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Impact of climate change on grassland production and soil carbon worldwide

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Abstract

The impact of climate change and increasing atmospheric CO_2 was modelled for 31 temperate and tropical grassland sites, using the CENTURY model. Climate change increased net primary production, except in cold desert steppe regions, and CO_2 increased production everywhere. Climate change caused soil carbon to decrease overall, with a loss of 4 Pg from global grasslands after 50 years. Combined climate change and elevated CO_2 increased production and reduced global grassland C losses to 2 Pg, with tropical savannas becoming small sinks for soil C. Detection of statistically significant change in plant production would require a 16% change in measured plant production because of high year to year variability in plant production. Most of the predicted changes in plant production are less than 10%.

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Introduction

Grasslands and the Global Carbon Cycle

The potential effects of climate change on grassland biogeochemistry have received much less attention compared with forests (Hall & Scurlock 1991). The effects of changes in temperature, water and nutrients are relatively well understood, and interactions with the long-term effects of CO_2 fertilization are now beginning to be sufficiently well-developed to evaluate changes in C fluxes (Schimel *et al.* 1990, 1991; Long 1991; Owensby *et al.* 1993). Grassland ecosystems store most of their carbon (C) in soils, where turnover times are relatively long (100–10,000 years), and so changes, though they may occur slowly, will be of significant duration. Changes in grassland C storage will have a significant and long-lived effect on global C cycles.

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Fluxes of C through plant and soil organic matter in grasslands, especially in the tropics, may have been underestimated in the past (Long *et al.* 1989). Grasslands are one of the most widespread vegetation types worldwide, covering nearly one-fifth of the world's land surface (24×10^6 km^2), and containing >10% of global soil C stocks (Eswaran *et al.* 1993). Grasslands are also an important habitat for wildlife, humans and their domestic livestock and are subject to conversion to both dryland and irrigated agriculture.

Under the aegis of a collaborative SCOPE (Scientific Committee on Problems of the Environment) project (Breymeyer & Melillo 1991), the CENTURY model of plant-soil interactions has been applied to a broad range of grasslands worldwide (Parton *et al.* 1993). The SCOPEGRAM group has assembled long-term data from 31 sites in both temperate and tropical grasslands, in order to evaluate the robustness of the CENTURY model and the simulated response of grasslands to climate change scenarios.

Several recent studies estimate the response of soil organic matter (SOM) to environmental change. Jenkinson *et al.* (1991) estimated substantial and rapid release of C from soils as a result of global warming (61 Pg over 60 years), while Schlesinger (1990) argued that undisturbed soils will have a low potential for added C storage and can only change slowly. Most previous studies have had recognized limitations: Schlesinger's study used inferential soil chronosequence studies, while the model of Jenkinson *et al.* (1991) did not consider the feedback between soil processes and climate change effects on primary production, a key feature of CENTURY. Indeed, Jenkinson *et al.* (1991) noted that in order to determine how climate change affects the flux of CO_2 between soil and atmosphere, their model 'would have to be coupled to another which specifies how global plant production is altered by increasing concentrations of greenhouse gases' (Jenkinson *et al.* 1991).

The objective of this paper is to evaluate the factors controlling the sensitivity of grassland ecosystems to climate change and increasing atmospheric CO_2 concentration. We focus on plant productivity, soil C changes, decomposition, and biogeochemical feedbacks in grasslands in different ecoregions of the world. A secondary objective is to assess the difficulty of observing change, especially at arid sites where precipitation typically shows great variance. We also analyse the differences between the transient response over 50 years and the long-term 'equilibrium' response to increased atmospheric CO_2 concentration and climate change, such as have been presented by other workers (Melillo *et al.* 1993). We did not attempt to model climate-driven redistribution of grassland regions, but the world area of grasslands is expected to increase in future or at least remain constant in most scenarios of future climate.

Materials and methods

CENTURY is a simulation model of plant-soil interactions in grasslands, forests, crops and savannas. It incorporates simplified representations of key processes relating to carbon assimilation and turnover, based on existing models, and has been previously described in detail (Parton *et al.* 1993, 1987, 1988). CENTURY has been used extensively to investigate agroecosystems (Paustian *et al.* 1992), forests (Sanford *et al.* 1991), and the regional responses of grasslands to climate change and land use (Schimel *et al.* 1990, 1991; Burke *et al.* 1991; Ojima *et al.* 1990).

CENTURY simulates the dynamics of carbon (C) and nitrogen (N) for different plant-soil systems. Plant production in grasslands is a function of soil temperature and available water, limited by nutrient availability and a self-shading factor. The model includes the impact of fire and grazing on grassland ecosystems (Ojima *et al.* 1990; Holland *et al.* 1992). A submodel simulates the flow of C and nutrients through the different inorganic and organic pools in the soil, running on a monthly time step. Version 3.0 of CENTURY was used for these model runs (Parton *et al.* 1993).

The effect of increased atmospheric concentrations of CO_2 on the photosynthetic response of C3 plants has been well documented. In addition to its direct effects, increased atmospheric CO_2 concentration has been observed to increase water and nitrogen use efficiency (NUE) in both C3 and C4 plants (Owensby *et al.* 1993a,b). In CENTURY, we modified the plant production parameters under a 'double-CO_2' climate by changing the relationship between potential evapotranspiration (PET), NUE and production for both C3 and C4 grasslands (Ojima *et al.* 1993; Hall *et al.* 1994). We allowed a 20% decrease in total PET (which in CENTURY incorporates stomatal resistance—hence its use in this algorithm) and a 20% decrease in N concentration with a change in atmospheric CO_2 concentration from 350 ppm to 700 ppm, via a linear function based on results from a tallgrass prairie (Owensby *et al.* 1993a,b).

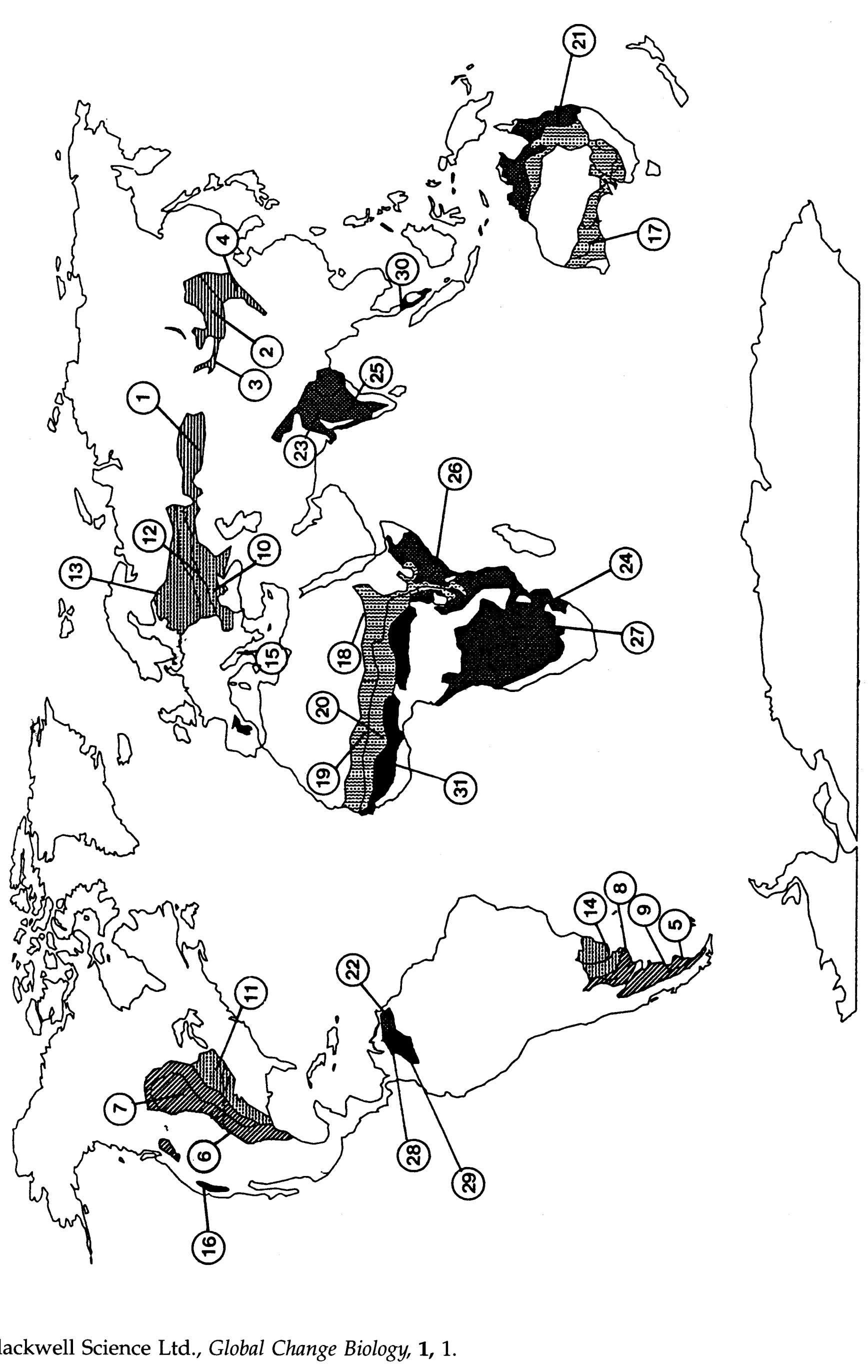
For each grassland site, the model was run to equilibrium for 5000 years, using a repeated 25-year pattern of observed current weather data. Site-specific patterns of grassland management (i.e. burning and grazing) were incorporated in these long-term runs as previously described (Parton *et al.* 1993).

Evaluation of grassland response to climate change

Sites were selected to represent a broad range of grassland regions based on climate factors and ecosystem properties (Fig. 1). These include 15 temperate and tropical sites for which detailed monthly data were available on vegetation biomass and plant detritus. A detailed comparison of simulated and observed peak live biomass and plant production for these 15 sites showed good correlations (r^2 = 0.45 and 0.70, respectively). Soil C levels were predicted very well (r^2 = 0.93). We assembled at least 25 years of monthly weather data for our 15 sites and a further 16 grassland sites derived from the literature. The regions ranged from temperate ecosystems with highly seasonal temperature patterns to tropical regions where temperature varied little. Precipitation at all of the sites displayed a marked seasonality, and in most cases a high degree of variability between years.

On the basis of temperature, rainfall and seasonality of climate, we grouped the 31 sites into 7 bioclimatic regions based upon a modification of Bailey ecoregions which consider climatic and ecological factors (Bailey 1989) (Tables 1 and 2). The three divisions of Bailey's dry domain are based on temperature, with the cold desert steppes having a regional mean annual temperature of

☆1. Shortandy, Kazakhstan
☆2. Tummensogt, Monogolia
☆3. Tuva, Russia
☆4. Xilinhot, China
5. Comodoro Rivadavia, Argentina
☆6. CPER, USA
☆7. Havre, USA
8. Santa Rosa, Argentina
9. Sarmiento, Argentina
☆10. Khomutov, Ukraine
☆11. Konza, USA
☆12. Kursk, Russia
☆13. Otradnoye, Russia
14. Montevideo, Uruguay
15. Bari, Italy
16. Davis, USA
17. Kalgoorlie, Australia
18. Khartoum, Sudan
19. Menaka, Mali
☆20. Niamey, Niger
21. Charleville/Warra Australia
22. Cuidad Bolivar, Venezuela
23. Kurukshetra Ludhiana, India
24. Marondera, Zimbabwe
25. Nagpur, India
☆26. Nairobi, Kenya
☆27. Towoomba, South Africa
28. Calabozo/San Fernando, Venezuela
29. Carimagua, Colombia
☆30. Hat Yai, Thailand
☆31. Lamto, Ivory Coast



HUMID TEMPERATE/PRAIRIE
DRY SANANNA/STEPPE
DRY TEMPERATE/STEPPE
DRY CONTINENTAL/STEPPE DESERT
SAVANNA
HUMID SAVANNA
MEDITERRANEAN

Fig. 1 Map showing location of grassland sites and boundaries of Bailey ecoregions representing grasslands worldwide.

Table 1 Long-term mean annual precipitation, temperature, potential evapotranspiration rate, and ratio of annual precipitation to potential evapotranspiration rate (PPT/PET), for the seven grassland regions based on Bailey (1989)

Biome type	Mean annual precipitation (mm)	Mean annual temperature (°C)	Mean annual potential evapotranspiration (mm)	PPT/PET	Global area (10^6 km^2)	Vegetation type
Cold Desert Steppe	299	–0.3	960	0.334	2.095	C_3
Temperate Steppe	301	10.2	1041	0.294	2.943	C_3/C_4
Humid Temperate	700	9.3	997	0.680	3.958	C_4
Mediterranean	497	15.7	1253	0.401	0.161	C_3/C_4
Dry Savanna	387	24.1	1977	0.165	5.109	C_4
Savanna	788	23.4	1491	0.554	7.990	C_4
Humid Savanna	1555	27.4	1404	1.195	1.708	C_4

Table 2 Simulated mean annual above- and belowground plant production, total SOC, mean annual abiotic decomposition factors, and net N mineralization rates for each of the seven grassland regions prior to climatic changes.

Biome type	Aboveground production (gm^{-2})	Belowground production (gm^{-2})	Total Soil C (0–20 cm) (gm^{-2})	Net N mineralization (g N m^{-2}y^{-1})	Abiotic decomposition rate (0–1)
Cold Desert Steppe	60	92	5530	3.11	0.093
Temperate Steppe	36	59	2020	2.67	0.158
Humid Temperate	134	161	7171	4.81	0.194
Mediterranean	79	103	3005	3.44	0.184
Dry Savanna	55	85	2275	2.58	0.173
Savanna	191	222	4306	5.73	0.339
Humid Savanna	340	344	3273	6.61	0.644

−0.3 °C, the temperate steppes having 10.2 °C and the dry savannas 24.1 °C. Bailey's humid tropical domain was divided into savannas and humid savannas on the basis of precipitation, the former receiving a regional annual mean of about 800 mm and the latter about 1550 mm. The simulated results for each bioclimatic region was calculated by averaging results from the sites that are in a specific bioclimatic zone.

Model runs under climate change conditions

The doubled CO_2 climatologies used to drive the CENTURY model in the present study were derived from two global climate models (GCMs), the Canadian Climate Centre (CCC) and the Geophysical Fluid Dynamics Laboratory High Scenario (GFHI), which provide monthly projections of temperature and precipitation for 2.5° grid cells worldwide. We took the values projected for a doubling of atmospheric CO_2 concentration, and assumed that these would be reached within 50 years from the present, corresponding roughly to IPCC Scenario A (Houghton *et al.* 1990). Projected changes in mean annual and seasonal temperature and precipitation are shown in Fig. 2.

The two GCMs simulate similar changes in the mean annual air temperature (2–5 °C); however, changes in precipitation were different between the models. The GFHI model showed increases in precipitation for all of the regions, whilst the CCC model showed decreases in precipitation for the temperate steppe and humid savanna regions and increases for the other regions (Fig. 2).

We assumed that changes in precipitation and temperature at each site were linear over a 50-year period, at which point they stabilized at the modified 'double CO_2' climate. Atmospheric CO_2 concentration is specified as 350 ppm prior to climatic change, increasing linearly over a 50-year period and is stabilized at 700 ppm after year 50 (Fig. 3). The results from the 25-year period immediately following this represent the transient response to climate change. Results were analysed for changes in the level of soil organic matter C, plant productivity, N mineralization and the model-calculated effect of climate on decomposition (abiotic decomposition factor). The abiotic decomposition factor is calculated as the project of soil temperature and soil moisture functions (Parton *et al.* 1993). Simulated total grassland SOC stocks (0–20 cm depth) were estimated by averaging SOC levels for all of the sites in an ecoregion and multiplying by the area of the ecoregion.

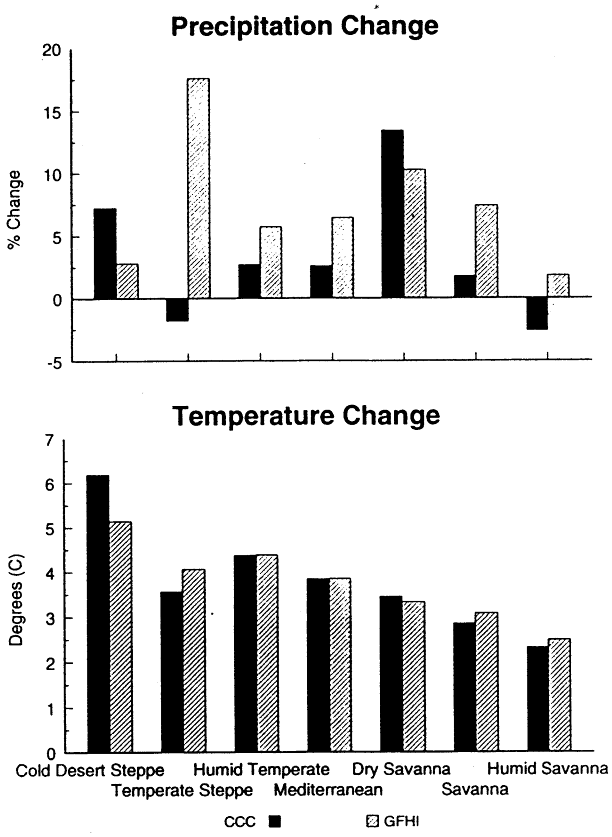


Fig. 2 Changes in temperature and precipitation for each ecoregion under CCC and GFHI scenarios.

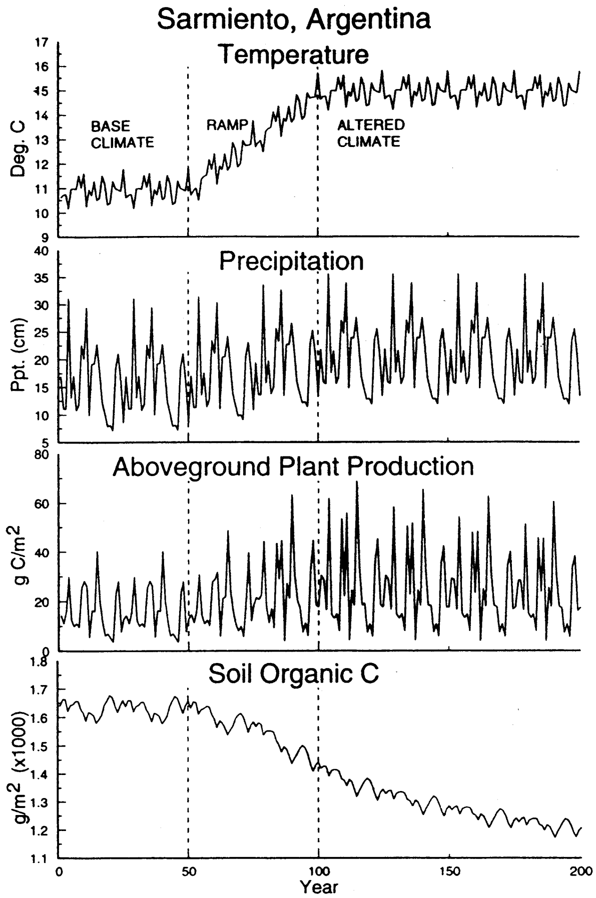


Fig. 3 GFHI climatic change patterns of temperature and precipitation for the Sarmiento, Argentina site, and the response of aboveground production and soil organic C to the altered climate. Two cycles of 25-year weather data are followed by 50 years (two cycles) of climate change up to the double-CO_2 weather, which then continues in similar 25-year cycles.

Results

Climate change sensitivity

The impacts of the two GCM climate change scenarios on total plant production (aboveground + belowground), soil organic carbon (SOC), N mineralization and decomposition are shown in Fig. 4. These values represent the means for the 25 years of 'double-CO_2' climate immediately following the 50-year climate change period; the numerical average for each ecoregion is shown, not taking into account any area weighting. Results show that the cold desert steppe region had a substantial reduction in plant production (about 25%) while the humid temperate sites had increases greater than 12%. All the savannas showed relatively small changes (< 5%). Statistical analysis of these results shows that changes in total plant production are positively correlated to changes in precipitation (P) and N mineralization (N), and negatively correlated to changes in air temperature (T), with N mineralization being the most important term ($y = 4.07 + 0.55\,P + 1.36\,N - 4.04\,T$; $r^2 = 0.85$; $P = 0.0001$). The main exception to this is in the cold desert steppe region. Substantial differences in plant productivity between the GCMs are primarily related to differences in growing season drought stress. These results are in broad agreement with those of Melillo *et al.* (1993), whose Terrestrial Ecosystem Model (TEM) predicted a 10–15% increase in equilibrium of grassland NPP for double-CO_2 climate scenarios; however, TEM does not show differences between contrasting grassland ecoregions.

Soil C results show substantial losses of SOC for all the temperate sites, including the Mediterranean region, with the largest losses occurring in the cold desert steppe and temperate steppe regions. Soil C losses are low in all three savanna regions, with the highest losses being in the humid savannas (7%). The changes in soil C are negatively related to changes in decomposition (D) and positively related to changes in productivity (PRO) ($y = -10.4 + 0.254\,PRO - 0.355\,D$; $r^2 = 0.79$; $P = 0.0001$). Soil

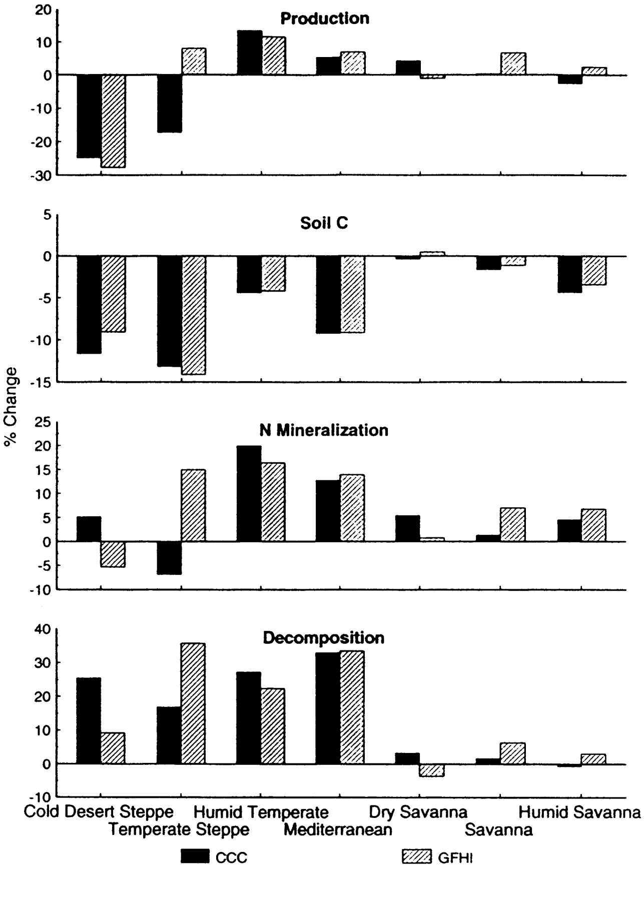


Fig. 4 Effect of climate change alone on (a) production (b) soil carbon (c) N mineralization, and (d) abiotic decomposition factor, for each ecoregion, for the CCC and GFHI scenarios. Plant production is positively correlated to changes in N mineralization and precipitation, while changes in soil organic C are positively correlated to C inputs and negatively correlated to the abiotic decomposition factor.

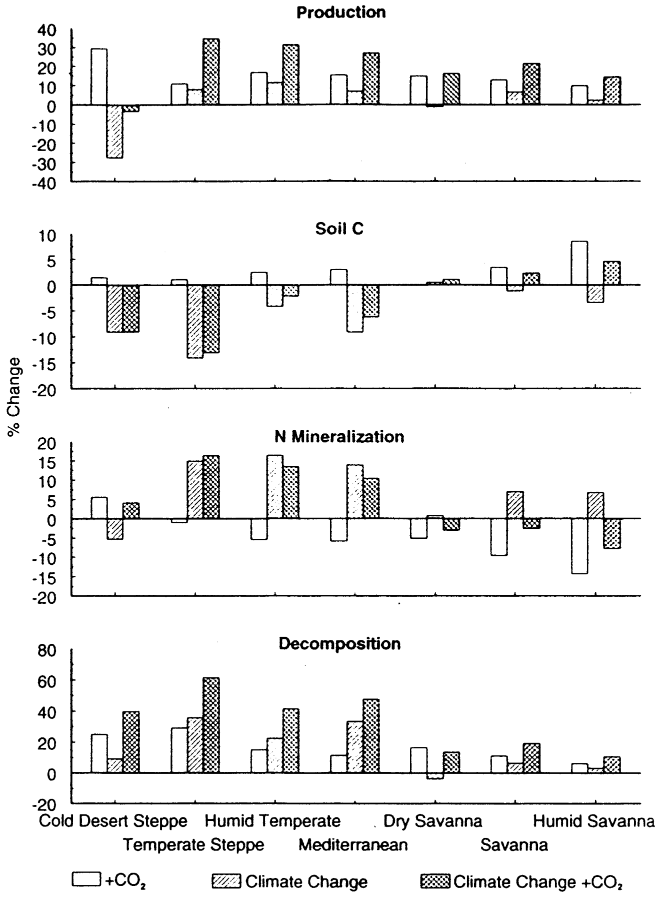


Fig. 5 Effect of CO_2 alone, climate change alone (GFHI scenario), and combined CO_2 and climate change for each ecoregion, for (a) production (b) soil carbon (c) N mineralization, and (d) abiotic decomposition factor. (The results are for the first 25-years after the transition to a new climate).

C changes do not vary much as a result of the different GCM scenarios.

N mineralization rates tended to increase for all sites, with the largest increases observed for the humid temperate, mediterranean and temperate steppe ecoregions. Under the climate change simulations, decomposition rates are increased more in the temperate sites compared with the relatively small changes simulated in the tropical regions. The apparent differences between the temperate and tropical regions in this analysis are the result of the relative changes in the temperature projections; more than 25% increase in mean annual temperature for the temperate regions, compared with approximately 10% increase for the tropics.

Effect of increased atmospheric CO_2 concentration and CO_2/climate interaction

We simulated the impact of increasing the atmospheric CO_2 concentration on grassland ecosystems with and without the inclusion of climate change (Fig. 5). Overall, the effect of increasing atmospheric CO_2 concentration under current climatic patterns was to increase total plant production, abiotic decomposition rate and SOC storage, whereas N mineralization rates decreased. Production increased the most in the cold desert steppe region, and SOC storage increased most for the humid savannas. Soil C increases were negatively correlated with changes in decomposition rate [compare Fig. 5 (b) and (d)]. N mineralization rates decreased in most regions, resulting from an increased input of lower quality litter with higher C/N ratio (Melillo *et al.* 1982), but increased for the cold desert steppe region. The simulated increases in decomposition under elevated CO_2 resulted from improved soil water relationships at the cold dry sites (cold desert steppe, temperate steppe), with smaller increases for the warmer and more humid sites. When relative changes in total plant production, SOC, N mineralization, and decomposition were compared between (i) the combined impact of increased atmospheric CO_2 concentration and climate and (ii) the independent impacts of CO_2 and climate change, a linear additive effect was demonstrated (r^2 = 0.97, 0.98, 0.97 and 0.91, respectively).

Increased atmospheric CO_2 concentration enhanced total plant production regardless of the climate change impact, consistent with the results of Melillo *et al.* (1993). This enhancement in plant production reduces the SOC losses which result from climatically driven changes in SOM decomposition. The direct CO_2 effect reduces C losses throughout the grassland systems and results in a SOC sink region in the tropical savanna and humid savanna regions, regardless of climatic effects.

The impact of these climate and CO_2 changes on current grassland SOC stocks indicates that climatic effects alone will result in a net loss of about 4 Pg C (Table 3), with all regions becoming C sources as a result of SOC decomposition. However, the effect of increasing atmospheric CO_2 is to offset the SOC losses due to climatic changes. The CO_2 effect reduced the net global losses from grasslands by approximately 50% in the CCC case and 66% in the GFHI case, suggesting a net carbon source of 2 Pg C over 50 years, or 0.04 Pg C per annum. In the tropical regions, savannas and humid savannas actually become SOC sinks with the inclusion of CO_2 and climate changes together, regardless of GCM scenario (Table 3; Fig. 6).

These results contrast with those of Jenkinson *et al.* (1991), who estimated a net source of 61 Pg C globally over the next 60 years from soil organic matter worldwide. Grassland soils (temperate steppes and tropical savannas) accounted for about 20% of present world SOC stocks in this analysis, suggesting a grassland source of about 12 Pg C over 60 years, or 0.2 Pg C per annum, based on Jenkinson's calculations.

Detecting changes in grasslands

The ability to detect the impact of climate changes on plant production and SOC levels, given the observed natural variability, was evaluated using the CENTURY model results. The 25-year average annual plant production and SOC levels for all of the 31 sites prior to climate change were compared with the average values for the 25-year period following the start of climate change for both of the GCM scenarios, and a statistical *t*-test was used to determine if the mean values were significantly different at the 5% level.

Only 8% of the 62 model runs showed significantly different plant production (predominantly those with low productivity), with plant production changes averaging +22% (range 17–31%). The non-significant comparisons had an average change in plant production of +7% (range 0–16%). Eighty-one percent of the comparisons showed significant changes in mean SOC, with SOC changes averaging −7% (range −1 to -33%). SOC changes of less than 1% were non-significant.

These results suggest that simulated SOC and plant production would have to change by at least 1% and 16%, respectively, in order to be statistically detectable. Note that it would be impossible to detect a 1% change in SOC in the field because of the large spatial variability in SOC (Yonker *et al.* 1988) and it would take a 5–15% change to be detectable. The number of comparisons showing significant differences in mean plant production and SOC did not change with time (for years 25–50, 50–75, and 75–100 following the start of climate change). Changes in plant production or SOC induced by climate

Table 3 Simulated ecoregion SOC stocks (Pg) in the upper 20 cm of soil and differences following 50-year climate change (CC) period,with and without doubling of atmospheric CO_2, for GFHI and CCC scenarios.

Biome type	Present-day SOC stock (Pg) *Global grassland total =* 105.51 Pg	CO_2 alone	Canadian Climate Centre CC	Canadian Climate Centre CO_2 + CC	GFHI CC	GFHI CO_2 + CC
Cold Desert Steppe	12.65	0.15	−1.64	−1.80	−1.09	−1.12
Temperate Steppe	7.72	0.03	0.44	−0.42	−0.45	−0.43
Humid Temperate	28.89	0.61	−1.18	−0.56	−1.11	−0.60
Mediterranean	0.25	0.01	−0.02	−0.01	−0.02	−0.01
Dry Savanna	12.79	−0.02	−0.05	−0.01	−0.06	0.11
Savanna	39.46	1.30	−0.74	0.48	−0.33	0.95
Humid Savanna	3.76	0.24	−0.05	0.16	−0.09	0.12
Net Change		2.01	−4.12	−2.16	−3.16	−0.98

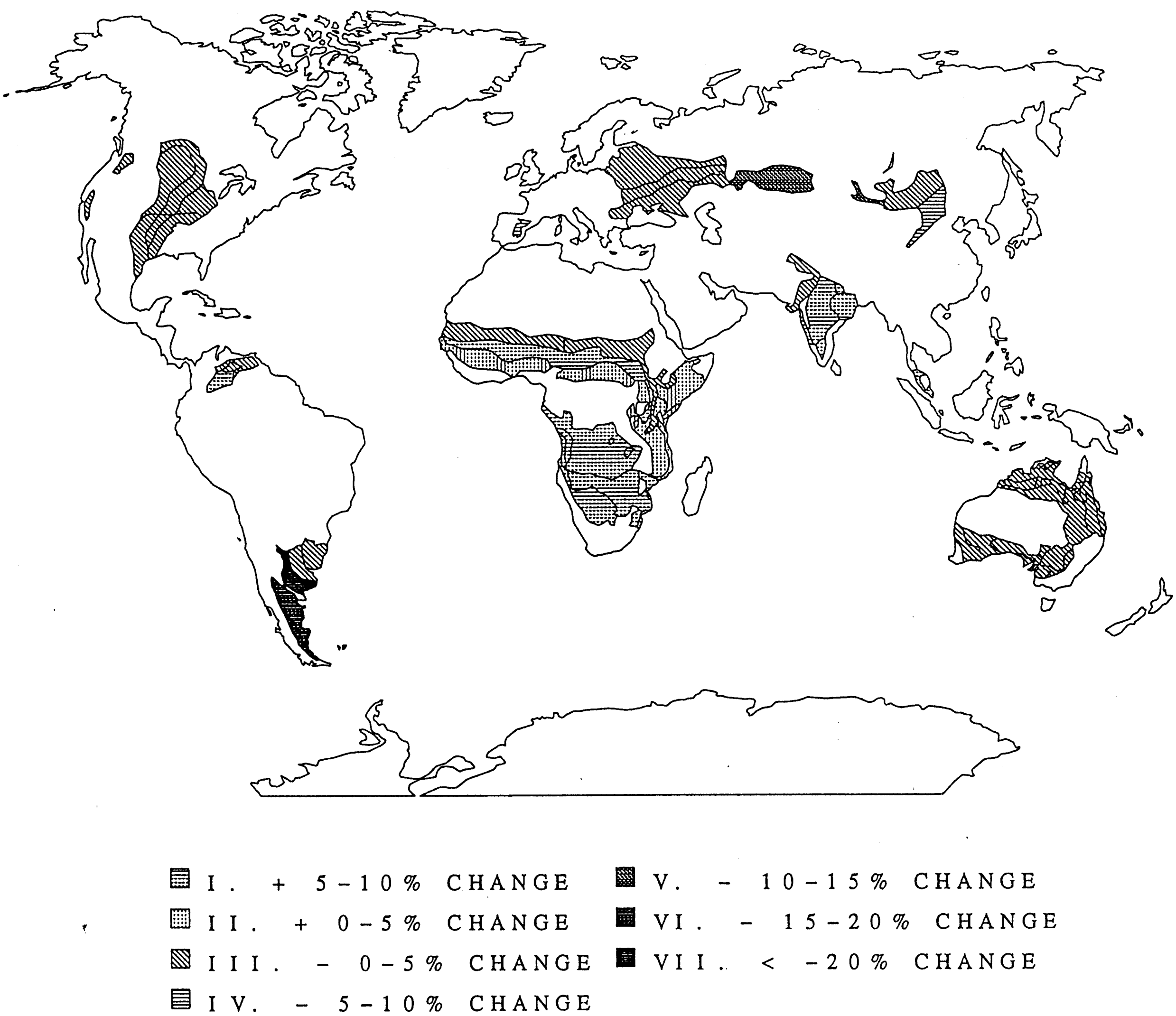


Fig. 6 Worldwide distribution of changes in soil carbon for GFHI climate change scenario and CO_2 effect combined.

change and increasing atmospheric CO_2 concentrations will therefore have to be substantial, overcoming inter-annual variability and sampling variance, respectively, in order to be detectable. Comparison of the predicted changes in plant production (see Figs 3 and 4) with this statistical analysis suggests that most of the predicted changes in plant production would be difficult to detect.

Figure 3 shows that the perturbations induced by the 50-year climate change period for the site at Sarmiento, Argentina, continue beyond the new equilibrium levels of atmospheric CO_2 concentrations and climate. Although plant production has stabilized 75 years after the start of climate change, SOM has not reached a new steady state, although the rate of change in SOM has decreased. Comparison of transient and long-term (5000-year) equilibrium levels of SOM show that only 26% of the long-term change in SOM has occurred 50–75 years after the initiation of climate change. It is therefore important to distinguish between the transient responses induced immediately by climate change and the long-term equilibrium response.

Discussion

The impact of increasing atmospheric CO_2 concentration under two different climate change scenarios was modelled for 31 grassland sites, both temperate and tropical, representing 7 ecoregions of the world. The model's output under current climate was validated against monthly field data for 15 of these sites, representing a unique synthesis of detailed and long-term data from both temperate and tropical grasslands. The two global climate models (GCMs) showed similar temperature changes, but contrasted in their predicted changes in precipitation for certain of these ecoregions, notably the temperate steppes and the humid savannas.

Climate change alone resulted in an increase in total above- and belowground production for the mesic regions (humid temperate and mediterranean), mainly attributable to increased N mineralization, and a decrease in the cold desert steppe regions. Soil organic matter decreased in all the mesic and colder regions, due to increased decomposition. The tropical savanna regions were affected the least, due to the smaller temperature changes projected for this region by the GCMs.

CO_2 increase alone resulted in a significant increase in production in all regions, with the greatest proportional increase in SOM in tropical savanna regions. When combined with predicted climate change, CO_2 had an additive effect, tending to diminish the climate change effects. The net effect of climate change and CO_2 was a significant increase in NPP in mesic regions as well as in dry savannas, with little or no net change in cold desert steppe or humid tropical regions. Overall, SOM showed a decrease, especially in temperate steppes and cold desert steppes due to stimulation of decomposition by both climate change and increasing CO_2 concentration. Tropical savanna and humid savanna regions were soil C sinks due to CO_2 fertilization under both GCM scenarios.

Climate change alone predicts a C loss of 3–4 Pg after 50 years of climate change. However, a CO_2 enhancement effect amounting to 2 Pg over the same period results in a smaller net loss of 1–2 Pg over 50 years. These numbers are substantially lower than other estimates. Nevertheless, since the world area of grasslands is likely to increase due to deforestation, desertification, abandonment of arable land, etc., the carbon in grassland soils will continue to be an important part of the world C budget.

Most of the significant (i.e. detectable) changes in plant production and SOM occur during the first 25 years after climate change begins; we indicate that $> 16\%$ and $> 1\%$ changes, respectively, will be required in order to detect the effects of climate change on ecosystems. Changes in plant production reach near-equilibrium conditions within 50–75 years, whereas only 30% of the equilibrium changes in SOC are reached within 50–75 years.

The present version of CENTURY, tested in detail against data from 11 grassland sites worldwide (Parton *et al.* 1993), incorporates the vegetation response to climate change and increases atmospheric CO_2 concentration, as has been suggested (Jenkinson *et al.* 1991). However, in common with recent modelling work elsewhere (Melillo *et al.* 1993), we have not considered climate-induced redistribution of grassland areas, nor have we attempted to model present and future conversion of grasslands to agriculture. Future studies are intended to address these issues.

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