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Competing roles of rising CO₂ 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 CO₂. Here we use the land-surface and carbon cycle model JULES to simulate the contemporary European carbon balance and its sensitivity to rising CO₂ and changes in climate. We find that the impact of climate change is to decrease the ability of Europe to store carbon by 97 TgC yr⁻¹. In contrast, the effect of rising atmospheric CO₂ has been to stimulate increased uptake and storage. The CO₂ effect is currently dominant leading to a net increase of 114 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. 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 CO₂, 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

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(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 (Stephens et al., 2007). 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., 2005b; Magnani et al., 2007). CO₂ 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 CO₂ and climate change in the contemporary European carbon balance. Previous studies

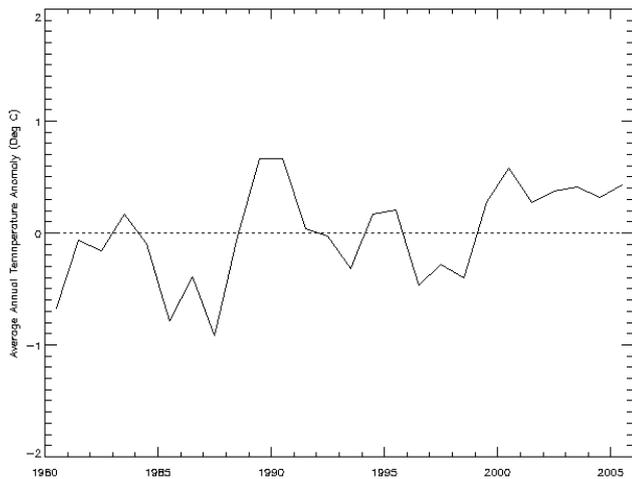


Fig. 1. European average annual temperature anomaly (°C), relative to 1980–2005 average.

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). Rising CO₂ 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 CO₂ 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) and present results from simulations where we separate and quantify the competing effects of CO₂ and climate on contemporary European carbon balance.

2 Model description and experimental design

JULES (Joint UK Land Environment Simulator, <http://www.jchmr.org/jules/>) is a UK community land-surface model. It is based on the MOSES2 land surface scheme (Essery et al., 2003) used in the Met Office Hadley Centre climate model HadGEM (Johns et al., 2006). It also incorporates the TRIFID DGVM (Cox, 2001; Cox et al., 2000). In JULES stomatal conductance connects transpiration and the influx of carbon dioxide for photosynthesis and is a third-generation land surface processes model (Sellers et al., 1997). An impact of increased atmospheric CO₂ is therefore to increase CO₂ available for photosynthesis and also reduce the loss of moisture through the stomata (since the same amount of CO₂ is taken in through smaller stomatal openings; Cox et al. 1998).

The model of photosynthesis used in JULES is that of Collatz et al. (1991) for C₃-type photosynthesis and Collatz et al. (1992) for C₄-type photosynthesis, as described in Cox et al. (1999). Photosynthesis is also directly sensitive to the leaf nitrogen concentrations (specified) and the leaf temperature. JULES has a simplified representation of phenology for tree plant functional types. Details of this process are given in Cox (2001), Sect. 4. The phenological status alters the leaf area index (LAI) of the canopy and is solely a function of leaf temperature (with pre-specified tolerances to low temperatures) and includes the effects of leaf dropping and budburst in a way corresponding to a chill-day parametrization.

JULES is a new name for an existing model, MOSES2, which has been shown to improve the simulation of global surface climate when included in a climate model (Cox et al., 1999), but has also been tested at field site and hydrological catchment scales. Harding et al. (2000) validated MOSES against field site surface flux data from southern England. Harris et al. (2004) compared MOSES2 against field site data in Brazil demonstrating its ability to simulate surface fluxes, and Essery and Clark (2003) tested the impact of improved representations of snow processes on simulated run-off at the catchment scale (in Sweden), showing that MOSES2 was able to successfully simulate observed run-off.

When incorporated into a general circulation model (HadCM3LC, Cox et al., 2001), MOSES2 was able to well simulate observed global carbon cycle response to ENSO (Jones et al., 2001) and volcanic eruptions (Jones and Cox, 2001). When the GCM was forced with observed sea surface temperatures (Jones and Warnier, 2004), the terrestrial carbon cycle component was able to simulate regional 1990s carbon uptake in good agreement with observationally constrained estimates from the TransCom inversion study of Gurney et al. (2002). It has more recently been used for future climate change impact projections, in which representing the connection of moisture use efficiency and atmospheric CO₂ concentration is critical (Betts et al., 2007).

JULES differs from MOSES2 scientifically in its inclusion of a more sophisticated representation of the vertical profiles of light and nitrogen through the canopy (Mercardo et al., 2007). Global simulations using JULES show that this innovation improves large-scale predictions of GPP (Alton et al., 2007). Mercado et al. (2007) showed that improved representation of the vertical profiles improved simulated carbon fluxes when compared against site data for a coniferous forest site in Netherlands.

In this study we follow the experimental protocol of Vetter et al. (2007) JULES is driven by prescribed climate data from the REMO regional model. The REMO dataset includes daily mean meteorological parameters between 1948 and 2005. Figures 1 and 2 show time series of European average temperature and precipitation respectively between 1980 and 2005 (the analysis period in this study). The first decade of driving data was used in the model spin-up. Figures 3

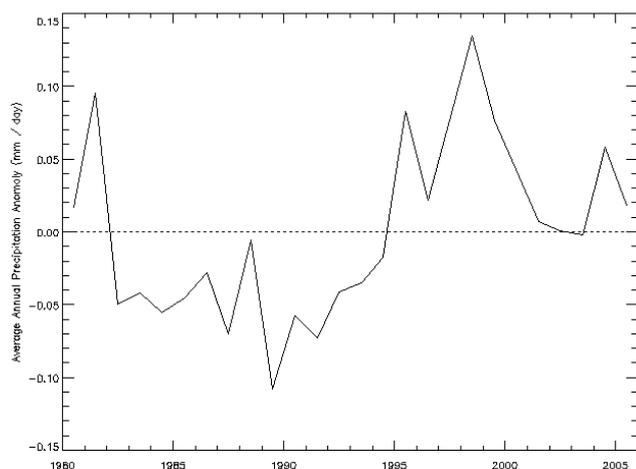


Fig. 2. European average annual precipitation anomaly (mm/day) relative to 1980–2005 average.

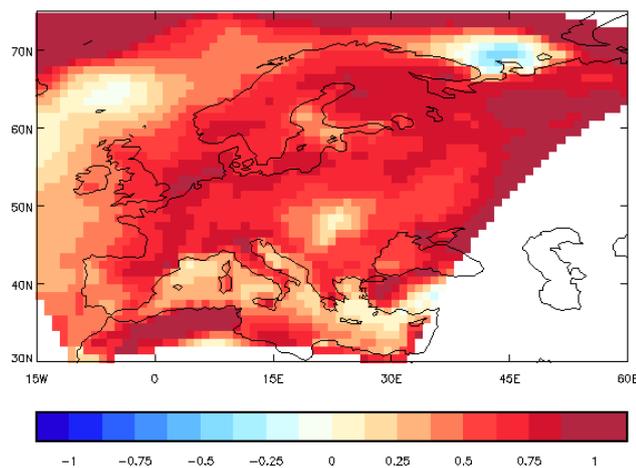


Fig. 3. Difference in annual average temperature (°C) between 1948–1959 (spin-up period) and 1995–2005.

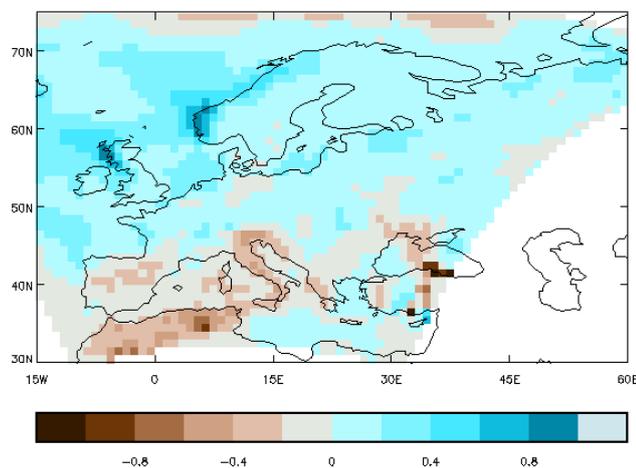


Fig. 4. Difference in annual average precipitation (mm/day) between 1948–1959 (spin-up period) and 1995–2005.

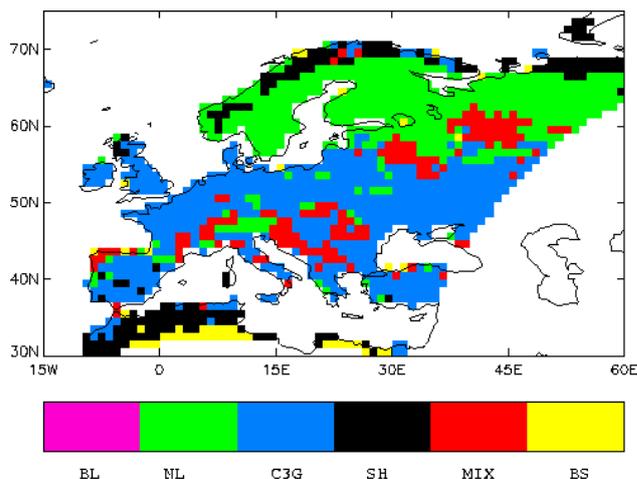


Fig. 5. Dominant vegetation fractions in each model grid cell. BL is broad leaf tree, NL is needle leaf tree, C3G is C3 grass, SH is shrub, MIX is BL and NL both >30%, and BS is bare soil.

(for temperature) and 4 (for precipitation) illustrate the difference in the climate of 1948–1959 and 1995–2005. The last decade, particularly outside the Mediterranean region, was generally warmer and wetter than the decade used for model spin-up. In this study sub daily variations of temperature, shortwave radiation and precipitation have been imposed on the daily mean driving data.

The vegetation dynamics component of JULES is disabled in this study, and vegetation fractions are held static throughout the experiments, using the same configuration as was used in Vetter et al. (2007) and are based on the SYNMAP database (Jung et al., 2006). SYNMAP is a database of modern vegetation distributions, including the effects of land-use change (large-scale conversion from forest to grass/crops). The vegetation fractions applied in this study are shown in Fig. 5. JULES has 5 vegetation classes, broadleaf and needleleaf tree, C3 and C4 grass and shrub. As JULES does not explicitly simulate crop growth, crop areas are treated as natural C3 grass in this study. The impact of land-use change is apparent in SYNMAP where grass dominates south of 55° N. Needleleaf trees dominate land north of 55° N.

We have conducted two simulations, following similar methodology to Vetter et al. (2007), but at a spatial resolution of 1°. 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, both climate and CO₂ changes 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, atmospheric CO₂ has been imposed at a constant pre-industrial level (285 ppm) to isolate the influence of climate. The effect of observed CO₂ rise on carbon balance can be inferred from the difference between the two simulations.

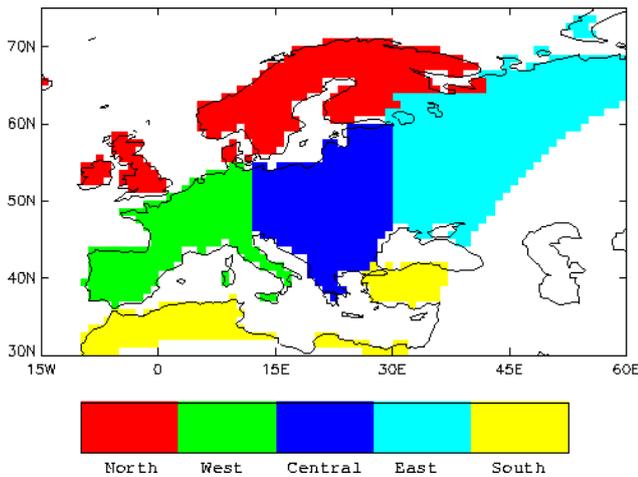


Fig. 6. Study analysis regions.

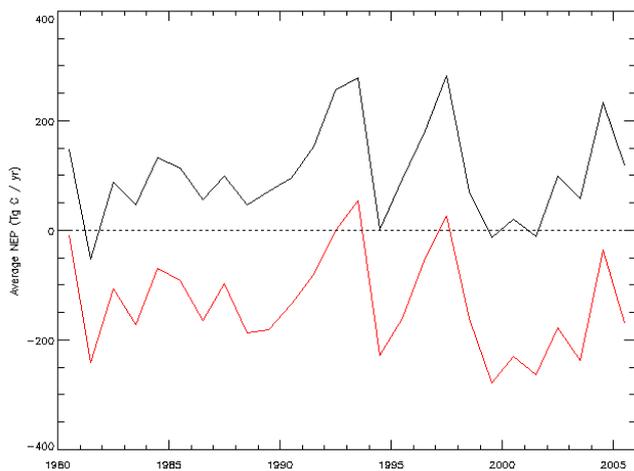


Fig. 7. Annual mean European NEP (Tg C/yr) 1980–2005. The black line is from a simulation that prescribes climate and CO₂ change. The red line is from a simulation with constant CO₂.

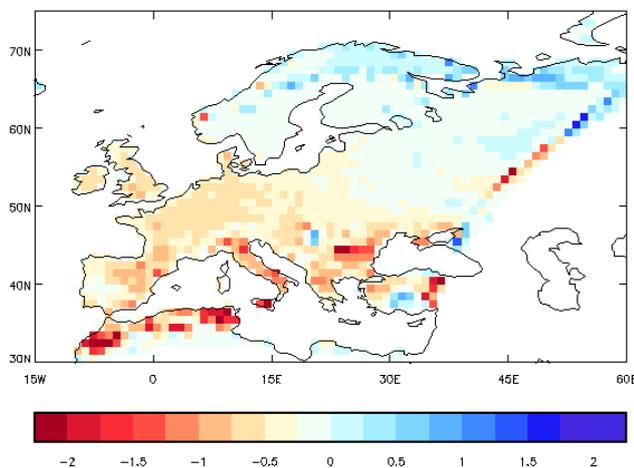


Fig. 8. Change in Carbon Storage (kg C m^{-2}) between 1980 and 2005 due to changes in climate only.

To maintain compatibility with the CarboEurope-IP study of Vetter et al. (2007), our analysis focuses on the same four regions (North, West, Central and East), shown in Fig. 6, to examine the regional variation in terrestrial CO₂ exchange.

3 Results

3.1 Impact of climate

3.1.1 Climate variability

The results of our two experiments with and without rising CO₂ clearly show that climate variability is the dominant control of terrestrial carbon cycle inter-annual variability. Figure 7 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 CO₂ concentrations as discussed in Sect. 3.2, but the timing and magnitude of the variability is almost identical.

Vetter et al. (2007) 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. This anomaly was centred in western Europe, whereas for the whole continent, compensating regions of increased uptake reduced the net anomaly. JULES was one of the least sensitive of the models presented in Vetter et al. (2007) to the 2003 climate anomaly, and this is seen in the relatively small magnitude of carbon flux anomaly in Fig. 7. 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. Further analysis of the 2003 anomaly is underway to establish to what extent model differences are due to hydrological response to climatic drought, or to physiological response to hydrological drought.

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 global scale observational evidence. Better process based understanding of inter-annual variability in the biosphere is essential to our understanding and to reducing uncertainty in future carbon cycle feedbacks.

3.1.2 Carbon storage

In the absence of rising CO₂, climate would, on average, drive a decrease in European carbon storage. Figure 8 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.

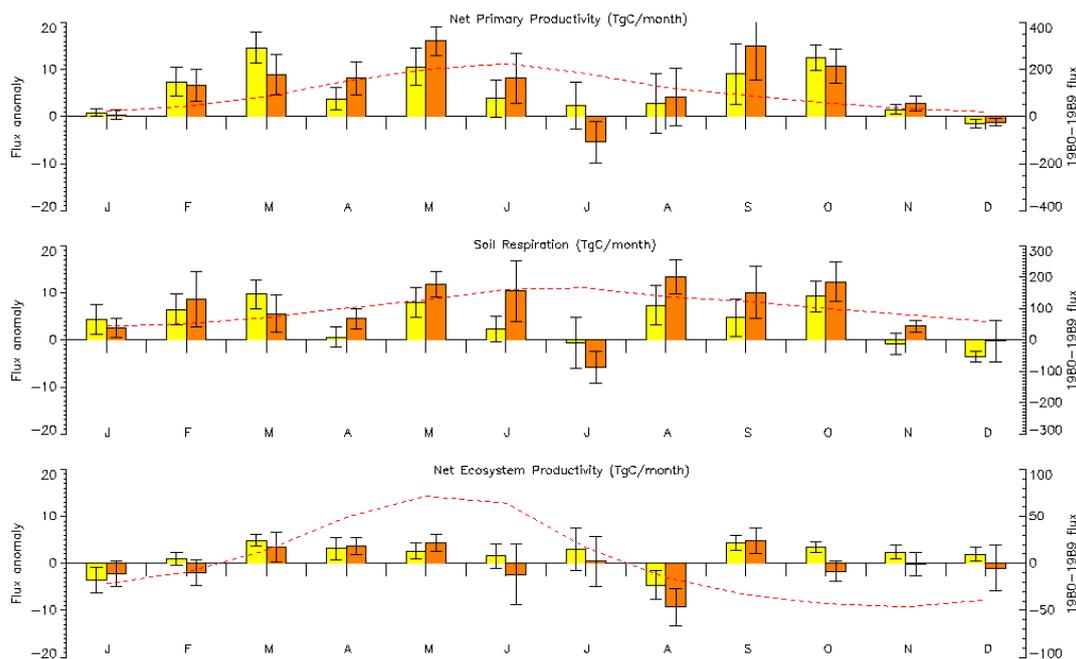


Fig. 9. Decadal seasonal average changes in carbon fluxes for the West Europe region (Tg C/month). Top panel – NPP, centre panel – soil respiration and bottom panel – NEP. Yellow and orange bars correspond to anomalies from the 1980–1989 mean seasonal fluxes (yellow – 1990–1999, orange – 2000–2005), with error bars showing the standard error associated with the decadal means (corresponding to the left axes). The red, dashed line shows the 1980–1989 mean seasonal cycle for each field (corresponding to the right axes). Both axes have units of Tg C/month.

An average carbon flux into the atmosphere is simulated in all regions in the simulation with constant CO₂. This flux ranges from 41 Tg C yr⁻¹ in the West region to 7 Tg C yr⁻¹ in the North region.

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. 8).

Figure 9 shows seasonal changes in carbon fluxes in western Europe from the 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 cessation of carbon uptake as the carbon release period begins earlier. Respiration persists for longer due to changes in climate, and increasing NPP in September and October decreases carbon loss in Autumn and early Winter. There is only a small 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 budburst. The relatively simplistic representation of phenology response in JULES may mean we underestimate the impor-

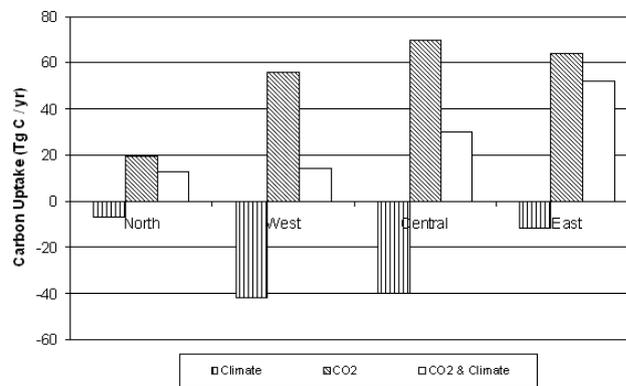


Fig. 10. Net long term carbon uptake in Tg C/yr by European region due to climate, observed CO₂ rise and a combination of both (CO₂ and Climate).

tance of this effect. JULES represents changes in phenological state through simulated leaf area which responds to leaf onset once temperatures exceed a given threshold (specific to each plant functional type). The limited number of plant functional types in JULES is also clearly insufficient to study such changes at the species-level detail of Davi et al. (2006).

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

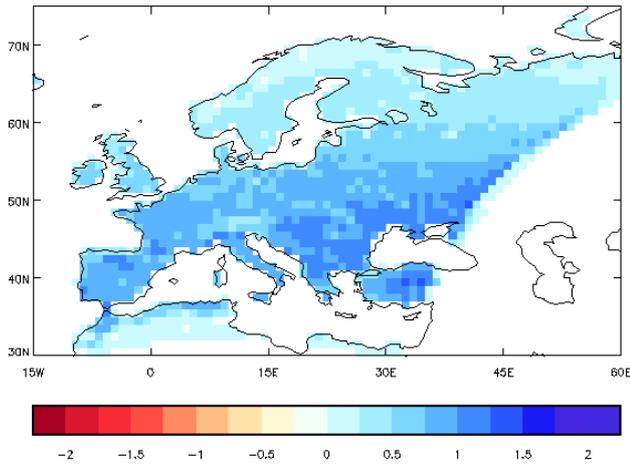


Fig. 11. The impact of observed CO₂ rise on carbon storage (kg C m^{-2}) between 1980 and 2005. Calculated as the difference between a simulation that prescribes climate and CO₂ change and a simulation with constant CO₂.

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. 8).

The climate impact on carbon storage is interrupted in the

early 1990s with a clear period of increased uptake apparent in Fig. 7. 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 97 TgC yr^{-1} .

3.2 Impact of rising CO₂

Figure 10 shows the simulated net long term (1980–2005) carbon uptake by European Region, due to climate, the observed CO₂ increase, and a combination of the two. In all regions observed CO₂ increase results in additional uptake and storage by the land. Conversely, over the period 1980–2005, climate drives a net release of CO₂ from the land surface in all regions. The resulting overall uptake varies by region from 54 TgC yr^{-1} in the East to 13 TgC yr^{-1} in the North.

Climate driven carbon flux into the atmosphere from Mediterranean ecosystems dominates the signal in the West and Central Regions (Fig. 8). In the North region the climate driven CO₂ flux is into the atmosphere over the UK and Ireland and out of the atmosphere over Scandinavia leading to a smaller net signal from climate change.

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 between 135 and 205 TgC yr^{-1} . This compares well with our estimate of a mean sink of 114 TgC yr^{-1} since 1980. Clearly an exact comparison with real estimates is of limited use 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 CO₂ effects are comparable with observed estimates of the current net carbon balance of Europe.

Figure 11 shows the influence of observed CO₂ rise on carbon storage. Observed CO₂ rise drives an increase in carbon storage directly through CO₂ 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 CO₂ rise. This may lead to an indirect impact of CO₂ on productivity through enhanced water use efficiency. As atmospheric CO₂ concentration increases plants

close stomata and transpire less water (Betts et al, 2007), 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 CO₂ rise is prescribed compared with the climate-only simulation, presumably due to reduced evapotranspiration but identical 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 CO₂ induced uptake.

The effect of elevated CO₂ is to increase GPP, NPP and soil respiration relative to the climate-only simulation. When only climate changes, those regions of Europe dominated by grass (Fig. 5) have a reduced carbon content by the end of the simulation (relative to the period 1980–1989), typically on the order of 0.075 kgC m⁻² but with spatial heterogeneity. Under elevated CO₂ levels the increased NPP produces an increase in vegetation carbon over most of Europe of the order of 0.1–0.2 kgC m⁻². Vegetation carbon content in regions dominated by Needleleaf trees increases in both simulations, typically by 0.1 kgC m⁻².

Soil carbon content in both simulations strongly reflects the overlying PFT; grass dominated regions have soil carbon contents between 10 and 25 kgC m⁻² and regions dominated by Needleleaf PFT typically have soil carbon contents between 3 and 15 kgC m⁻² (in both simulations). The impact of climate change only on the soil carbon pool is a decrease in carbon content by the end of the simulation relative to the 1980s, of the order of 0.3–0.5 kgC m⁻². This signal is strongest south of 55° N and corresponds to regions of high carbon content (associated with grass dominated regions). This region experiences a surface warming of around 0.1–0.3°C and an increase in soil moisture content by up to 25 kg m⁻² in the top 3 m of soil. In JULES soil carbon decomposition is sensitive to soil moisture content and temperature and proportional to the soil carbon amount (Cox, 2001). When rising CO₂ levels are included soil carbon content increases by the end of the simulation relative to the 1980s. This increase is strongest in Spain, France and also in eastern Europe where the increase is typically between 0.375 and 0.75 kgC m⁻². There are only small differences in soil moisture content or temperature when CO₂ rises are included and the sensitivity of stomatal conductance to atmospheric CO₂ has a negligible impact on the soil conditions in this simulation and is not likely to have affected soil respiration. The increased soil respiration and soil carbon content are therefore driven by the increased carbon input from vegetation. In regions dominated by Needleleaf tree soil carbon content is largely unchanged. In regions dominated by shrub (north of 65° N) soil content increases in both simulations relative to the 1980s, by around 0.15 kgC m⁻².

Therefore, the increased carbon storage of the European terrestrial carbon cycle reflects increases in both vegetation

carbon and soil carbon contents, however in our simulations increased soil carbon content accounts for most of the storage. The increased soil carbon is, however, driven by the photosynthesis of the overlying PFT, with the main increase in storage associated with C3 type grass ecosystems.

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 as discussed in the following paragraphs. 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 hydrological simulation may be as important as their carbon flux simulation in determining the ecosystem response to changing conditions. The hydrology in JULES (MOSES2) 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. This is true in tropical forest ecosystems (Saleska et al., 2007), but to what extent it is true in temperate

ecosystems is not clear. 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).

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 CO₂ 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 97 TgC yr⁻¹. In contrast, the effect of rising atmospheric CO₂ has been to stimulate increased uptake and storage. The CO₂ effect is currently dominant leading to a net increase in stored carbon of 114 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 CO₂ on European carbon storage. Like us, they found decreased storage as a result of climate changes and increased uptake due to fertilisation from rising CO₂. The CO₂ 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 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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