SECTION 8

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

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

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Abstract

Future climatic conditions, [CO_2] and nitrogen deposition rates are expected to modify current forest carbon sequestration rates, thus altering the scale and functioning of forests as global carbon sinks. The objective of this study was to assess the effects of climate change, increased [CO_2] and future nitrogen deposition rates on productivity and carbon sequestration of plantation forests at six sites geographically distributed across the UK. This study uses the Edinburgh Forest Model (EFM) for both coniferous and deciduous plantation forests. Model computations included past, present and future climatic conditions, atmospheric CO_2 concentrations and N deposition rates. Warmer climatic conditions, elevated [CO_2] and increased N deposition rates all enhanced forest productivity and YC, irrespective of forest type or location. YC values are predicted to increase from current day levels by on average 65 % for conifers and 78 % for broadleaves. More northerly sites will continue to be most productive for conifer plantations, top YC values being 22 , and the more southerly ones more productive for deciduous tree, top YC values 10. The relative aboveground carbon accumulation of coniferous stands will increase by 27 % in Grampian to 48 % in Hampshire. However, in Hampshire coniferous YC values are lower than the rest of the UK and soil C content is predicted to fall resulting in a smaller increase in C sequestration potential than at other sites. In Southern England environmental changes will have a bigger positive impact on deciduous plantations than coniferous ones while the opposite is true for Scottish sites. In southern Scotland nearly 50 % of the increase in C content of coniferous trees can be attributed to changes in N deposition while 35 and 16 % are as a result of [CO_2] and climate change. In contrast soil C content was primarily affected by [CO_2].

Introduction

Global warming, elevated [CO_2] and increased nitrogen deposition are likely to influence the carbon stock in UK forests. This is a result of current plantation productivity being limited by temperature, growing season duration, photosynthetic capacity and nutrient availability; primarily nitrogen, though in some instances P may be the limiting nutrient.

During recent decades, nitrogen availability has been increased by atmospheric deposition of nitrogen. Prior to 1940 total atmospheric N deposition across the UK was on average 5 kg N ha^{-1} y^{-1} (Pitcairn *et al.*, 1995). Since then this value has risen steeply with current and annual deposition ranging between 12 and 32 kg N ha^{-1} y^{-1} (NEGTAP, 2000). With such a steep rise in deposition rates of atmospheric N, provided N saturation has not occurred, forest growth and productivity are likely to be enhanced in the future and indeed has been proposed as one reason for improvements in past and current forest growth across Europe (Spiecker *et al.*, 1996).

The global and UK climate is expected to change due to an enhancement of greenhouse gases emissions. In the UK the temperature is predicted to increase around 1.2 - 2 ^{o}C in summer and 2 – 3.2 ^{o}C in winter during 1990-2050, with a pattern of larger increases in the southeast of the country than in the northwest (Hulme and Jenkins 1998). Annual precipitations will also increase by between 0-10 % over England and Wales and 5-20 % over Scotland. However, there are predicted to be large seasonal differences with wetter winters throughout the UK and drier summers in the southeast of the England. These projections imply longer and warmer growing seasons, appreciably milder winters with a possibility of less extreme minimum temperatures, but perhaps more unseasonable frosts and potentially more frequent summer droughts in the southeast.

Increasing atmospheric CO_2 concentration not only has an indirect affect on forest growth via its greenhouse gas properties and hence global warming, but also a direct affect through the photosynthetic process carried out by trees themselves. At current atmospheric CO_2 concentrations photosynthesis is limited by CO_2 and therefore any increase in its level is expected to stimulated photosynthesis. Under adequate light levels tree photosynthesis requires a [CO_2] of between 800-1000 µmol.mol^{-1} for saturation (Lawlor and Mitchel, 1991). The importance of photosynthesis to forest productivity is therefore highly significant, as any stimulation in it functioning, as a result of increased [CO_2] is expected to enhance growth and hence terrestrial carbon transfer.

Understanding the critical link between forests and their environmental atmosphere and hence terrestrial carbon transfer is important especially when trying to establish the potential benefits of Forest planning through forest management. One possible goal for forest management could be the improvement of carbon sequestration of forests, e.g. as a consequence of meeting the emission reduction targets agreed in Kyoto 1997 (UNFCCC, 1997). The objective of this study was to assess the effects of altered nitrogen deposition, increased [CO_2] and changing climate (higher temperature and precipitation) on the UK's coniferous and deciduous forest plantations.

Methodology

Edinburgh Forest Model

The 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. Detailed descriptions of the model can be found in Thornley (1991) and Thornley and Cannell (1992).

This model simulates plantation tree growth of uniform trees growing in either a broadleaf forest or coniferous forest. All trees in the plantation are the same age and were initially planted at a density of 2500 trees per ha. They are regularly thinned and harvested every 60 years for Sitka spruce and 90 years for beech forests. Biomass growth is converted into standing stem volume increment and hence yield class over a rotation period is given. This sophisticated ecosystem model integrates physiological processes to simulate forest growth and hence carbon sequestration of the forest ecosystem. 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 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.

The model has been developed as a generic conifer forest ecosystem model and hence modelling the growth of a deciduous tree species such as beech required not only simple changes in parameters but also revision of part of the model structure, in particular phenological development. Hence, a new phenological submodel was developed for use within an EFM version for beech.

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

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.

Forests receive N in rain, cloud and gases in both an oxidised and reduced form as a result of fossil fuel burning and agriculture, respectively. 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. Future deposition rates were assumed to remain constant at each site. A more sophisticated approach to N deposition rates will be developed in future using a modelling approach based on the STOCHEM model (Stevenson *et al*. 1998) and PhD results (Dentener, 1993).

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).

Model runs

The EFM model was initialised for each site using the climate data of 1900 appropriate to that site and 20 60-year (Sitka) or 90-year(beech) rotations to equilibrium. The model was then run for 60-year rotations seven times starting in 1900 with the six subsequent runs at 20-year intervals ending in 1960, 1980, 2000 – 2080. These runs were carried out at all six sites for Sitka spruce and two sites, Grampian and Hampshire for beech. Each run was repeated with either no climate or [CO_2] change, and a decrease in N deposition to 10 kg ha^{-1} y^{-1}, separately or in combination.

Results and Discussion

The results of running the EFM model for the different sites and different environmental scenarios described below show that simulated forest growth and production were site and species specific and thus depended strongly on the weather input data used to drive the model at each site and EFM version used, i.e. conifer or deciduous version. Table 2 below outlines the variation in predicted climatic change for two of the environmental variables used as input variables into the model. Although the values represented here are not the absolute values used within the model; e.g. monthly variations were calculated and used and in some cases differed significantly from the annual mean, the general trend of a warmer wetter climate was true across all six sites.

Nitrogen deposition

	Kg N ha^{-1} y^{-1}
Central Grampians	12
Scottish Borders	24
Yorkshire	32
Cardigan	24
East Anglia	12
Hampshire	18

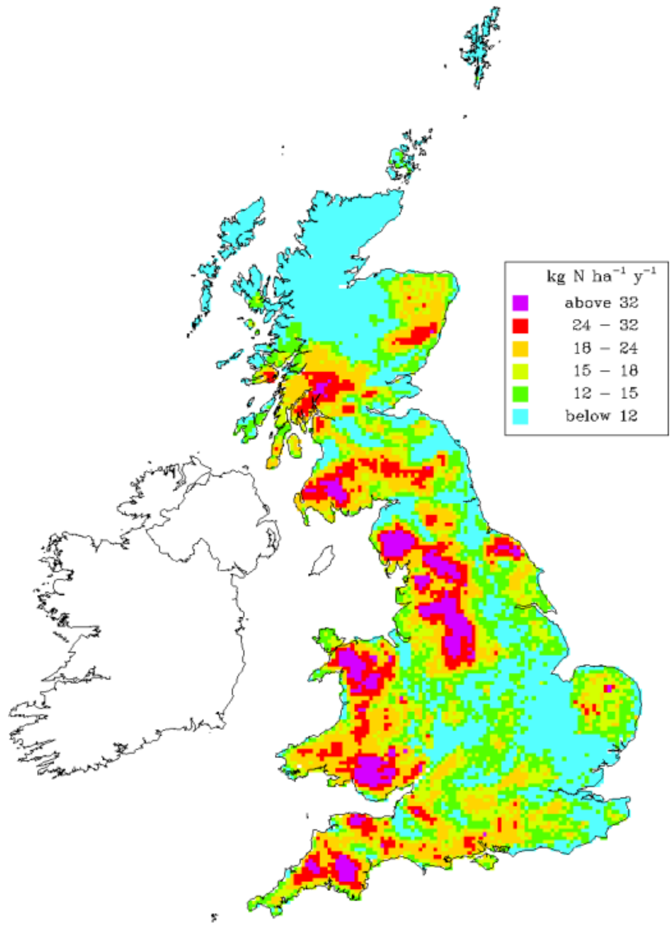


Figure 1. Annual total deposition of N across the UK, consisting of wet and dry deposition of oxidised and reduced N. Taken from the NEGTAP report (1996).

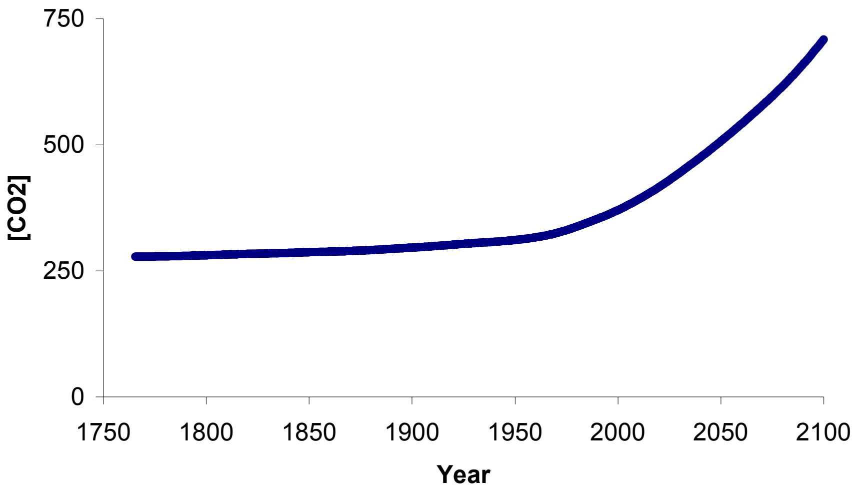


Figure 2. The scenario of historic and future changes in atmospheric CO_2 concentration assumed to occur at all sites in this study.

Table 2. Indication of geographical differences in climate change scenarios used for each of the six UK sites.

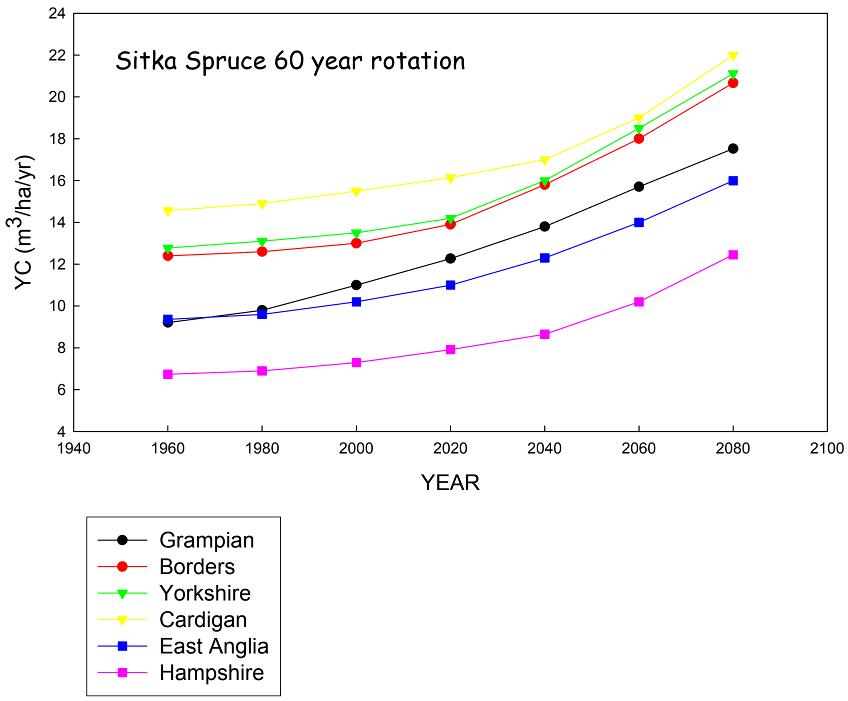
SITE		***Change in mean annual temperature / precipitation***	
		°C	% wrt 1961-90
1 Central Grampians	56°45'N 4°15'W	+2.3	+16
2 Scottish Borders	55°15'N 2°45'W	+2.5	+14
3 Yorkshire	53°15N 1°45'W	+2.5	+14
4 Cardigan	52°15'N 3°45'W	+2.7	+8
5 East Anglia	52°15'N 0°45'E	+2.8	+5
6 Hampshire	51°15'N 1°15'W	+3.2	+2

N.B. Annual figures disguise the monthly variations which were taken into account during simulations. E.g. Summer rainfall figures fall below current values for sites south of Yorkshire.

Future increases in Yield Class of Sitka spruce and beech

Figure 3 presents future increases in yield classes predicted by the EFM for both Sitka and beech plantation forests across all six UK sites. The model predicts a substantial increase in YC and consequently enhanced carbon sequestration capacity in response to future predicted climate, N deposition and CO_2 change scenarios. The simulation predicted present day YC values within the ranges currently measured across the UK for both conifer and deciduous plantations. Across the UK conifer YC values are predicted to steadily rise from 7.3 to 11 $m^3\ ha^{-1}\ y^{-1}$ at the slowest growing southerly site (Hampshire) and from around 13 to 22 $m^3\ ha^{-1}\ y^{-1}$ at the faster growing Welsh and Scottish sites. Whilst the YC of beech plantations will increase steeply both north and south of the border, those plantations growing in the most southerly regions will see a two fold increase in above ground productivity (Figure 3*b*).

(a)



(b)

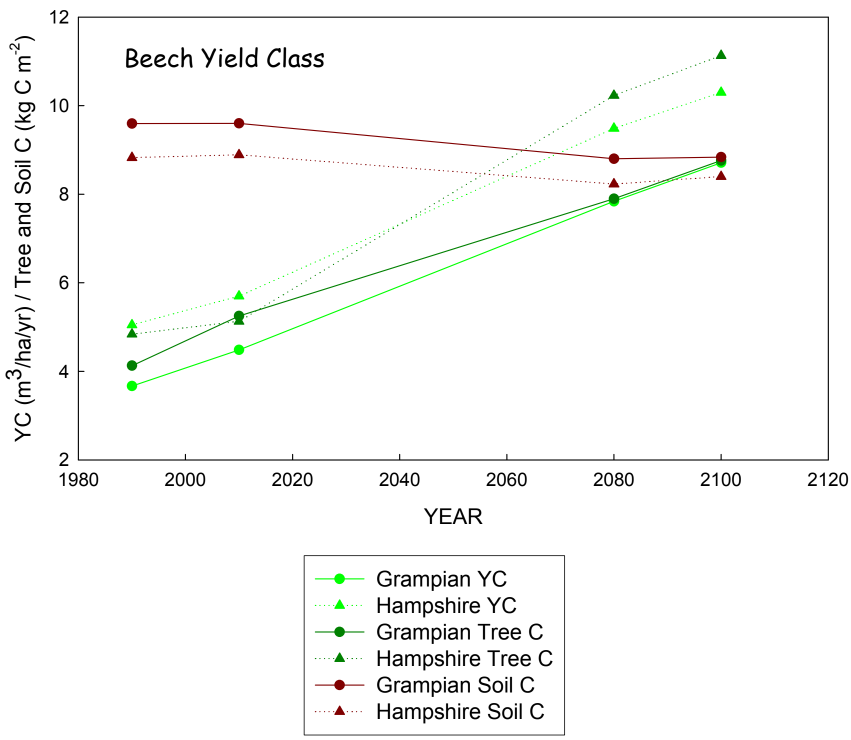


Figure 3. EFM predicted Yield Classes ($m^3ha^{-1}a^{-1}$) of a (a) 60 year rotation coniferous forest growing at six sites across the UK and (b) 90 year deciduous forest growing at two UK sites.

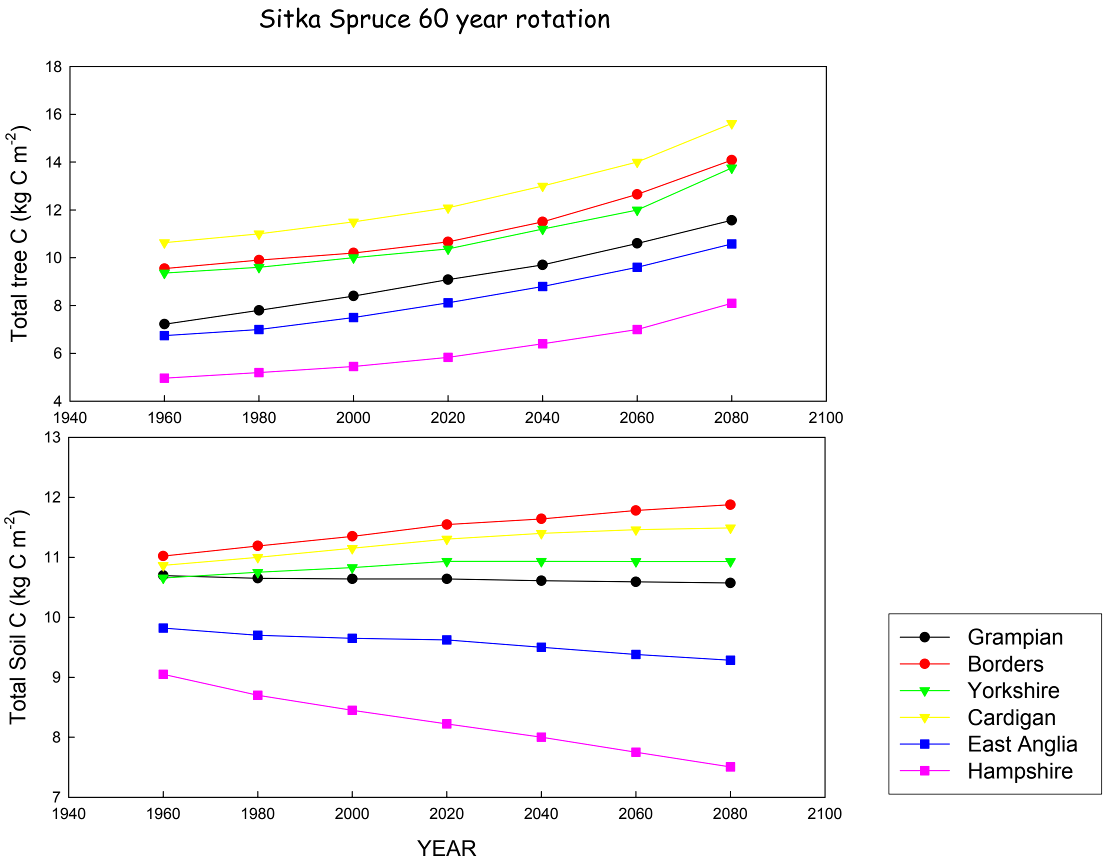


Figure 4. Changes in total above and below ground carbon contents of a 60-year rotation coniferous forest growing at six locations across the UK, between 1960 and 2080.

There was both an increase and decrease in total soil C across the sites (Figures 4 and 5). Borders, Yorkshire and Cardigan Bay all had small increases ranging from 4 to 0.7 %, while the remaining three sites had a decrease in soil C. Of those sites showing a decrease, Hampshire was the most affected at 13.5 %. This result may be attributable to increases in the decomposition rates of SOM resulting from the warmer temperatures, a theory that will be examined over the course of the next reporting period. Throughout the UK total tree C is predicted to increase gradually over the course of the next 100 years (Figure 4). This increase will be greatest at the most southerly site, Hampshire and smallest at the most northerly, Grampian. All six sites are predicted to have a net increase in C sequestration, with increases in total tree C outweighing the small if any decreases in total soil carbon. It is therefore predicted that in the future there will be a net increase in C sequestered in all conifer plantations throughout the UK. More significantly this increase will be greatest at the two sites in regions most currently populated by coniferous plantations, namely the Borders and Cardigan Bay. Consequently the total pool of C contained in coniferous UK forests is predicted to increase as a result of climate change, N and CO_2 fertilisation. That is, in the future forests will naturally become more effective carbon sinks, irrespective of any adoptive changes in forest management and silviculture practices.

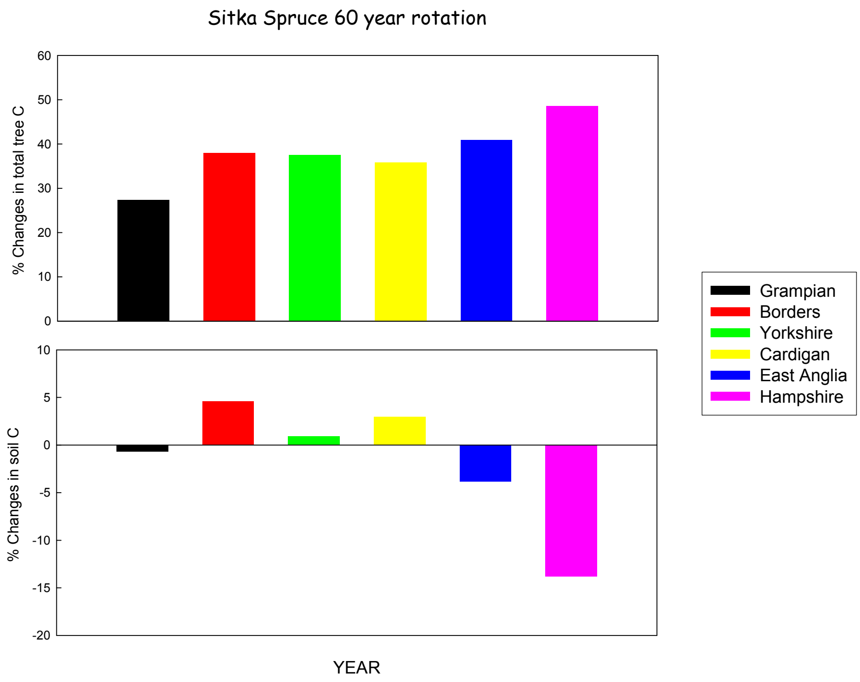


Figure 5. Predicted increases in tree and soil C content in response to increases in N deposition, atmospheric CO_2 concentration and climate change over the period 1960 to 2080.

Changes in carbon content attributable to specific shifts in atmospheric [CO_2], N deposition and climate change are given for a coniferous forest plantation growing in the Scottish borders in Table 3. At this site the large increases in tree C occurred because of the combined promotive effect of all three environmental factors while changes in soil C was primarily as a result of increased [CO_2]. Nearly 50 % of the enhancement in total tree C was attributable to increases in N deposition rates with the remainder being split 35, 16 % to [CO_2] and climate change respectively. The positive response to soil C content at this site was entirely due to increased [CO_2]. Both N deposition and climate change were both shown to have a detrimental impact upon soil C accumulation. It is likely that increasing temperatures caused the C flux from SOM (decomposition) to accelerate resulting in the small decrease in soil C observed under the climate change only scenario.

Table 3. Predicted changes in carbon content of a coniferous plantation in southern Scotland in response to climatic change, increased N deposition and increased [CO_2] over the period 1900 to 1980.

Scottish Borders 55°15'N 2°45'W

	Tree C	Soil C
[CO_2]	35 %	100 %
N deposition	49 %	-1 %
Climate Change	16 %	-9 %

A similar scenario is predicted by the EFM for deciduous plantation forests to that of coniferous ones. Associated with a predicted increase in stem volume production total stand C will increase considerably (Figure 3b). In line with results obtained for the conifer plantation, total soil C is predicted to decrease while total tree C increases, again resulting in a net gain in sequestered ecosystem C (Figure 3b).

Conclusions

In the UK rising [CO_2], climate change and increased N deposition rates have had and are having a positive effect on forest growth, productivity and hence C sequestration. Increased N deposition alone will have a positive impact on forest growth and in combination with elevated [CO_2] will amplify this response. Future YC of Sitka and beech will continue to differ across the UK, with more northerly sites continuing to be the most productive for Sitka and southerly one for beech.

The resulting increase in tree C accumulation attributable to human induced activities will increase by 27% in Grampian to 48% in hampshire. However in Hampshire conifer YC are lower than the rest of the UK and soil C contents are predicted to decrease so the absolute increase in C sequestered is likely to be less than at other sites.

The results of this study suggest that future UK climatic conditions as predicted by the HaDCM3 global climate model will increase yield class and hence carbon sequestered by managed forests. Currently N would appear to be a limiting factor contributing to some 49 % of this increase.

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