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Climate change and its impact on soil and vegetation carbon storage in Kenya, Jordan, India and Brazil

Pete Falloon[a,*], Chris D. Jones[a], Carlos Eduardo Cerri[b], Rida Al-Adamat[c], Peter Kamoni[d], Tapas Bhattacharyya[e], Mark Easter[f], Keith Paustian[f], Kendrick Killian[f], Kevin Coleman[g], Eleanor Milne[h]

[a] The Met. Office, Hadley Centre for Climate Change, Fitzroy Road, Exeter, Devon EX1 3PB, UK
[b] CENA, Univ. de São Paulo, Av. Centenario 303, CEP 13400, 970 Piracicaba, Brazil
[c] Jordan Badia Research and Development Center, P.O. Box 902, Amman 11941, Jordan
[d] National Agricultural Research Laboratories, P.O. Box 14733, Nairobi, Kenya
[e] NBSS&LUP, ICAR, Amravati Road, Nagpur 440010, India
[f] The Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO 80523-1499, USA
[g] The Agriculture and Environment Division, Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK
[h] Department of Soil and Crop Science, Colorado State University, Fort Collins, CO 80523-1170, USA

Abstract

The terrestrial biosphere is an important global carbon (C) sink, with the potential to drive large positive climate feedbacks. Thus a better understanding of interactions between land use change, climate change and the terrestrial biosphere is crucial in planning future land management options. Climate change has the potential to alter terrestrial C storage since changes in temperature, precipitation and carbon dioxide (CO_2) concentrations could affect net primary production (NPP), C inputs to soil, and soil C decomposition rates. Climate change could also act as a driver for land use change, thus further altering terrestrial C fluxes. The net balance of these different effects varies considerably between regions and hence the case studies presented in this paper (the GEFSOC project countries Kenya, Jordan, Brazil, and India) provide a unique opportunity to study climate impacts on terrestrial C storage. This paper first presents predicted changes in climate for the four case study countries from a coupled climate-C cycle Global Circulation Model (HadCM3LC), followed by predicted changes in vegetation type, NPP and soil C storage. These very coarse assessments provide an initial estimate of large-scale effects. A more detailed study of climate impacts on soil C storage in the Brazilian Amazon is provided as an example application of the GEFSOC system. Interestingly in the four cases studied here precipitation seems to control the sign of the soil C changes under climate change with wetter conditions resulting in higher soil C stocks and drier conditions in lower soil C stocks, presumably because increased NPP in wetter conditions here will override any increase in respiration. In contrast, globally, it seems to be temperature that controls changes in C stocks under climate change. Even if there is a slight increase in precipitation globally, a decrease in C stocks is predicted—in other words, the regional response to precipitation differs from the global response. The reason for this may be that whilst temperature increases under climate change were predicted everywhere, the nature of precipitation changes varies greatly between regions.

Keywords: Climate change; Soil carbon; Ecosystems; GCM; RothC; Net primary production; Modelling

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1. Introduction

The GEFSOC project (Milne et al., 2007—Global Environment Facility (GEF) co financed project number GFL-2740-02-4381) developed the GEFSOC Modelling

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* Corresponding author. Tel.: +44 1392 886336; fax: +44 1392 885681.
E-mail address: pete.falloon@metoffice.gov.uk (P. Falloon).

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System, a generically applicable, spatially explicit system for estimating soil organic C (SOC) stocks and changes at the national and sub national scale. The system incorporates the RothC and Century soil C models and the empirical IPCC soil C method and was developed using data from four contrasting eco regions: the Brazilian Amazon, Jordan, Kenya and the Indian part of the Indo Gangetic Plains (Easter et al., 2007). However, the analyses performed with the GEFSOC system to date have focussed on land use change impacts, and have not yet included analysis of climate change impacts on soil C storage.

Climate change could alter terrestrial C storage as changes in temperature, precipitation and atmospheric CO_2 concentration could affect net primary production (NPP), C inputs to soil and soil C decomposition rates. Climate change could also act as a driver for land use change, thus further altering terrestrial C fluxes. Due to of the large size of terrestrial C pools, they have considerable potential to drive large positive climate feedbacks because increased CO_2 concentrations in the atmosphere will enhance climate change (Cox et al., 2000; Friedlingstein et al., 2001, 2003, 2006; Jones et al., 2003). Therefore, a better understanding of the interactions between land use change, climate change and the terrestrial biosphere is crucial in planning future land management options.

Cox et al. (2000) and Jones et al. (2003) presented global scale assessments of climate-C cycle feedbacks using a coupled climate-C cycle Global Circulation Model (GCM), HadCM3LC. In these studies, increased soil respiration due to rising temperatures during the 21st century exceeded enhanced biospheric C uptake due to elevated atmospheric CO_2 levels. Hence the rate of increase in atmospheric CO_2 and thus the rate of climate change were accelerated. Decreases in soil C stocks were predicted across most of the globe, even in areas where C inputs to soil from vegetation had increased (Jones et al., 2003), although the C stock had increased during the 20th century. Drying of the Amazon Basin as a result of climate change resulted in a dieback of the Amazon forest and a strong reduction in the C input to soil also resulting in soil C losses in this region, with the Amazon dieback accounting for around 11% of the global climate-driven C losses (Cox et al., 2004). Biogeophysical effects of the forest dieback are also important locally, acting to further reduce rainfall (Betts et al., 2004). Jones et al. (2005) compared global changes in soil C feedbacks predicted by HadCM3LC and RothC driven by HadCM3LC forcing data, concluding that there were strong similarities between the behaviour of the two soil C models although RothC tended to simulate slightly smaller changes in global soil C stocks for the same forcing.

The aim of this paper is to analyse the impacts of climate change on C storage (in vegetation and SOC (excluding soil inorganic C)) in the GEFSOC case study countries using two different SOC models and to assess (a) how the global scale approach of Jones et al. (2005) might be applied in the context of the GEFSOC project and (b) developments needed for future work. This paper first presents predicted changes in climate for the four case study countries from a coupled climate-C cycle Global Circulation Model (GCM), HadCM3LC, followed by predicted changes in vegetation type, vegetation C storage and soil C storage. Soil C storage estimates were provided both by the original single-pool soil C model of HadCM3LC, and from the RothC model driven by HadCM3LC input data as in Jones et al. (2005). These very coarse assessments provide an initial estimate of large-scale effects. A more detailed study of climate impacts on soil C storage in the Brazilian Amazon is provided as an example application of the GEFSOC Modelling System.

2. Models

The Hadley Centre's coupled climate-C cycle general circulation model (GCM) (HadCM3LC, Cox, 2001) is a version of the Hadley Centre's third generation climate model HadCM3 (Gordon et al., 2000) with lowered ocean horizontal resolution (2.50° × 3.75°) coupled to terrestrial and ocean C cycle models (TRIFFID: Cox, 2001) and HadOCC (Palmer and Totterdell, 2001), respectively. HadCM3LC has recently been used in studies of climate-C cycle feedbacks (Cox et al., 2000; Jones et al., 2003). Soil C is modelled within HadCM3LC using a single pool with a single decay rate and takes no account of input quality. Hence it cannot simulate the dynamics of different classes of soil C. Jones et al. (2005) compared predictions of soil C changes under climate change from HadCM3LC and its single pool soil C model with simulations using the multi-pool soil C model RothC (Coleman and Jenkinson, 1999) driven by climate and litter output from HadCM3LC. These two soil C models have been described in detail by Cox (2001) and Coleman and Jenkinson (1999).

Briefly, the HadCM3LC soil C model uses a single pool of SOC with a single first-order decay rate dependent on soil temperature and soil moisture. The RothC model has four active SOC compartments, decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO) and humified organic matter (HUM) plus a pool of inert organic matter (IOM) that is resistant to decay. Each active pool has an individual decay rate, which is modified according to functions of moisture, temperature and plant cover and soil type. Organic C inputs to soil are split between DPM and RPM according to vegetation type—for example arable crops are assumed to be more readily decomposable than forest litter, and hence contain a greater proportion of DPM than RPM. All active pools decay to release CO_2 to the atmosphere and to form new BIO and HUM. The split between CO_2 released and BIO and HUM formed is also a function of soil texture.

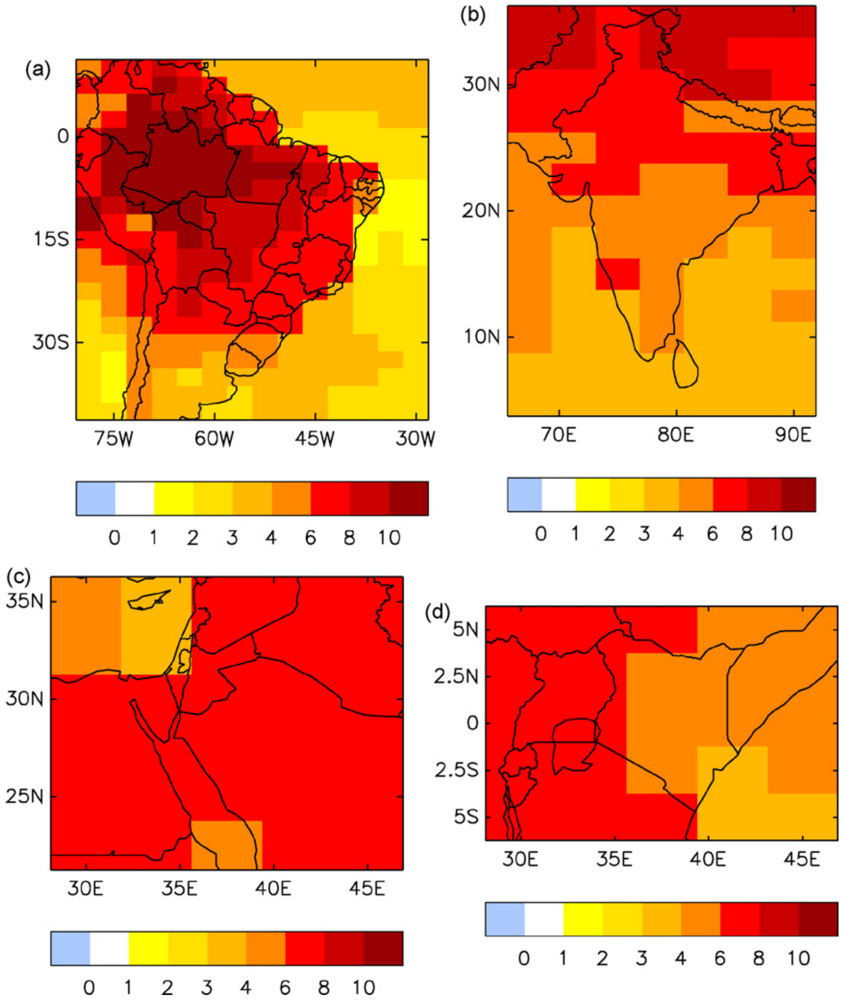

Fig. 1. Change in temperature (°C) from 2000 to 2100 for (a) Brazil, (b) India, (c) Jordan and (d) Kenya—HadCM3LC model (IS92a emissions scenario).

3. Experimental design

The experimental design for the simulations presented here has been described in detail by Jones et al. (2005). Briefly, both models were equilibrated at an initial state using the climate from the first decade (1860s) of the climate change simulation.

Table 1
Changes in annual average temperature and annual total precipitation predicted by HadCM3LC model (IS92a scenario) globally, and for the case study countries

	Change in annual average temperature (°C)		Change in annual total precipitation (mm)	
	1860–2000	2000–2100	1860–2000	2000–2100
Global	0.4 (0.2)	4.6 (1.6)	1.2 (−0.2)	44.4 (9.9)
Brazil	0.7 (0.2)	8.8 (3.0)	53.8 (4.2)	−770.6 (−54.5)
India	1.2 (0.4)	6.0 (2.0)	−147.5 (−28.0)	165.0 (−26.58)
Kenya	0.9 (0.3)	5.9 (2.0)	−91.8 (−20.0)	213.1 (44.2)
Jordan	0.1 (0.1)	6.5 (2.3)	−2.9 (0.1)	−26.6 (−27.6)

NB: Values in parentheses are percent change relative to 1860 values.

The two soil C models were used in computer simulations to assess the sensitivity of soil C response to climate change with and without multi-pool soil C dynamics. Output climate forcing data and plant C inputs from a climate change simulation using HadCM3LC were used to drive the two models. In the original coupled climate-C cycle experiments (Cox et al., 2000; Jones et al., 2003) accumulation and release of soil C directly affected the atmospheric CO_2 concentration and hence the climate. In this study the output of the climate model was used to drive both of the soil C models in an ‘‘off-line’’ manner—in other words, there was no feedback between soil C changes and climate. The runs used monthly mean output from the GCM averaged over a decade for each month. The model simulates naturally occurring changes in vegetation, but disturbance due to agriculture is kept constant at present-day levels and no attempt is made to include the effects of anthropogenic land use changes. Further experiments were performed for a grid point representative of Central Brazil (60°W, 3°S), varying separately temperature, soil moisture and organic C inputs.

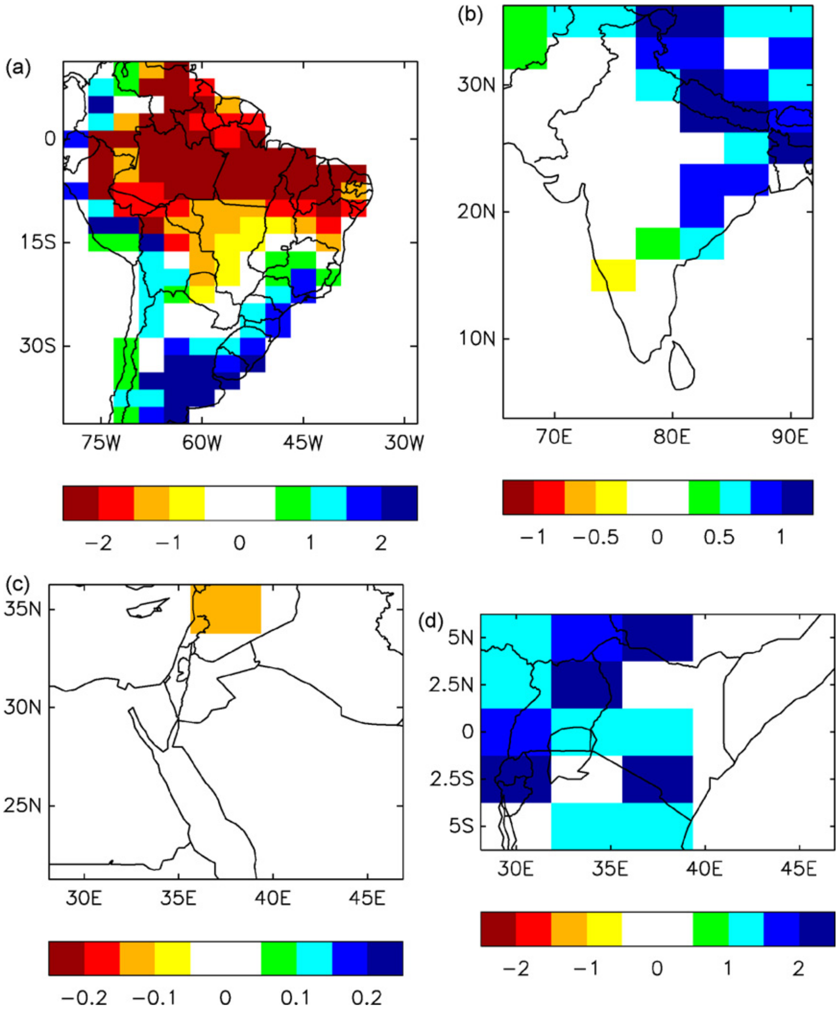

Fig. 2. Change in plant litter input (kg C m^{-2}) from 2000 to 2100 for (a) Brazil, (b) India, (c) Jordan and (d) Kenya—HadCM3LC model (IS92a emissions scenario).

The resulting simulation of soil C shows how each model responds to the separate forcings *viz* temperature, moisture and vegetation input.

4. Results

4.1. Climate change

Predicted climate change from 2000 to 2100 in the four case study countries varied considerably from the Global average, both for annual mean temperature and annual total precipitation (Table 1). Given IS92a emissions of CO_2, the model simulated a global mean atmospheric CO_2 concentration of 980 ppm by 2100, with temperature increases in excess of 5 °C predicted for all countries. Brazil was predicted to experience the greatest warming and the greatest drying of the four countries; decreases in rainfall were also predicted for Jordan, whilst increases in rainfall were predicted for Kenya and India. Spatial differences in predicted climate change within countries included greater temperature increases in Northern Brazil, Northern India and Western Kenya (Fig. 1).

4.2. Changes in land cover and litter inputs

Large differences in changes in plant C inputs to soil from 2000 to 2100 between countries were predicted (Fig. 2). This can be explained partly as a result of changes in predicted land cover for the case study countries and partly as a result of changes in net primary production (NPP). For example, large decreases in plant C inputs were predicted in North-eastern Brazil, largely due to a change in the dominant land cover from broadleaf tree to grasses and bare soil. These changes were the result of drying of the Amazon Basin and have been discussed in detail by Cox et al. (2000, 2004) and Betts et al. (2004). Increases in plant C inputs to soil were predicted in North-eastern India, as a result of land cover changes from grasses to scrub. Virtually no change in C input for Jordan was predicted, with the dominant land cover remaining as bare soil—majority of the area is desert. This is in contrast with observed vegetation patterns that include

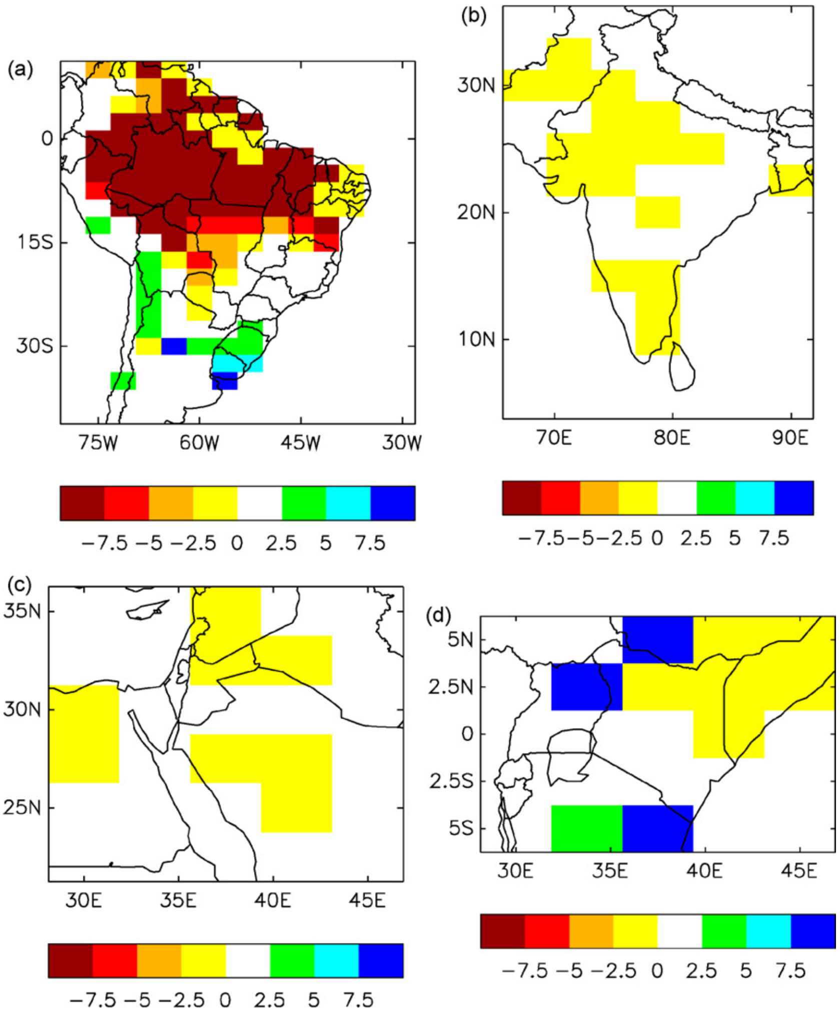

Fig. 3. Changes in vegetation carbon storage from 2000 to 2100 (kg C m^{-2}) predicted by HadCM3LC model (IS92a emissions scenario) for (a) Brazil, (b) India, (c) Jordan, and (d) Kenya.

significant plant growth during the growing season (February–May). Increases in plant C inputs in Kenya were predicted due to land cover changes from grasses to scrub in the West of the country.

4.3. Changes in soil and vegetation C storage

Large changes in vegetation C storage from 1860 to 2100 were predicted by HadCM3LC (Table 3, Fig. 3). Decreases in vegetation C storage were predicted for Brazil whilst increases were predicted for India and Kenya; little change in vegetation C storage was predicted for Jordan.

Database-derived estimates of baseline total soil C stocks to 1 m depth for the case study countries are available from Batjes et al. (2007) for Brazil (42.3 Pg C), India (1.2 Pg C), Jordan (0.1 Pg C) and Kenya (3.7 Pg C). However, the estimate for Brazil applies only to the Amazon region of Brazil and that for India applies only to the Indo-Gangetic

Table 2
Total soil and vegetation carbon storage predicted by HadCM3LC model (IS92a scenario) for the case study countries

	Soil carbon storage (Pg C except Jordan, t C)			Vegetation carbon storage (Tg C)		
	1860	2000	2100	1860	2000	2100
Global	1180	1240	1100	493	544	552
Brazil	58.28	63.01	24.32	172.42	187.06	112.78
India	8.62	6.55	8.51	0.68	0.65	1.17
Kenya	2.21	2.34	2.12	10.80	11.87	16.52
Jordan	3742	7815	0	0.03	0.02	0.01

Table 3
Total soil carbon storage predicted by RothC model driven by HadCM3LC data (IS92a scenario) for the case study countries

	Soil carbon storage (Pg C except Jordan, t C)		
	1860	2000	2100
Global	951.00	983.00	897.00
Brazil	41.86	45.30	22.83
India	8.00	6.78	7.37
Kenya	1.48	1.45	1.48
Jordan	0.00	977.0	0.00

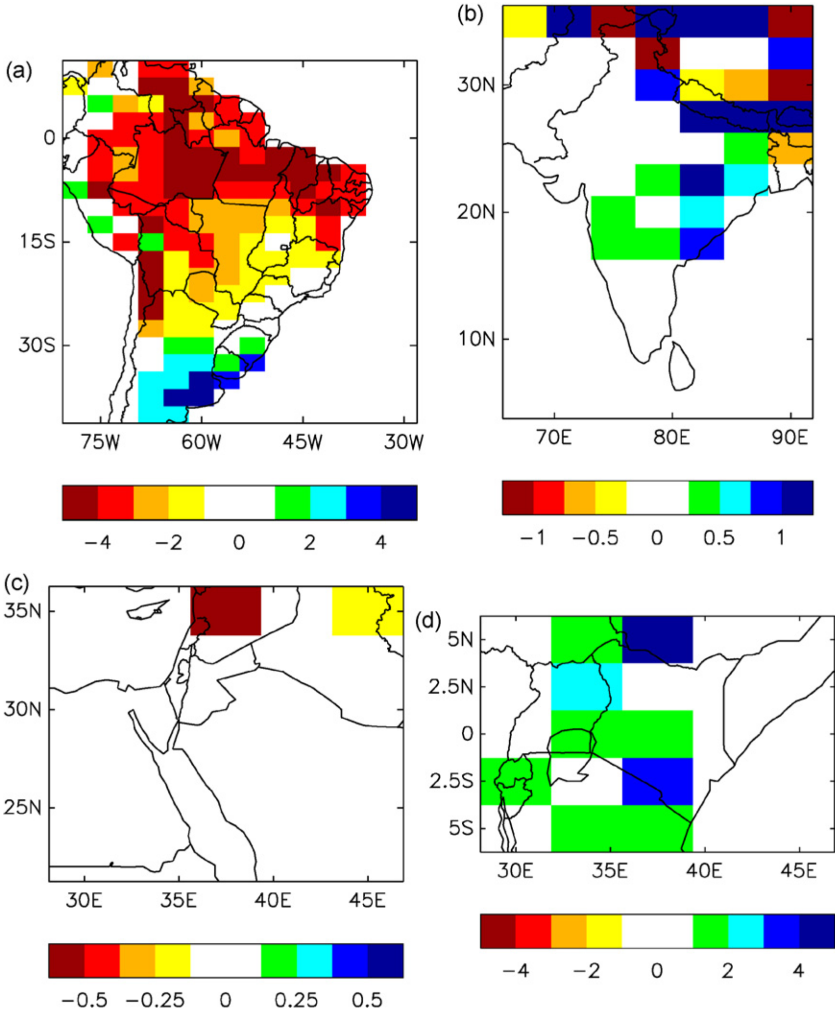

Fig. 4. Changes in soil carbon from 2000 to 2100 (kg C m^{-2}) predicted by RothC model driven with HadCM3LC data (IS92a emissions scenario) for (a) Brazil, (b) India, (c) Jordan, and (d) Kenya.

Plains region of India. In light of this, and of the coarse nature of GCM grid-box predictions, the total soil C stocks in 2000 for the case study countries predicted by HadCM3LC (Table 2) and RothC (Table 3) are generally similar to those of Batjes et al. (2007). The model-based estimates for Brazil are higher than those of Batjes et al. (2007) as would be expected. The model-based estimates for Kenya and Jordan are lower than those of Batjes et al. (2007), considerably so for Jordan, which was predicted to have a dominant land cover of bare soil, with virtually no soil C content. The total organic C stock in Indian soils was estimated as 9.55 Pg (0–30 cm depth) taking soil data collected during 1980 (Bhattacharyya et al., 2005). This shows that SOC stock prediction through soil survey data is higher than the model-based estimates (see comments above). Total soil C stocks predicted by RothC are generally lower than those predicted by HadCM3LC, as discussed by Jones et al. (2005). We have not compared our estimates of soil C stocks with those generated by the GEFSOC Model System using RothC, CENTURY and the IPCC method (reported elsewhere in this special issue) since our approach modelled the whole profile—the GEFSOC approach modelled only the top 20 or 30 cm depending on the output chosen.

For both RothC and HadCM3LC soil C stocks were predicted to increase from 1860 to 2000 for Brazil and Jordan, remain constant for Kenya and decrease for India. Soil C stocks were predicted to decrease from 2000 to 2100 for Brazil and Jordan by both models, whilst an increase in soil C stocks was predicted for India, and little change in Kenyan C stocks was predicted. The spatial patterns of changes in soil C predicted by RothC (Fig. 4) and HadCM3LC (Fig. 5) were generally similar and approximately followed changes in vegetation C storage and litter inputs although RothC estimates of changes in soil C were generally smaller than HadCM3LC estimates (Jones et al., 2005).

4.4. C dynamics for a single grid point in Brazil

The response of each model to the three forcings (temperature, soil moisture and organic C input) was investigated at a grid point (60°W, 3°S) that was representative of central Brazil, under forest vegetation

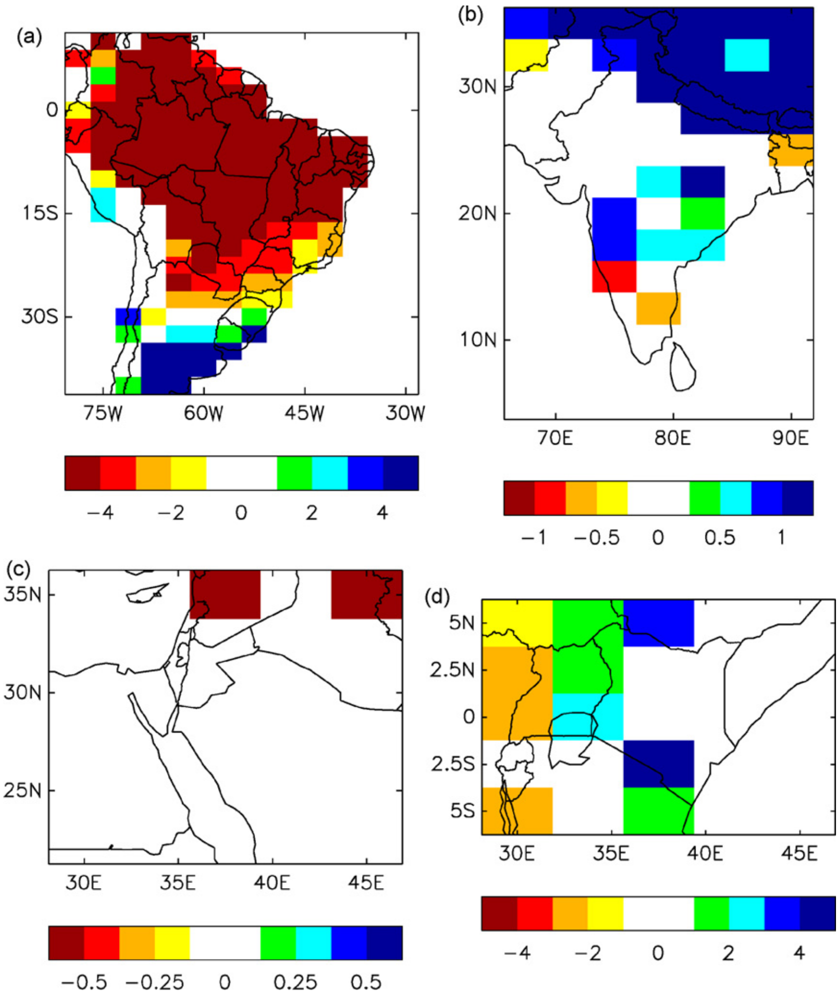

Fig. 5. Changes in soil carbon from 2000 to 2100 (kg C m^{-2}) predicted by HadCM3LC model (IS92a emissions scenario) for (a) Brazil, (b) India, (c) Jordan, and (d) Kenya.

with soil C content 4.69 kg m^{-2}. The offline experiments were repeated but allowing only one of the forcings to change at a time with the other forcings kept constant at their initial values. This separates the direct effects of temperature and moisture on C turnover from indirect effects via changes in vegetation productivity. Fig. 6 shows the soil C evolution for four cases: (a) all forcings (i.e. the original experiment), (b) temperature changing as before but all other forcings held constant, (c) organic C inputs changing but other forcings held constant, and (d) moisture changing but all other forcings held constant.

Both increases in temperature and decreases in plant C inputs act to decrease soil C, although the effect of reduced moisture acts to increase soil C through soil dryness inhibiting decomposition. The combined effect of all forcings results in a large decrease in C stocks for the gridbox in Central Brazil. Similar trends were noted for a gridbox in Amazonia by Jones et al. (2005).

The changes in soil C from 1860 to 2100 for the run using temperature forcing only, predicted by RothC and HadCM3LC were −1.65 and −4.02 kg m^{-2}, respectively. The corresponding figures for litter forcing only were −4.08 and −5.48 kg m^{-2}; those for moisture forcing only were −1.65 and +11.02 kg m^{-2} and the values for the runs including all forcings were −4.34 and −5.47 kg m^{-2}, respectively.

5. Discussion

As in Jones et al. (2005), RothC and HadCM3LC showed similar patterns, but different magnitudes of soil C response to climate change. Climate change clearly has the potential to considerably alter soil and vegetation C storage in the four case study countries and therefore needs to be considered in any estimates of future C sequestration potential via land management strategies, although our simulations only considered the effects of climate change driven land use change, not anthropogenic land use change. Decreases in soil C stocks by 2030 due to land use change alone are predicted for most of the GEFSOC project case study countries (Al-Adamat et al., 2007; Bhattacharyya et al.,

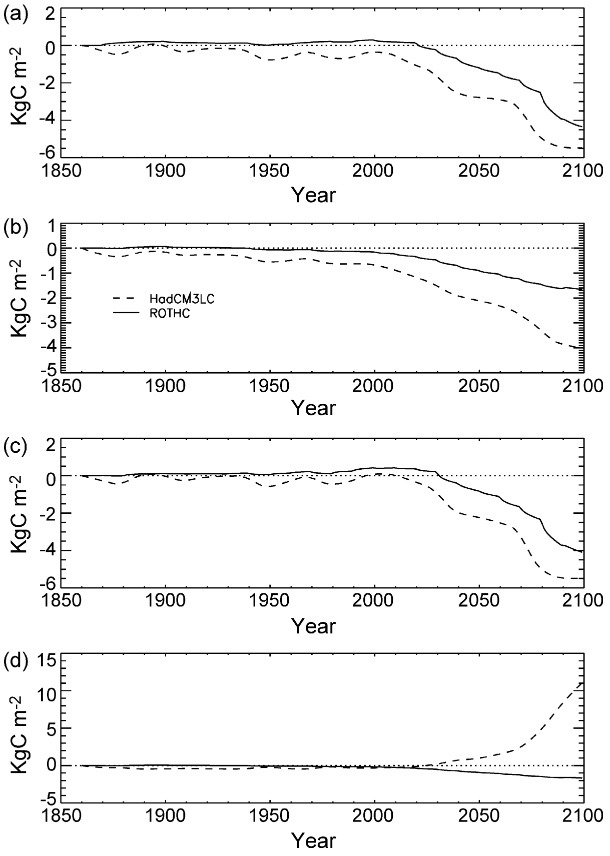

Fig. 6. Change in soil carbon content (kg C m^{-2}) for a point in Brazil (60°W, 3°S) for the off-line runs of HadCM3LC (dashed line) and RothC (solid line) (a) Results from the fully forced experiment. (b) Results from the experiment where all forcing was held constant except temperature. (c) Results from the experiment where all forcing was held constant except for organic carbon inputs. (d) Results from the experiment where all forcing was held constant except for soil moisture.

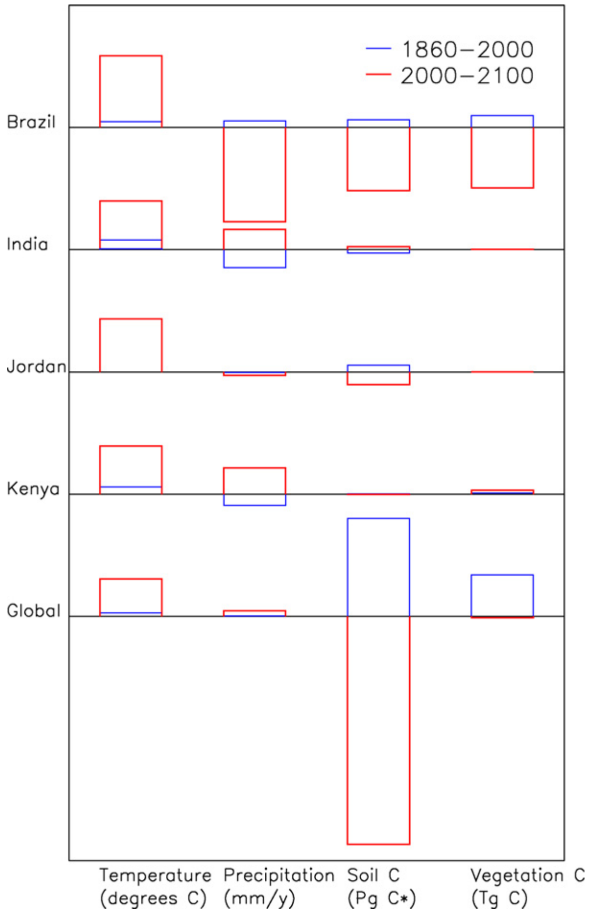

Fig. 7. Changes in temperature, precipitation, soil C and vegetation from the HadCM3LC runs between 1860–2000 and 2000–2100 for the case study countries.

2007; Cerri et al., 2007; Kamoni et al., 2007). In the Brazilian grid point presented in this study, regardless of vegetation changes, the soil C sequestration potential of future land management options would be greatly reduced by climate change. Less dramatic changes were predicted for India, Kenya and Jordan. Falloon (2004) has already used RothC to show that in the UK soil C sequestration potential could be reduced by climate change and results obtained from simulations including both climate and land use change were not equal to the simple sum of simulations including either climate change or land use change alone.

Climate change could also limit the feasibility of the different land management options. If the predicted dieback of the Amazon forest (Cox et al., 2000, 2004; Jones et al., 2003; Betts et al., 2004; Cowling et al., 2004) is correct then clearly land management options favouring forestry will be severely limited in the Amazon region. Considerable reductions in forest cover are also expected due to the expansion of logging schemes and clearance of land for agricultural expansion (Laurance et al., 2004). Land use change itself can also drastically change local and regional climates via direct physical effects including recycling of water through vegetation, surface resistance and windspeed, and albedo (Betts et al., 2007). The presence of forest cover in the Amazon region helps to maintain precipitation (Betts,

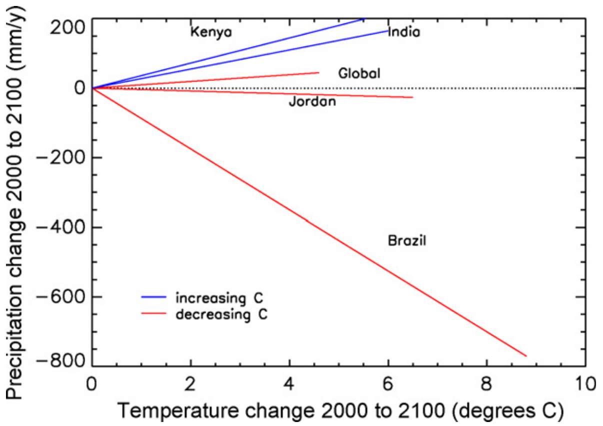

Fig. 8. Change in temperature against change in precipitation from the HadCM3LC runs between 2000 and 2100 for the case study countries. Blue lines indicate increases in soil C stocks, red lines indicate decreases in soil C stocks. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

1999)—total or partial Amazonian deforestation would result in considerable local drying and potentially alter large scale circulation patterns (Gedney and Valdes, 2000). Reforestation in the boreal zone could potentially warm the local climate (since forest cover has a lower albedo than lying snow) and could also have a net warming effect on the global climate, opposite to that intended (Betts, 2000).

Uncertainties in predicted climate change for the four countries could arise from missing or incomplete descriptions of processes in GCMs, uncertainties in future emissions of greenhouse gases, uncertainties in GCM parameters, or differences between models. The latter two can be investigated using multi-member ensemble runs of the same climate model run with different parameter sets (e.g. Murphy et al., 2004), and by inter-model comparisons (e.g. Friedlingstein et al., 2006). Uncertainties in future emissions of greenhouse gases can be investigated using a wide range of emissions scenarios (e.g. IPCC, 2000), although different scenarios are more likely to affect the magnitude of response rather than the pattern or sign of change.

Interestingly in the four cases studied here precipitation seems to control the sign of the soil C changes under climate change (Figs. 7 and 8). Wetter conditions tend to result in higher soil C stocks, and drier conditions in lower soil C stocks, presumably because increased NPP in wetter conditions here will override any increase in respiration. In contrast, globally, it seems to be temperature that controls changes in C stocks under climate change. Even though there is a slight increase in precipitation globally, a decrease in C stocks is predicted—in other words, the regional response to precipitation differs from the global response. Presumably this is because whilst temperature increases are predicted everywhere, the nature of precipitation changes varies greatly between regions.

Although this study has addresses uncertainties in soil C model structure, the nature of soil and vegetation C response to climate change could also be influenced by factors not currently included in either RothC or HadCM3LC. For example, neither model includes nutrient cycling and although large amounts of soil C are stored in organic soils and subsoils, RothC has not been parameterised for these situations (Falloon et al., 1998).

The resolution of climate model outputs must also be considered. At the resolution of the HadCM3LC a small country such as Jordan is only covered by one GCM grid box and thus no spatial heterogeneity in climate can be achieved. In the UK a nested approach using regional climate models (RCMs) to downscale GCM results has been utilised (Hulme et al., 2002). The finer resolution of RCMs makes their simulation of local climates much more realistic, although the horizontal resolution of the latest generation Hadley Centre climate model, HadGEM1 (Martin et al., 2006), is around half that of HadCM3 giving roughly four times as many gridpoints.

Considerable improvement in understanding the potential impacts of climate change on soil and vegetation C storage in the four case study countries could therefore be achieved by (a) using outputs from the latest GCM simulations (e.g. HadGEM—Johns et al., 2006), (b) investigating a range of emissions scenarios, (c) utilizing information from existing climate model uncertainty studies, (d) using outputs from RCMs to improve upon local climate model outputs, (e) investigating climate change scenarios in combination with land use change scenarios in the GEFSOC modelling system, and (f) taking low-resolution climate anomalies from the GCM and adding them to the existing observed climate (at high resolution).

6. Conclusions

Climate change in Brazil, India, Jordan and Kenya is likely to include warming in excess of 5 °C, with greater warming expected in Brazil than the other countries. Brazil and Jordan are likely to experience reductions in annual rainfall totals, whilst wetter conditions could be expected for Kenya and India. In the case study regions investigated here, precipitation rather than temperature would appear to control the sign of predicted changes in soil C, largely through the influence of precipitation on litter inputs to soil. The reason for this result is likely to be that whilst temperature increases were predicted in all regions, there were large regional variations in precipitation changes due to climate change.

Soil and vegetation C storage is likely to respond differently to climate change in the four case study countries—large reductions in C storage are predicted for Brazil, whilst C storage could increase in Kenya and smaller changes are likely in India and Jordan. The RothC and HadCM3LC models used to investigate soil C responses in this study predict similar patterns of change although the magnitudes were different. Since it could greatly alter future C storage, climate change clearly needs to be considered in conjunction with land use change when making estimates of future C sequestration potential.

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References

Al-Adamat, R., Rawajfih, Z., Easter, M., Paustian, K., Coleman, K., Milne, E., Falloon, P., Powlson, D.S., Batjes, N.H., 2007. Predicted soil organic carbon stocks and changes in Jordan between 2000 and 2030 made using the GEFSOC Modelling System. In: Milne, E., Powlson, D.S., Cerri, C.E.P. (Eds.), Soil Carbon Stocks at Regional Scales. Agric. Ecosyst. Environ. 122, 35–45.

Batjes, N.H., Al-Adamat, R., Bhattacharyya, T., Bernoux, M., Cerri, C.E.P., Gicheru, P., Kamoni, P., Milne, E., Pal, D.K., Rawajfih, Z., 2007. Preparation of consistent soil data sets for modelling purposes: secondary SOTER data for four case study areas. In: Milne, E., Powlson, D.S., Cerri, C.E.P. (Eds.), Soil Carbon Stocks at Regional Scales. Agric. Ecosyst. Environ. 122, 26–34.

Betts, R.A., 1999. Self-beneficial effects of vegetation on climate in a General Circulation Model. Geophys. Res. Lett. 26, 1457–1460.

Betts, R.A., 2000. Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. Nature 408, 187–190.

Betts, R., Falloon, P., Klein Goldewijk, K., Ramankutty, N., 2007. Biogeophysical effects of land use on climate: model simulations of radiative forcing and large-scale temperature change. Agric. For. Meteorol. 142, 216–233.

Betts, R.A., Cox, P.M., Collins, M., Harris, P.P., Huntingford, C., Jones, C.D., 2004. The role of ecosystem–atmosphere interactions in simulated Amazonian precipitation decrease and forest dieback under global climate warming. Theor. Appl. Climatol. 78, 157–175.

Bhattacharyya, T., Pal, D.K., Velayutham, M.V., Chandran, P., Mandal, C., 2005. Total carbon stock in Indian soils: issues, priorities and management. In: Land Resource Management for Food Environment security (International Conference on Land Resource Management). Soil Conservation Society of India, New Delhi, pp. 1–46.

Bhattacharyya, T., Pal, D.K., Easter, M., Batjes, N.H., Milne, E., Gajbhiye, K.S., Chandran, P., Ray, S.K., Mandal, C., Paustian, K., Williams, S., Killian, K., Coleman, K., Falloon, P., Powlson, D.S., 2007. Modelled soil organic carbon stocks and changes in the Indo-Gangetic Plains, India from 1980 to 2030. In: Milne, E., Powlson, D.S., Cerri, C.E.P. (Eds.), Soil Carbon Stocks at Regional Scales. Agric. Ecosyst. Environ. 122, 84–94.

Cerri, C.E.P., Easter, M., Paustian, K., Killian, K., Coleman, K., Bernoux, M., Falloon, P., Powlson, D.S., Batjes, N.H., Milne, E., Cerri, C.C., 2007. Predicted soil organic carbon stocks and changes in the Brazilian Amazon between 2000 and 2030. In: Milne, E., Powlson, D.S., Cerri, C.E.P. (Eds.), Soil Carbon Stocks at Regional Scales. Agric. Ecosyst. Environ. 122, 58–72.

Coleman, K., Jenkinson, D.S., 1999. RothC-26.3, A Model for the Turnover of Carbon in Soil: Model Description and User's Guide. Lawes Agricultural Trust, Harpenden, UK.

Cowling, S.A., Betts, R.A., Cox, P.M., Ettwein, V.J., Jones, C.D., Maslin, M.A., Spall, S.A., 2004. Contrasting simulated past and future responses of the Amazonian forest to atmospheric change. Phil. Trans. R. Soc. London. 359, 539–547.

Cox, P.M., 2001. Description of the TRIFFID dynamic global vegetation model. Technical Note 24. Hadley Centre, Met Office.

Cox, P.M., Betts, R.A., Collins, M., Harris, P.P., Huntingford, C., Jones, C.D., 2004. Amazonian forest dieback under climate-carbon cycle projections for the 21st Century. Theor. Appl. Climatol. 78, 137–156.

Cox, P.M., Betts, R.A., Jones, C.D., Spall, S.A., Totterdell, I.J., 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature 408, 184–187.

Easter, M., Paustian, K., Killian, K., Williams, S., Feng, T., Al Adamat, R., Batjes, N.H., Bernoux, M., Bhattacharyya, T., Cerri, C.C., Cerri, C.E.P., Coleman, K., Falloon, P., Feller, C., Gicheru, P., Kamoni, P., Milne, E., Pal, D.K., Powlson, D.S., Rawajfih, Z., Sessay, M., Wokabi, S., 2007. The GEFSOC soil carbon modelling system: a tool for conducting regional-scale soil carbon inventories and assessing the impacts of land use change on soil carbon. In: Milne, E., Powlson, D.S., Cerri, C.E.P. (Eds.), Soil Carbon Stocks at Regional Scales. Agric. Ecosyst. Environ. 122, 13–25.

Falloon, P.D., Smith, P., Coleman, K., Marshall, S., 1998. Estimating the size of the inert organic matter pool for use in the Rothamsted carbon model. Soil Biol. Biochem. 30, 1207–1211.

Falloon, P., 2004. Using RothC with climate and land use change at the 1 km scale. Section 7. In: Milne, R. (Ed.), Carbon Sequestration in Vegetation Soils. Annual Report for DEFRA Contract GA01054, May 2004. Centre for Ecology Hydrology, Bush, Edinburgh, U.K.

Friedlingstein, P., Bopp, L., Ciais, P., Dufresne, J., Fairhead, L., LeTreut, H., Monfray, P., Orr, J., 2001. Positive feedback between future climate change and the carbon cycle. Geophys. Res. Lett. 28, 1543–1546.

Friedlingstein, P., Dufresne, J.L., Cox, P.M., Rayner, P., 2003. How positive is the feedback between climate change and the carbon cycle? Tellus B 55B, 692–700.

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Doney, S., Eby, M., Fung, I., Govindasamy, B., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H.D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K.G., Schnur, R., Strassmann, K., Thompson, S., Weaver, A.J., Yoshikawa, C., Zeng, N., 2006. Climate-carbon cycle feedback analysis, results from the C4MIP model inter comparison. J. Climate 19, 3337–3353.

Gedney, N., Valdes, P.J., 2000. The effect of Amazonian deforestation on the northern hemisphere circulation and climate. Geophys. Res. Lett. 27, 3053–3056.

Gordon, C., Cooper, C., Senior, C.A., Banks, H., Gregory, J.M., Johns, T.C., Mitchell, J.F.B., Wood, R.A., 2000. The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Clim. Dyn. 16, 147–168.

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R., Hill, S., 2002. Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK, 120 pp.

IPCC, 2000. In: Nakicenovic, N., Swart, R. (Eds.), Special Report on Emissions Scenarios. A Special Report of the IPCC. Cambridge University Press, UK, 570 pp.

Johns, T.C., Durman, C.F., Banks, H.T., Roberts, M.J., McLaren, A.J., Ridley, J.K., Senior, C.A., Williams, K.D., Jones, A., Rickard, G.J., Cusack, S., Ingram, W.J., Crucifix, M., Sexton, D.M.H., Joshi, M.M., Dong, B.W., Spencer, H., Hill, R.S.R., Gregory, J.M., Keen, A.B., Pardaens, A.K., Lowe, J.A., Bodas-Salcedo, A., Stark, S., Searl, Y., 2006. The new Hadley Centre climate model HadGEM1: evaluation of coupled simulations. J. Climate 19, 1327–1353.

Jones, C.D., Cox, P.M., Essery, R.L.H., Roberts, D.L., Woodage, M.J., 2003. Strong carbon cycle feedbacks in a climate model with interactive CO_2 and sulphate aerosols. Geophys. Res. Lett. 30, 1479, doi:10.1029/2003GL016867.

Jones, C.D., McConnell, C., Coleman, K.W., Cox, P., Falloon, P.D., Jenkinson, D., Powlson, D., 2005. Global climate change and soil carbon stocks; predictions from two contrasting models for the turnover of organic carbon in soil. Global Change Biol. 11, 154–166, doi:10.1111/j.1365-2486.2004.00885.x.

Kamoni, P.T., Gicheru, P.T., Wokabi, S.M., Easter, M., Milne, E., Coleman, K., Falloon, P., Paustian, K., 2007. Predicted soil organic carbon stocks and changes in Kenya between 1990 and 2030. In: Milne, E., Powlson, D.S., Cerri, C.E.P. (Eds.), Soil Carbon Stocks at Regional Scales. Agric. Ecosyst. Environ. 122, 3–12.

Laurance, W.F., Albernaz, A.K.M., Fearnside, P.M., Vasconcelos, H.L., Ferreira, L.V., 2004. Deforestation in Amazonia. Science 304, 1109–1111.

Martin, G.M., Ringer, M.A., Pope, V.D., Jones, A., Dearden, C., Hinton, T.J., 2006. The physical properties of the atmosphere in the new Hadley Centre Global Environmental Model, HadGEM1. Part 1. Model description and global climatology. J. Climate 19, 1274–1301.

Milne, E., Al-Adamat, R., Batjes, N.H., Bernoux, M., Bhattacharyya, T., Cerri, C.C., Cerri, C.E.P., Coleman, K., Easter, M., Falloon, P., Feller, C., Gicheru, P., Kamoni, P., Killian, K., Pal, D.K., Paustian, K., Powlson, D., Rawajfih, Z., Sessay, M., Williams, S., Wokabi, S., 2007. National and sub national assessments of soil organic carbon stocks and changes: the GEFSOC modelling system. In: Milne, E., Powlson, D.S., Cerri, C.E.P. (Eds.), Soil Carbon Stocks at Regional Scales. Agric. Ecosyst. Environ. 122, 3–12.

Murphy, J.M., Sexton, D.M.H., Barnett, D.N., Jones, G.S., Webb, M.J., Collins, M., Stainforth, D.A., 2004. Quantification of modelling uncertainties in a large ensemble of climate change simulations. Nature 430, 768–772.

Palmer, J.R., Totterdell, I.J., 2001. Production and export in a global ocean ecosystem model. Deep-Sea Res. 48, 1169–1198.