15’N 2°45’W	24 Kg N ha^{-1} y^{-1}
3.	Yorkshire	53°15N 1°45’W	32 Kg N ha^{-1} y^{-1}
4.	Cardigan	52°15’N 3°34’W	24 Kg N ha^{-1} y^{-1}
5.	East Anglia	52°15’N 0°45’E	12 Kg N ha^{-1} y^{-1}
6.	Hampshire	51°15’N 1°15’W	18 Kg N ha^{-1} y^{-1}

Generated monthly weather data

The monthly climate data used in the above 1900 – 2100 simulations is a combination of actual Climate Research Unit (CRU05) weather data and GCM results. The climate change scenarios were constructed using the Hadley Centres Global Climate Model (GCM0) (HadCM3) experimental results.

Using the rate changes obtained from the above HadCM3 simulation runs, weather variable time courses, for each of the six weather variables required to run the EFM (*tmax, tmin, prec, rhum, dswf* and *wind*), were calculated on a monthly basis at each of the six sites (432 regressions).

These were then combined with the monthly climate time series (1901-1996) obtained for each site from the Climate Research Unit (CRU05), producing a weather variable data set for 1997 – 2100 at each site. Combining both data sets provided a monthly climate time series from 1901 to 2100 that represented both past and future climatic conditions specific to each site.

Nitrogen deposition rates

In this study the scenario adopted for N deposition, within the EFM, was 5 kg N ha^{-1} y^{-1} prior to 1940 across all six sites and from 1940 to the present day a linear rise to the individual values outlined at each site in Figure 1. In addition to this the current study used a more sophisticated approach to future N deposition rates using a modelling approach based on the STOCHEM model (Stevenson *et al*. 1998) and PhD results (Dentener, 1993). Site specific reductions in N-deposition were assumed until 2010 and then held constant thereafter.

Atmospheric CO_2 Concentration

In this study a CO_2 time course was selected which is consistent with the IS92a emissions scenario as prepared by the IPCC, see figure 2. These global values have been calculated using the "Bern model" (Siegenthaler, U. & Joos, F. 1992; Joos *et al*. 1996). Further information on the CO_2 time course and model can be obtained from the Technical Support Unit of Working-Group 1 of the IPCC (Hadley Centre for Climate Prediction and Research).

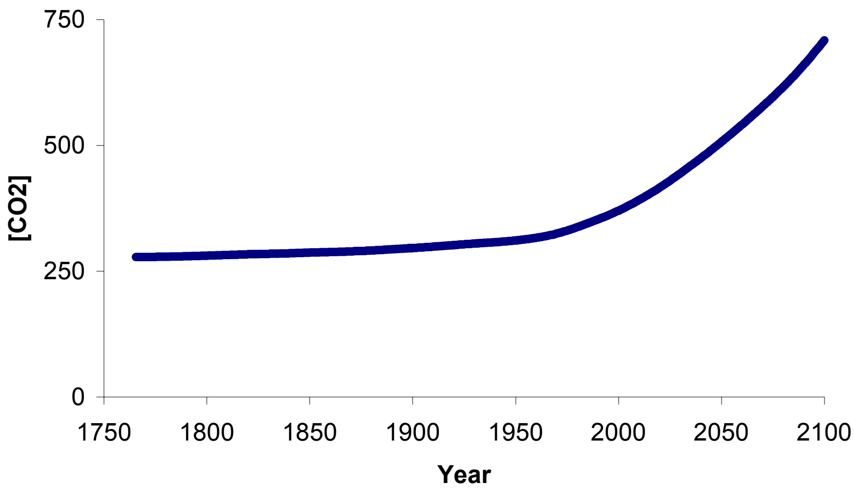

Figure 1. The scenario of historic and future changes in atmospheric CO_2 concentration assumed to occur at all sites in this study.

Model runs

The EFM model was initialised for each site using the climate data of 1900 appropriate to that site and 60-year (Sitka) or 90-year (beech) rotations to equilibrium. The model was then run for 60 or 90-year rotations (sitka and beech, respectively) eight or six times starting in 1900 with subsequent runs at 20-year intervals ending in 1960, 1980, 2000 etc. These runs were carried out at all six sites for both Sitka spruce and beech.

In addition to the scenarios described above one or more of the predicted environmental changes were held at current day (2000) values during the 21st century i.e. either climate, N-deposition or CO_2 concentration. This provided a starting point from which the relative impact of each environmental variable on forest productivity could be assessed.

Results and discussion

In this study the process based Edinburgh forest model was used to address the question "How will future changes in environmental variables impact on UK forestry?" In addition, we address the question to which degree does each of the three variables; nitrogen deposition, climate and CO_2 concentration contribute toward these changes? As previously reported future changes in weather variables used to drive the model were site specific with individual sites differing in the amount, frequency and duration of climatic events. For example, climate induced NPP responses in more southerly sites are more likely to be attributed to shifts in precipitation patterns whilst those in the North to temperature increases.

Past scenario simulations (1910 / 1940 - 2000)

For past scenario simulations where N deposition , CO_2 concentration and climate followed observed values between the years 1910 or 1940 and 2000 for beech and Sitka spruce plantations, respectively, mean predicted yield classes (YC, m^3 ha^{-1} y^{-1}) were 4.5 (beech) and 10.2 (Sitka spruce) (Figure 3). Beech YC was positively correlated with decreasing latitude, thus growing better on the warmer more southerly sites. On the other hand, Sitka spruce performed least well when grown on the two more southerly sites. The lower YC at these sites was the result of climatic conditions and in particular lower precipitation levels. Sitka spruce originates from Queen Charlotte Islands where the climate is mild and moist so is better suited to the wetter more northerly sites within the UK.

Future scenario simulations (2000 – 2060 /2090)

For future scenario simulations where N deposition rates, CO_2 concentration and climate all varied accordingly with each site, YC continued to increase across all six sites for both plantation species (Figure 3).

Changes in atmospheric CO_2 concentrations were uniform across all six sites increasing around 30 % over the course of this century. As current day concentrations of this gas severely limit photosynthetic rates any enhancement will impact strongly across the whole country, irrespective of forest location or species. For both species growing in the borders, Yorkshire and Cardigan bay the environmental change effects in NPP (t DM ha^{-1} y^{-1}) were additive, totalling around 14 % for Sitka and ranging between 10 % and 16 % for beech (Figure 2). However, as many recent experimental studies have shown while stomatal responses to elevated CO_2 is a common phenomenon (Mott 1990, Jackson *et al* 1994, Thomas *et al*, 1994), it is also one which is highly likely to interact with other environmental variables such as temperature, water stress and even light (Eamus and Jarvis, 1989). At more southerly sites where precipitation events such as droughts have been predicted to increase, especially during the summer months, resulting decreases in stomatal conductance may be the reason changing climate patterns appeared to reduce the overall impact in future net primary productivity (NPP) of both species (Figure 2).

Although past scenario changes in NPP could primarily be attributed to large changes in N deposition rates, future changes were less affected. Atmospheric CO_2 concentration has now become the primary environmental driver of NPP change, particularly at the more northerly sites. This reduction in the regulation of forest growth by N deposition is likely to continue beyond the current century as atmospheric pollution rates continue to fall and CO_2 concentrations continue to rise along with it's correlated changes in climate. This study has highlighted the highly variable responses between species, across sites and to specific environmental driving forces.

It is exactly these interactions between environmental resources currently limiting the growth of UK forests that will be critical to the analysis and prediction of any future changes in their primary productivity and hence carbon sequestering power. Many experimental studies have shown the ameliorating powers of elevated CO_2 to water stress (Tolley and Strain, 1985: Conroy *et al*, 1986). This is primarily as a result of increased water use efficiency (Hollinger, 1987) through enhanced photosynthetic capacity and decreased stomatal conductance. It may therefore initially be surprising to observe that this study predicts a reduction in future NPP resulting from climatic changes at those sites most affected by precipitation changes i.e. East Anglia and Hampshire, as one might have predicted a better response under future elevated CO_2 concentrations. However, it is likely that reductions in NPP would have been even greater had there not been a concurrent rise in atmospheric CO_2 levels.

Conclusions

- Changes in the three primary driving forces for forest growth, namely N deposition rates, atmospheric CO_2 concentration and climate change have had and will continue to have a significant impact on NPP in the UK.
- Differences in productivity predictions between this report and that of previous studies are attributable to modifications to the N deposition scenario used within the model simulations.
- The influence of atmospheric CO_2 concentrations on future NPP values will be greater than that of nitrogen deposition.
- For Sitka spruce forests the percent increase in NPP across all six sites is fairly uniform (averaging around 12.5 %) although the relative importance of each environmental driving variable differs.
- The response of Beech forests however, will vary according to site, with the largest response observed at Cardigan Bay (16 %). The two most southerly sites growth response will be modified by reductions attributable to changes in climate and in particular precipitation patterns.

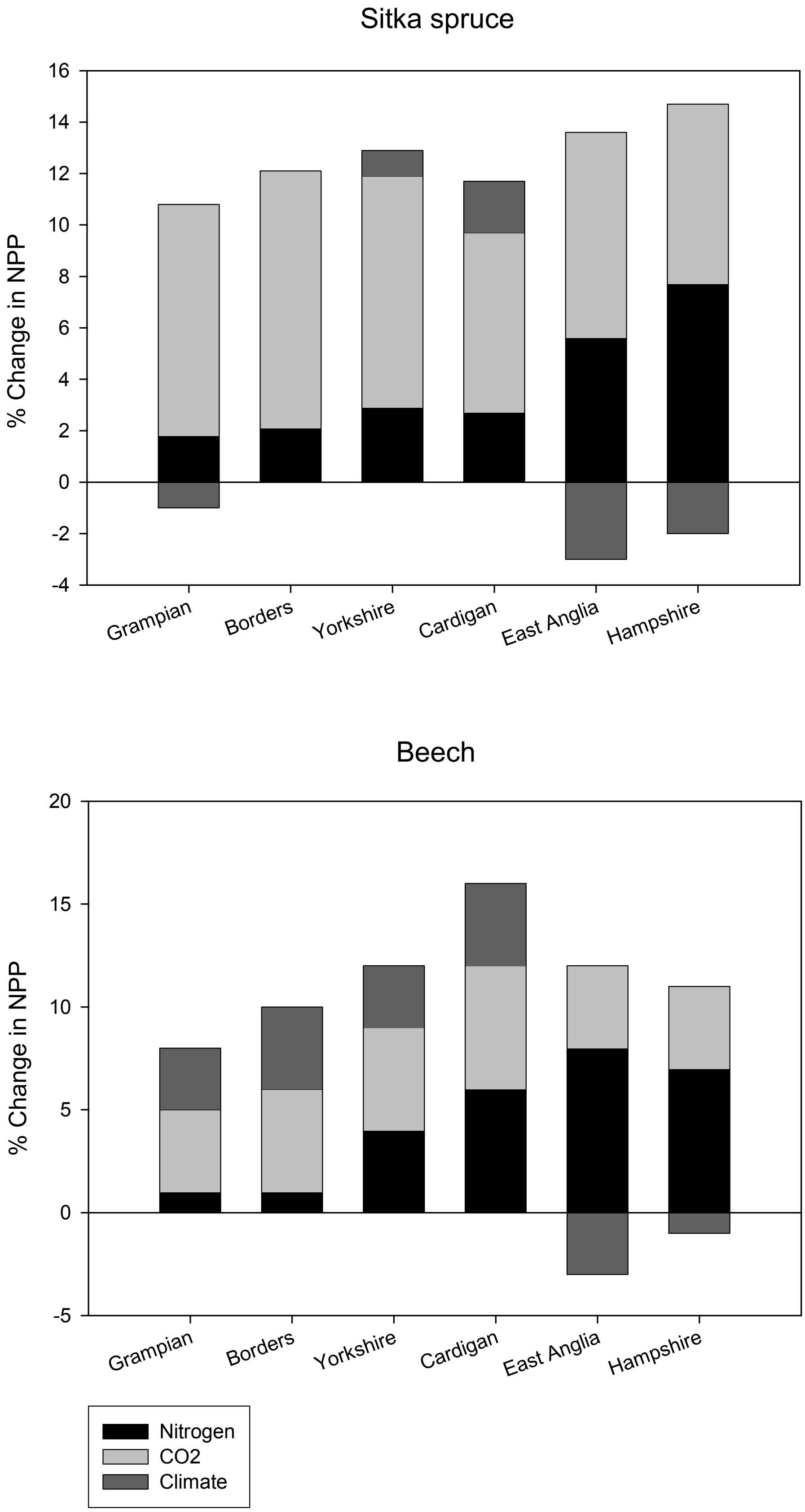

Figure 2. Simulated changes in plantation forest net primary productivity (NPP) over the periods 2000 –2060 and 2000-2090 for sitka and beech plantations, respectively. Differently shaded parts within each column indicate single factor effects.

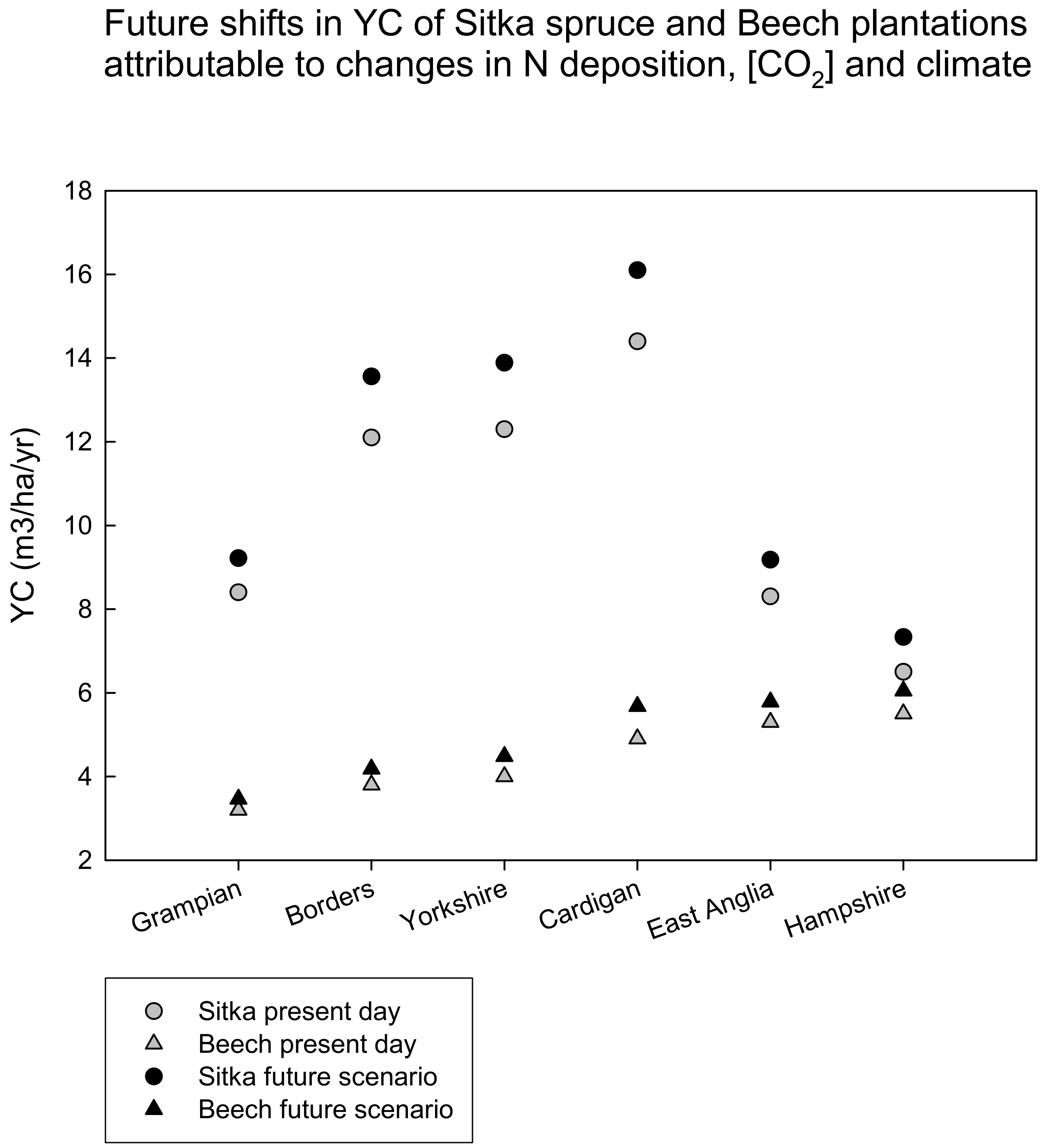

Figure 3. Simulated changes in rates of net primary productivity (NPP, t DM ha-1 y-1) between 2000 and 2060 and 2090 for Sitka spruce and beech, respectively.

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