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Competing roles of rising CO_2 and climate change in the contemporary European carbon balance

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Abstract

Natural ecosystems respond to, and may affect climate change through uptake and storage of atmospheric CO_2. Here we use the land-surface and carbon cycle model JULES to simulate the contemporary European carbon balance and its sensitivity to rising CO_2 and changes in climate. We find that the impact of climate change is to decrease the ability of Europe to store carbon by about 175 TgC yr^{-1}. In contrast, the effect of rising atmospheric CO_2 has been to stimulate increased uptake and storage. The CO_2 effect is currently dominant leading to a net increase of around 150 TgC yr^{-1}. Our simulations do not at present include other important factors such as land use and management, the effects of forest age classes and nitrogen deposition.

There seems to be an emerging consensus that changes in climate will weaken the European land-surface's ability to take up and store carbon. It is likely that this effect is happening at the present and will continue even more strongly in the future as climate continues to change. Although CO_2 enhanced growth currently exceeds the climate effect, this may not continue indefinitely. Understanding this balance and its implications for mitigation policies is becoming increasingly important.

1 Introduction

Natural ecosystems have been shown to not only respond to climate change, but also to be able to influence it. The global carbon cycle currently absorbs about half of anthropogenic emissions of CO_2, but the processes which control it are known to be sensitive to climate. Potentially large feedbacks between climate and the carbon cycle could significantly accelerate the rate of climate change (Cox et al., 2000). A recent study found strong consensus that future climate change would decrease the ability of the terrestrial carbon cycle to absorb anthropogenic carbon, but the magnitude of this feedback is very uncertain (Friedlingstein et al., 2006).

It is essential to be able to understand and predict the behaviour of the terrestrial carbon cycle in order to determine appropriate mitigation policies for stabilising climate change. Without knowing the impact of climate on natural carbon uptake, it is not possible to determine the implications of future carbon emission reduction policies (Jones et al., 2006a). The amount of permissible emissions to achieve climate stabilisation is uncertain and strongly dependent on the strength of the climate-carbon cycle feedback (Jones et al., 2006b).

Globally, the land biosphere takes up about 25% of fossil fuel and deforestation emissions (Prentice et al., 2001) but our understanding of this carbon sink, mainly located north of the Tropics, is incomplete. Its partitioning regionally between Europe, North America and Asia, and into its controlling mechanisms and its vulnerability to changes in climate are important steps, but still very uncertain. CarboEurope-IP aims to understand and quantify the present terrestrial carbon balance of Europe and its controlling mechanisms such as climate change and variability, and changing land management practices.

Across Europe we expect many processes to contribute to net annual carbon balance. Land use and management is especially important. Several studies have shown a negative impact of agriculture on terrestrial carbon storage. Simulations by Bondeau et al. (2007) predict that globally agriculture has decreased vegetation carbon storage by 24% and soil carbon storage by 10%. On a local scale, Miglietta et al. (2007) found that a European agricultural area could be a net source of carbon even in summer when growth might be expected to be greatest. Across Europe, Janssens et al. (2005) found that crop lands are net annual sources of carbon whilst non-crop regions are carbon sinks. Meanwhile, expansion of European forest area, forestry management practices and Nitrogen deposition are likely to create a substantial carbon sink (Janssens et al., 2005; Ciais et al., 2005a). CO_2 fertilisation (Norby et al., 2005; Ciais et al., 2005b) and changes in long-term climate (Davi et al., 2006) will also affect European carbon storage.

In this paper we neglect land-use and management effects, but plan to include them in future work, and attempt to quantify the competing roles of rising CO_2 and climate change in the contemporary European carbon balance. Previous studies have shown the importance of both of these drivers and the balance between them for global and regional carbon balance (Cox et al., 2000; Friedlingstein et al., 2006; Sitch et al., 2007[1]). Rising CO_2 levels stimulate plant growth, whereas climate change can accelerate decomposition and in some regions reduce productivity (often through drought limitation). At least part of the present day global terrestrial carbon sink is likely due to CO_2 fertilisation (Norby et al., 2005), but the size of the effect is uncertain and varies regionally (Ciais et al., 2005b). Similarly, impacts of climate warming and hydrological changes on productivity and decomposition are uncertain both in local studies (Reichstein et al., 2007; Dunn et al., 2007) and in terms of global modelling (Matthews et al., 2005; Jones et al., 2005).

Here we build on the European biosphere simulations of Vetter et al. (2007)[2] and present results from simulations where we separate and quantify the competing effects of CO_2 and climate on contemporary European carbon balance.

2 Experimental design

JULES (Joint UK Land Environment Simulator) is a UK community land-surface model. It is based on the MOSES-2 land surface scheme (Essery et al., 2003) used in the Hadley Centre climate model HadGEM (Johns et al., 2006). It also incorporates the

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TRIFFID DGVM (Cox 2001; Cox et al., 2000).

JULES estimates carbon, water and energy fluxes. In this study we follow the experimental protocol of Vetter et al. (2007)[2] JULES is driven by prescribed climate data from the REMO regional model. The REMO dataset includes daily mean meteorological parameters between 1948 and 2005. In this study sub daily variations of temperature, shortwave radiation and precipitation have been imposed on the daily mean driving data. JULES dos not simulate crops (which are represented as natural C3 grasses) and crop management. In this study land surface types are prescribed and held constant.

We have conducted two simulations. In both simulations the model was spun-up to equilibrium by repeating the first decade of driving data. Following the spin-up, in the first simulation, "climate and CO_2", both climate and CO_2 change between pre-industrial (1850) and the present day have been imposed. Prior to 1948 the first decade of climate data was cycled, as during the spin-up. From 1948 onwards changing climate is supplied. In the second, "climate" atmospheric CO_2 has been imposed at a constant pre-industrial level to isolate the influence of climate. The effect of observed CO_2 rise on carbon balance can be inferred from the difference between the "climate" and CO_2 and "climate" simulations.

To maintain compatibility with the CarboEurope-IP study of Vetter et al. (2007)[2], our analysis focuses on the same four regions (North, West, Central and East) to examine the regional variation in terrestrial CO_2 exchange.

3 Results

3.1 Impact of climate

3.1.1 Climate variability

The results of our two experiments with and without rising CO_2 clearly show that climate variability is the dominant control of terrestrial carbon cycle inter-annual variability. Figure 1 shows a timeseries of net ecosystem productivity (NEP, defined here as positive for terrestrial uptake) from 1980 to 2005 from both simulations. The near constant offset is due to the different CO_2 concentrations as discussed below, but the timing and magnitude of the variability is almost identical.

Vetter et al. (2007)[2] discuss the impact of an extreme climate event in 2003 on the European carbon balance, and conclude that the climate event drove a net reduction in carbon uptake in summer 2003 of up to 0.3 GtC. Ciais et al. (2005a) came to similar conclusions, with an anomalous source of about 0.5 GtC. Understanding such sensitivity of carbon flux and storage to climate variability is extremely important for improving our understanding of the sensitivity of the terrestrial carbon cycle to future climate change. The C4MIP study (Friedlingstein et al., 2006) demonstrated the large uncertainty associated with climate-carbon cycle modelling, and Jones et al. (2006b) showed the difficulty of constraining this feedback with observational evidence. Better understanding of inter-annual variability in the biosphere is essential to our understanding and reducing of uncertainty in future carbon cycle feedbacks.

3.1.2 Carbon storage

In the absence of rising CO_2, climate would, on average, drive a decrease in European carbon storage. Figure 2 presents the change in carbon storage (kg C m^{-2}) between 1980 and 2005 due to changes in climate only. The decrease in carbon storage is strongest in the south and west of Europe. From the West region an average carbon flux into the atmosphere of approximately 75 Tg C yr^{-1} is simulated in the 'climate' run. An average carbon flux into the atmosphere is also simulated in the Central and North regions although Scandinavia also represents a small sink. In the East region 'climate' drives a small increase of approximately 15 Tg C yr^{-1} in carbon storage.

The climate impact on carbon storage varies regionally. Where ecosystems are temperature limited in northern Europe (Reichstein et al., 2007), long term climate warming enhances carbon uptake and storage (Fig. 2).

Figure 3 shows seasonal changes in carbon fluxes in western Europe (using the same definition of sub-European regions as in Vetter et al., 2007[2]) from 1980s, 1990s and 2000–2005. Growing season changes throughout the period include a slightly earlier rise of NPP in February and March and later decrease of respiration from August to October. The net effect is little change in spring time carbon uptake, as respiration also begins to increase a little earlier to follow productivity, but there is a small decrease in the length of the carbon-uptake season due to an earlier autumn. Respiration persists for longer due to changes in climate, whereas NPP begins to decline in autumn slightly earlier. There is no discernable impact on the peak summer productivity or respiration levels – most of the changes happen in the timing of the seasons. Davi et al. (2006) did see greater uptake due to extended growing seasons, particularly in deciduous trees which experienced earlier bud-burst. Limitations of the phenology response of JULES may mean we underestimate the importance of this effect.

The other regions (not shown) all exhibit longer periods of high respiration into autumn before it decreases for winter, but changes in spring productivity are less widespread with most other regions showing little change in the onset of spring uptake. North and East regions also see raised summer peaks of respiration, but not productivity. Hence the overall result of these changes to the seasonal carbon flux is that respiration increases exceed productivity and there is a decreased total carbon uptake.

Changes in the growing season length are an oft cited potential cause of changes in carbon uptake. Since Myneni et al. (1997) reported greening of boreal forest ecosystems in the NDVI satellite record, increased growing season length has attracted much attention as a significant contribution to the net terrestrial carbon sink. However definitions of growing season, either phenological (such as length of leaf-on period), or defined by levels of GPP do not necessarily correspond to carbon uptake. As discussed in Valentini et al. (2000), NDVI greening does not necessarily imply carbon storage. Reichstein et al. (2007) show how GPP and ecosystem respiration covary with temperature and hence the net carbon balance is less strongly affected. By the same reasoning if increased temperature in spring increases ecosystem respiration as well as productivity, then a longer growing season may not increase carbon storage. Dunn et al. (2007) found respiration could exceed GPP as early in the summer as July in a boreal black spruce forest. Our results confirm that growing season changes in response to climate change may not necessarily increase carbon storage and may even decrease it.

Elsewhere in Europe, where growth is not typically temperature limited (especially in the south and west), warmer conditions and drier summers contribute to decreased productivity. Decreases in the south dominate over increases in the north and the net climate impact on European carbon balance is to decrease carbon storage (Fig. 2).

The climate impact on carbon storage is interrupted in the early 1990s with a clear period of increased uptake apparent in Fig. 1. This corresponds to a period when the climate may have been perturbed by the Pinatubo eruption of July 1991. Fischer et al. (2007a) show cooler wetter summers and warmer wetter winters in northern Europe following major volcanic eruptions, and both of these could have locally decreased carbon storage through decreased summer productivity and enhanced winter respiration. More significantly, cooler, wetter summers in the Mediterranean ecosystems of southern Europe could have substantially increased growth in the post-Pinatubo period.

We conclude that in the absence of any other factors than changing climate European land surface would be a source of carbon of about 174 $\mathrm{TgC\,yr^{-1}}$, and that the present day European carbon sink would be stronger still in the absence of climate change.

3.2 Impact of rising CO_2

Figure 4 shows the simulated net long term (1980–2005) carbon uptake by European Region, due to climate, observed CO_2 increase, and a combination of the two. In all regions observed CO_2 increase results in additional uptake and storage by the land. Conversely, over the period 1980–2005, climate drives a net release of CO_2 from the land surface and all regions except the East. The resulting overall uptake varies by region from approximately 110 Tg C yr^{-1} in the East to less that 5 Tg C yr^{-1} in the West.

Climate driven carbon flux into the atmosphere from Mediterranean ecosystems dominates the signal in the West and Central Regions (Fig. 2). In the North region the climate driven CO_2 flux is into the atmosphere over the UK and Ireland and out of the atmosphere over Scandinavia.

Global terrestrial carbon uptake for the 1980s was around 1900 Tg yr^{-1} (Prentice et al., 2001) not including land-use emissions. Janssens et al. (2003) estimate a net European uptake of around 135 and 205 TgC yr^{-1}. This compares well with our estimate of a mean sink of around 150 TgC yr^{-1} since 1980. Clearly an exact comparison with real estimates is not useful because our study neglects some very important factors such as the impact of land-management, land-use change and the dynamic response of vegetation. However, some of these factors may be opposing in sign, such as increased uptake in managed forests and carbon sources from agriculture. Our simulations indicate that the magnitude of the climate and CO_2 effects are comparable with observed estimates of the current net carbon balance of Europe.

Figure 5 shows the influence of observed CO_2 rise on increased carbon storage. Observed CO_2 rise drives an increase in carbon storage directly through CO_2 fertilisation. Additionally, although Reichstein et al. (2006) show how water use efficiency tends to be conserved across climatic events such as the 2003 drought, we might expect to see long-term changes due to CO_2 rise. This may lead to an indirect impact of CO_2 on productivity through enhanced water use efficiency. As atmospheric CO_2 concentration increases plants close stomata and transpire less water, increasing resistance to drought.

There is a clear latitudinal gradient of increased uptake, with the strongest increases in the south. Simulated soil moisture stores increase slightly, especially in the south, when observed CO_2 rise is prescribed compared with the climate-only simulation, presumably due to reduced evapotranspiration but constant precipitation. In these experiments with prescribed climate forcing there is no provision for the land-surface to feedback onto weather. Increased water-use efficiency in southern water-limited ecosystems has contributed to the north-south gradient of CO_2 induced uptake. Comparison of the vegetation and soil carbon stores shows that the increased productivity does not result in increased carbon storage in biomass; instead it is stored in the soil.

4 Discussion

Future work will assess which components of climate contribute to carbon flux variability, but it is likely that no single component is solely responsible. Temperature is often the focus of attention, as climate change is characterised by changes in global mean temperature, but in itself it may not be the most important factor. Reichstein et al. (2007) show how north European ecosystems are temperature limited and would therefore respond to climate warming, but elsewhere in Europe, water limitation is a stronger control on productivity. Ciais et al. (2005a) and Reichstein et al. (2006) both discuss how the 2003 carbon flux anomaly in Europe was likely driven more by the drought than the heatwave. Both GPP and ecosystem respiration were inhibited by the drought, but the GPP response dominated. However, in less water limited systems, water plays a less important role (Hibbard et al., 2005) and in some ecosystems carbon decomposition in peat rich soils is inhibited by increased precipitation and so drought could enhance respiration (Dunn et al., 2007).

In discussing the drought effect on ecosystems we mean it in terms of reduced soil moisture. Clearly, precipitation is a strong control on soil moisture, but temperature also plays a role. If warmer temperatures increase evaporation, then they can indirectly affect vegetation and soil activity through changes in moisture. Land-surface and ecosystem models are not generally driven by observed soil moisture values, but rather simulate soil water themselves in response to driving climate data. Hence it should be remembered that analysis of these model's hrydrological simulation may be as important as their carbon flux simulation in determining the ecosystem response to changing conditions. The hydrology in JULES (MOSES-2) was found to perform well in recent GSWP2 offline tests (Guo and Dirmeyer, 2006) and when coupled in HadGEM AR4 simulations (Li et al., 2007). Fischer et al. (2007b) show another important feedback involving moisture. They found that atmosphere-land surface coupling in Europe could be significant on seasonal timescales. In particular they conclude that when dry springs precede hot summers (as was the case in 2003), then reduced latent cooling can amplify the strength of the summer heatwave.

Solar radiation during the growing season is also important, and may be inversely related to precipitation. When it is unusually dry, there may be less cloud and hence more available light, offsetting the drought induced decrease in productivity. Weedon et al. (2007)[3] find radiation in Europe is more closely linked to CO_2 changes than temperature except in the North. Long-term changes in anthropogenic aerosol (Stanhill and Cohen, 2001; Roderick et al., 2001) may affect both the total light amount and the proportion of direct to diffuse radiation. More diffuse radiation can better penetrate the vegetation canopy and enhance productivity. Natural aerosol from volcanic eruptions, such as Pinatubo in 1991, may also have had a significant impact on global carbon balance (Gu et al., 2003; Angert et al., 2004) but this effect is not included in our driving data, although the climate effect of Pinatubo is (Fischer et al., 2007a).

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5 Conclusions

In this study we have used the land-surface and carbon cycle model JULES to simulate the contemporary European carbon balance and its sensitivity to rising CO_2 and changes in climate. We have found that the impact of climate changes since 1948 has been to decrease the ability of Europe to store carbon by about 175 $TgC\,yr^{-1}$. In contrast, the effect of rising atmospheric CO_2 has been to stimulate increased uptake and storage. The CO_2 effect is currently dominant leading to a net increase of around 150 $TgC\,yr^{-1}$. Our results clearly do not represent a complete attribution of the European carbon balance, as other factors are likely to be at least as important. Incorporating land use and management, and the effects of forest age classes and nitrogen deposition are important developments which are required to further our understanding of carbon cycling at continental scales.

Davi et al. (2006) made a similar attempt to assess the relative impacts of climate change and rising CO_2 on European carbon storage. Like us, they found increased storage as a result of climate changes and increased uptake due to fertilisation from rising CO_2. The CO_2 increase dominated, but by less so in their case than in our simulations. Their simulations covered the period 1960–2100 and so it would be expected that stronger climate changes by the end of this century increase the climate-driven decrease in carbon storage. Reichstein et al. (2007) also discuss that climate changes, and in particular warming, should not be assumed to increase carbon uptake. There seems to be a consensus that changes in climate will weaken the European land-surface's ability to take up and store carbon. It is likely that this effect is happening at the present and will continue even more strongly in the future as climate continues to change. Although CO2 enhanced growth currently exceeds the climate effect, this may not continue indefinitely. Understanding this balance and its implications for mitigation policies is becoming increasingly important.

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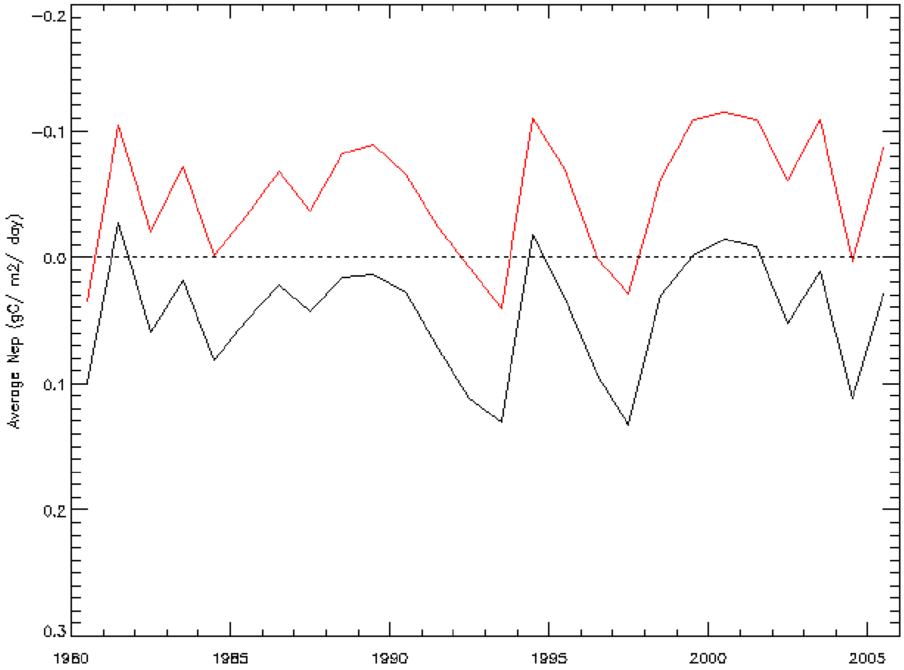

Fig. 1. Annual mean European NEP 1980–2000. The black line is from a simulation that prescribes climate and CO_2 change. The red line is from a simulation with constant CO_2.

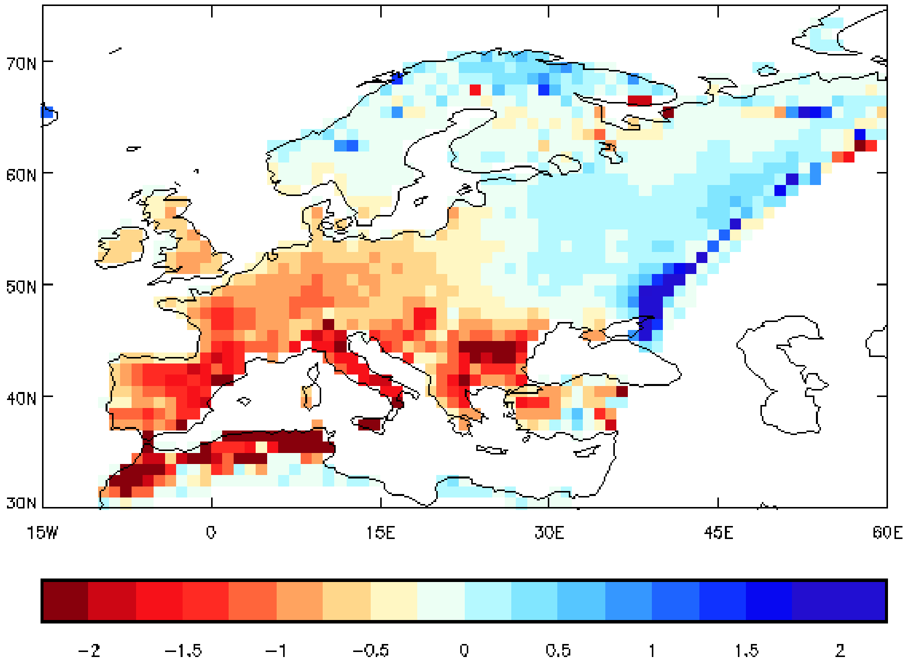

Fig. 2. Change in Carbon Storage (kg C m^{-2}) between 1980 and 2005 due to changes in climate only.

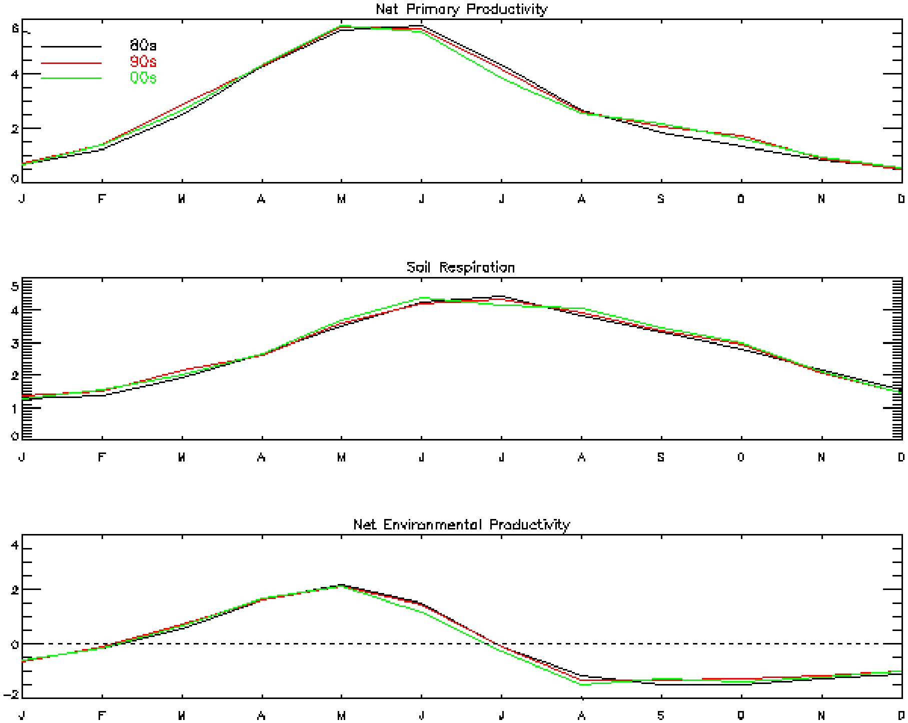

Fig. 3. Decadal seasonal average changes in carbon fluxes for the West Europe region. Top panel – NPP, centre panel – soil respiration, and bottom panel – NEP, for the 1980s – green line, 1990s red line and 2000–2005 – black line.

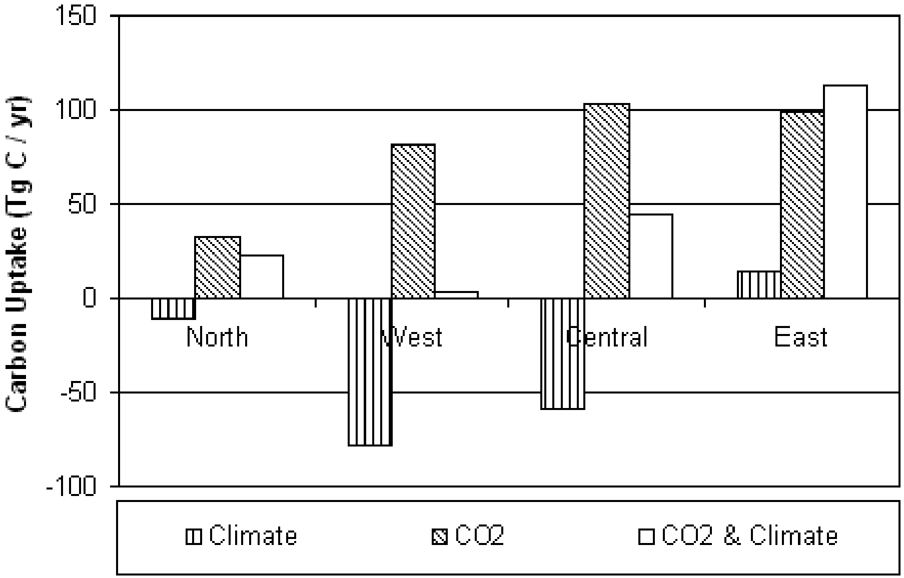

Fig. 4. Net long term carbon uptake in Tg C/yr by European region due to climate, observed CO_2 rise and a combination of both (CO_2 and Climate).

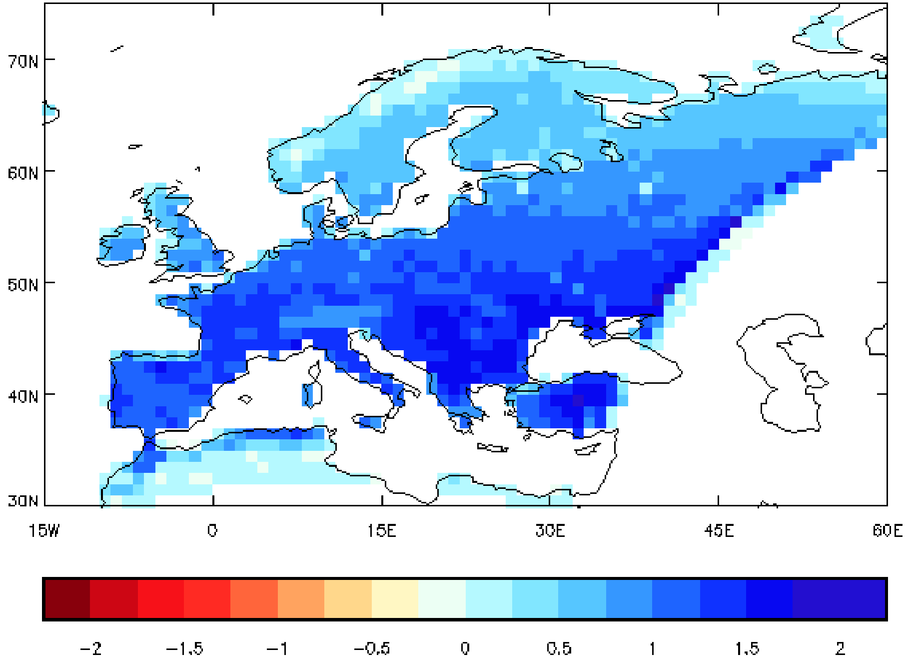

Fig. 5. The impact of observed CO_2 rise on carbon storage ($kg\,C\,m^{-2}$) between 1980 and 2005. Calculated from the difference in between the "CO_2 and climate" and "Climate" runs.