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Scenarios of Future Climate and Land-Management Effects on Carbon Stocks in Northern Patagonian Shrublands

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Abstract We analyzed the possible effects of grazing management and future climate change on carbon (C) stocks in soils of northern Patagonian shrublands. To this aim, we coupled the outputs of three (HadCM3, CSIRO Mk2, and CCSR/NIES) global climate models to the CENTURY (v5.3) model of terrestrial C balance. The CENTURY model was initialized with long-term field data on local biome physiognomy, seasonal phenologic trends, and prevailing land-management systems and was validated with recent sequences of 1-km Normalized Difference Vegetation Index (MODIS-Terra) images and soil C data. In the tested scenarios, the predicted climate changes would result in increased total C in soil organic matter (SOMTC). Maximum SOMTC under changed climate forcing would not differ significantly from that expected under baseline conditions (8 kg m^{-2}). A decrease in grazing intensity would result in SOMTC increases of 11% to 12% even if climate changes did not occur. Climate change would account for SOMTC increases of 5% to 6%.

Keywords Carbon sequestration · CENTURY model · Climate change · MODIS-Terra · Normalized Difference Vegetation Index · Semiarid land

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Introduction

Considerations about global climate changes during the current century are closely bound to quantitative predictions of changes in carbon (C) stocks in soils and vegetation of various world ecosystems. Arid, semiarid, and subhumid ecosystems cover >47% of the global land surface (Lal 2004) and provide most of the food and fiber for the human population by way of grazing and crop agriculture. The Patagonian (Argentina) semiarid shrubland ecosystems cover approximately 250000 km^2 and share many characteristics with sympatric semiarid ecosystems in the northern hemisphere (Mares and others 1985; Ares and others 1990).

In these ecosystems, primary productivity and C cycling are directly related to the amount and seasonal distribution of precipitation inputs (Sala and others 1988; Shen and others 2005) and may vary as much as fivefold among years (Walker 1993). Nonsustainable land use practices–such as inappropriate plowing, overgrazing by domestic animals, and excessive fuel wood extraction—are considered causes of land degradation in arid ecosystems (Le Houérou 1996; Hahn and others 2005). Because degradation implies among other effects, the loss of soil C (Lal 2001), a quantitative analysis of C budgets is of interest in the context of global change prognoses.

Results of modeling with existing soil organic matter (SOM) data sets and atmospheric ocean global climate (AOGC) models, as well as soil-warming experiments (Prentice and others 2001; Knorr and others 2005), raised the question of whether a warmer climate during this century would contribute to an accelerated decomposition of soil C stocks and further back-feed into atmospheric carbondioxide (CO_2)-enrichment. These studies showed that observed bulk decomposition rates of SOM are consistent with the assumption that accelerated decomposition of some nonlabile fractions of the soil C pools sensitive to temperature increases (Powlson 2005) could amplify climate change. Soil C balance is driven by SOM decomposition and C input through decaying plant litter, and primary productivity is also expected to increase because of CO_2 fertilization (Cox 2001). Accordingly, it is of interest to run coupled analyses of both losses and gains of soil C. Jones and others (2004), using climate-carbon–cycle simulations coupled to a physiognomic model of vegetation, showed that global CO_2 released from soil respiration would not be entirely fixed by the expected global increases in primary productivity, resulting in higher-than-previously-estimated atmospheric CO_2 buildup during this century.

There are several reasons to raise attention in testing these patterns in the case of arid and semiarid areas. First, an increase in atmospheric CO_2 concentration might improve water use efficiency in most plant species by increasing C uptake or decrease water loss (Grünzweig and others 2003). The decrease in water loss could have important implications in arid–semiarid ecosystems by improving soil moisture conditions, decreasing water stress, and extending water availability. All of these could eventually result in increased C sequestration (Grünzweig and others 2003). However, arid and semiarid shrublands are usually resource limited, dominated by slow-growing plants (Crawley 1998) that devote considerable C resources to chemical antiherbivore defenses (Coley 1988; Lauenroth 1998). Accordingly, it does not seem probable that increased CO_2 or precipitation inputs could strongly increase primary productivity in these ecosystems (Chapin 1991; Golluscio and others 1998; Tilman 1998; Poorter and Pérez-Soba 2002; Chesson and others 2004).

Second, the above-mentioned experiments at a global scale did not include the effects of anthropogenic land use, in particular, grazing. Most semiarid lands, including Patagonian shrublands, have been extensively grazed with domestic herbivores (Defossé and others 1990) and probably will continue to be grazed during the current century. Domestic herbivores substantially impact ecosystem structure and functioning (Díaz and others 2001; Hutchinson and others 2007). Grazing removes vegetation, returns nutrients to the soil, alters the root-to-shoot ratio of plants, and increases the nitrogen content of live shoots and roots (Holland and others 1992). It may also lead to shifting of species (Holland and others 1992; Adler and Lauenroth 2000) and increase the abundance of slow-growing woody species (Bisigato and Bertiller 1997). Grazing is a major modifying factor of C flows to the soil in rangelands (Rice and Owensky 2001) because changes in the quantity and quality of plant litter and herbivore faeces could affect decomposition and C mineralization rates (Alados and others 2004; Throop and others 2004). Therefore, the effect of grazing on C releases from rangeland soils seems highly relevant.

We analyzed the expected combined effects of climate change and grazing management on soil and vegetation C stocks in the arid northern Patagonian Monte during the current century by coupling the output of existing AOGC and C models with long-term field data obtained at these shrublands. We addressed the following hypotheses:

1. Global warming would contribute to decrease soil C stocks at the Patagonian Monte during the current century.
2. A decrease of present stocking rates of domestic herbivores would have a major effect on soil C balance comparable to that caused by expected climate changes.

To inspect these issues, we used climate and field data collected at the Patagonian Monte during the last century to run an available C-simulation model (CENTURY v5.3; CSU 2001). We explored the sensitivity of the model estimates to variations in the climate regime occurring across the region and validated the model output with a set of independent data. We obtained estimations of predicted climate anomalies during the current century by means of three publicly available AOGC models used them as input to the C model. We then compared the changes predicted in C balances respect with a baseline (no climate change) situation.

Materials and Methods

Study Area

The ecosystems selected for this study correspond to the Monte Austral or Patagonian Monte, located in northeastern Patagonia, in the Chubut and Río Negro Provinces (Argentina), covering an area of approximately 28,000 km^2 from 41°S to 43°S and from 64.5°W to 67°W (Fig. 1). Mean annual temperature at the southeast border of the region (where continuous meteorologic observations have been conducted since the beginning of the last century), is 13.4°C; the mean annual precipitation is 235.9 mm (1980 to 2003); and the aridity index is 0.19 (Bertiller and others 2006). Further details on the regional variability of the precipitation and temperature regimes as inferred from recent remotely sensed data are given in a later section. Precipitation shows a semiannual tendency with usual absolute maxima in fall (March to May in the southern hemisphere) and a secondary maximum in spring (September to November; Centro Nacional Patagónico 2004). According to a soil map at scale 1:1000000 from the

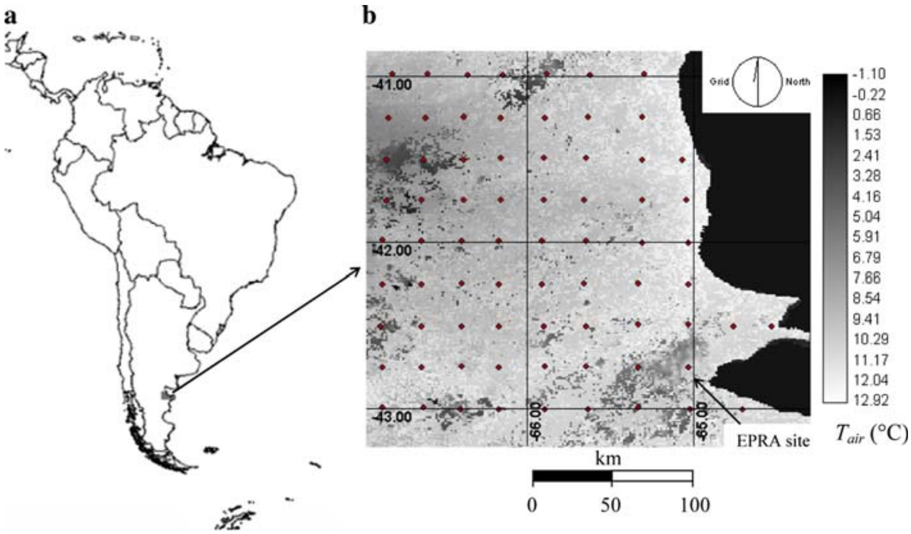

Fig. 1 (**a**) Map of South America with location of the study area. (**b**) Detail of study area as depicted by an AVHRR image (1 km, 10-day air temperature field [T_{air}]) obtained at 11-21/09/1992. Dots indicate sampling points used in this study. EPRA: Environmental Physics Research Area

National Institute of Agricultural Technology (INTA 1990), soils in this region are complexes of Typic Haplocalcids and Typic Torriorthents (40% of the area), Lithic Haplocambids and Typic Haplargids-Natrargids (30% of the area), Aridic Calcixerols and Torrifluvents (15% of the area) spatially mixed with Ustic Haplocalcids and Entic and Lithic Haplustolls (15% of the area) (del Valle 1998; Soil Survey Staff 1998; Table 1).

These ecosystems are for the most part used as pastures for sheep and are under extensive management. The vegetation corresponds to the shrubland of *Larrea divaricata* Cav. and *Stipa* spp., characteristic of the southern portion of the Monte Phytogeographic Province, which shares plant species with the Patagonian Phytogeographic Province (Cabrera 1976). Plants cover <40% to 60% of the soil and present a random patchy structure consisting of large

Table 1 Soil subgroups in the Patagonian Monte and their major textural characteristics according to Instituto Nacional de Tecnologia Agropecuaria (1990)

Map unit		%Area	Soil subgroup complex	%Complex	Texture ranges							
					0–20 cm				20–40 cm			
					%Sand		%Clay		%Sand		%Clay	
					L	H	L	H	L	H	L	H
20	DFtc	40	Typic Haplocalcids	60	85	100	0	10	85	100	0	10
			Typic Torriorthents	40	70	85	10	15	70	85	10	15
5	DGli	20	Lithic Haplocambids	50	70	85	10	15	50	80	15	20
			Typic Haplargids	30	50	80	15	20	55	100	20	35
			Typic Natrargids	20	25	55	8	29	0	50	55	100
6	DFut	15	Ustic Haplocalcids	50	50	80	15	20	50	80	15	20
			Typic Torrifluvents	30	70	85	10	15	50	80	15	20
			Xeric-Lithic Torriorthents	20	70	85	10	15	50	80	15	20
2	MRai	15	Aridic Calcixerolls	60	50	80	15	20	55	100	20	35
			Typic Torrifluvents	40	70	85	10	15	50	80	15	20
7	DFut	5	Ustic Haplocalcids	50	50	80	15	20	50	80	15	20
			Entic Haplustolls	30	25	55	8	29	25	55	8	29
			Lithic Haplustolls	20	85	100	0	10	25	55	8	29
13	DFtc	5	Typic Haplocalcids	50	85	100	0	10	85	100	0	10
			Typic Torrifluvents	30	70	85	10	15	50	80	15	20
			Lithic Haploxerolls	20	50	80	15	20	50	80	15	20

H = highest value; L = lowest value

shrub clumps encircled by perennial grasses, incipient plant patches composed by one shrub surrounded by perennial grasses, and isolated individuals of grasses or dwarf shrubs colonizing bare soil areas (Bisigato and Bertiller 1997). The main vegetative growing period is fall and early winter. In some years, precipitation events can also occur during spring and early summer, although these are of lower intensity than those that occur during the cold season. Plants species display characteristics of both aridopassive and aridoactive life forms because their root systems explore different soil depths and/or use water and nutrients at different times (Bertiller and others 1991).

Carbon Model and Simulation

Carbon modeling was performed with CENTURY (v5.3; CSU 2001). This is a one-site, process-based model of plant–soil ecosystems developed as part of the United States National Science Foundation Ecosystem Studies Research Projects at Colorado State University. The model simulates plant production and SOM dynamics (Parton and others 1987, 1993; Metherell and others 1993). It has been extensively used to explore the long-term dynamics of C in different soil–plant systems and management conditions (Wang and others 2002; Ärdo and Olson 2003; Hill 2003; Kemp and others 2003; Liu and others 2004). Several investigators (Burke and others 1991; Parton and others 1993, 1994, 1996; Smith and others 1997; Mikhailova and others 2000; Cerri and others 2004; Piñeiro and others 2006; Ogle and others 2007) have reported general good performance in various applications of this model.

The plant-production submodel includes the effects of soil moisture, temperature, and soil texture as well as the vertical distribution of root biomass in accessing available nutrient supplies. The SOM submodel is a multilayered (above- and below- ground litter pools, surface microbial pools functionally linked to decomposing surface litter, temperature, and soil–water balance), multipool (active, slow, passive C pools with characteristic turnover times) system. These conform presently recognized requirements to represent seasonality of C inputs to the soil and a differential decomposition rate of soil C pools (Curiel-Yuste and others 2004; Gu and others 2004). Major driving variables of the model are the monthly values of precipitation, minimum and maximum temperature, potential evapotranspiration, soil texture, and the quantity and quality of litter (Parton and others 1987). Per Holland and others (1992), the CENTURY model has an elaborate treatment of grazing effects on the C cycle. This includes the assumption of minor impacts of grazing on plant production at low grazing (LG) intensity, with return of nutrients from the plant biomass to the soil by animal urine and feces. At moderate grazing (MG) intensities, as those prevailing in northern Patagonia (Ares and others 2003), the model assumes a constant root-to-shoot ratio and a decrease in potential plant production depending on grazing intensity.

Baseline Model Parameters, Precipitation, and Air Temperature Data

Initial values of model parameters related to soil and physical controls, external nutrient input values, SOM, water content, and eventual erosion loss factors were obtained from long-term studies at the intensive sites of the CENPAT Terrestrial Ecology Research Area (Tables 2 and 3). The CENTURY model was run for the period 1900 to 2003 with monthly precipitation and maximum and minimum air-temperature data supplied by the Environmental Physics Research Area (EPRA; 42°46′20″S 65°02′15″W) of CENPAT (Puerto Madryn, Argentina). This data series was also used to construct a simulation algorithm to generate baseline series for the period 2003 to 2100 (see Appendix 1) in the hypothetical condition under which no global forcing would occur during the present century. Atmospheric [CO_2] was assumed to have increased during the last century from an estimated preindustrial (330 ppmv) up to present levels (371 ppmv).

Climate Anomalies Expected During the Current Century

Climate anomalies caused by global change during 2003 to 2100 were simulated with AOGC models by considering Intergovernmental Panel on Climate Change (IPCC 2001, 2007) possible climate change scenarios and were further compared with baseline scenarios. IPCC (2007) recognizes several groups of hypotheses about future scenarios of world development. We selected estimates of climate change by AOGC models for two rather extreme alternatives among them (A2 and B2 scenarios) as available from: http://ipcc-wg1.ucar.edu. The A2 scenario results in atmospheric [CO_2] $\approx$ 800 ppmv at the end of this century compared with [CO_2] $\approx$ 594 ppmv as predicted by the B2 scenario (Schlesinger and Malyshev 2001). To predict anomalies in the precipitation and temperature regimes corresponding to these scenarios, we used the following AOGC models: (1) HadCM3 (Hadley Centre for Climate Prediction and Research, Berkshire, UK; Gordon and others 2000; Pope and others, 2000); (2) CCSR/NIES (Center for Climate System Research-National Institute for Environmental Studies, Tokyo, Japan; Emori and others 1999); and (3) CSIRO Mk2 (Australia's Commonwealth Scientific

Table 2 Baseline values of CENTURY model parameters

Parameter[a]	Description	Value	Reference
NLAYER	Number of soil layers in the top level of the water model	4	1,2
THICK	Thickness of soil layers 1 through 4	0.20–0.40 m	1,2
SAND	Soil sand fraction of soil layers 1 through 4	67% to 71%	1–3
CLAY	Soil clay fraction of soil layers 1 through 4	9% to 11%	1,2
SILT	Soil silt fraction of soil layers 1 through 4	20% to 22%	1–3
BULCKD	Bulk density of soil layers 1 through 4	1.48–1.51 kg l^{-1}	2
AFIELD	Field capacity of soil layers 1 through 4	19% to 21%	4–7
AWILT	Wilting point of soil layers 1 through 4	0.09 to 0.10	4–6
DRAIN	Fraction of excess water lost by drainage	1	6
STORMF	Fraction of soil water flow between layers lost by storm flow	0	8
AGLCIS	Aboveground live unlabeled C	0.093 kg m^{-2}	3,7,9,10
BGLCIS	Belowground live unlabeled C	0.183 kg m^{-2}	9,10
CLITTR (1,1)	Surface plant litter unlabeled C	0.122 kg m^{-2}	7–9
CLITTR (2,1)	Soil plant litter unlabeled C	1.358 kg m^{-2}	7–9
RCELIT (1,1)	Surface plant litter C/N	19.71	5–9
RCELIT (2,1)	Soil plant litter C/N	13.00	9
RCES1	Surface organic matter fast- and intermediate- rate pool C/N	12.06	5–9
SOM1CI (1,1)	Surface organic matter fast-rate pool: unlabeled C	0.046 kg m^{-2}	11
SOM1CI (2,1)	Soil organic matter fast-rate pool: unlabeled C	0.195 kg m^{-2}	11
SOM2CI (1)	Soil organic matter intermediate- rate pool: unlabeled C	4.094 kg m^{-2}	11
SOM3CI (1)	Soil organic matter slow-rate pool: unlabeled C	2.159 kg m^{-2}	11
STDCIS	Standing dead unlabeled C	0.050 kg m^{-2}	11

[a] CENTURY acronym

[1] Rostagno and others 1991; [2] Cano and del Valle 1995; [3] Carrera 2003; [4] Bisigato and Bertiller 1999; [5] Mazzarino and others 1996; [6] Saxton 1986; [7] Carrera and others 2003; [8] Ares and others 2003; [9] Bertiller and others 2004; [10] Bertiller and others 2002; [11] Equilibrium value corresponding to $[CO_2]$ = 280 ppmv (Schlesinger and Malyshev 2001). The files needed to run the model are available from the authors on request

Table 3 Physiognomic characteristic of the plant community and prevailing land management

Physiognomy management	Description	Value
SEV	Ecosystem: Sevilleta-type desert grassland	Months 1 through 12
G3	Vegetation type: 50% of plant species grow during the warm season, and 50% of plant species grow during the cool season	Months 1 through 12
Growth start	Months in which plants begin to grow	1
Growth end	Month in which the plants conclude their growth	12
Management event		
GM	Grazing management: moderate (linear impact on above-ground production)	Months 1 through 12

and Industrial Research Organisation, Mordialloc, Australia; Gordon and O'Farrell 1997; Hirst and others 2000). All three models were used in a recent Coupled Model Intercomparison Project (Covey and others 2003), and the HadCM3 model partly supported the predictions in IPCC (2007). The outputs of runs of each model for the A2 and B2 scenarios were expressed as relative precipitation (P) or absolute maximum and minimum temperature (T_{max}, T_{min}) deviates with respect to predicted baseline values.

Coupling of AOGC Output to CENTURY Model Runs

The CENTURY model was run for 5000 years under baseline conditions to obtain steady-state concentrations of soil C; C in superficial organic matter with a fast turnover pool; and standing dead C. These initial values were then used to run the model for 200 years starting at 1900, assuming nearly preindustrial (330 ppmv) atmospheric CO_2 concentrations until the mid twentieth century, and linearly increasing [CO_2] through 371 ppmv at year 2000 up to 800 ppmv (A2 scenario) or 594 ppmv (B2 scenario) in 2100 (Schlesinger and Malyshev 2001). Six estimates of climate regime anomalies (three AOGC and models two IPCC scenarios) were tested for the period 2003 to 2100 in combination with maximum and minimum ranges of intraregional thermal variation. We first ran the model supposing moderate grazing (MG) intensities for the period 1900 to 2100 and then supposing low grazing (LG) intensities for the period 2003 to 2100 to explore the effects of decrease stocking rates on C pools in soil.

CENTURY Model Validation

CENTURY model output corresponding to the stock of C in above-ground live plant biomass (AGLIVC) for the period 2001 to 2003 was validated by comparing its standardized values with a series of standardized Normalized Difference Vegetation Index values from 16-day composite bands of the MODIS-Terra satellite sensor available at: http://daac.gsfc.nasa.gov/data/ dataset/MODIS/. Goodness of fit was evaluated through the significance ($p \leq 0.05$) of the parameters of harmonic functions fitting the 38-month series of both variables and the correlation between both serial fits. Soil organic matter total C (SOMTC) values were validated with field data as reported from various sources (Rostagno and del Valle 1988; Rostagno and others 1991; Mazzarino and others 1996; Carrera and others 2005; this study).

Estimation of Model Uncertainties and Model Sensitivity to Regional Variation

Exploring hypotheses about future scenarios of C balance at the Patagonian Monte involved comparing predicted changes related to global climate change, as estimated with current AOGC models, with regional baseline conditions as estimated from past climate records and regional soil properties. Also, extending the model results to estimates for the Patagonian Monte required a characterization of its sensitivity to the range of environmental variation (climate and soils) occurring in the region. We identified the following types of uncertainty in relation to these sources of variation and estimated their incidence on soil C estimates.

Type 1: Uncertainty About Future Baseline Precipitation Regime

Baseline precipitation during the current century was estimated based on the statistical characteristics of the climate series observed during the past century (Appendix 1). Uncertainty in mimicking the EPRA climate series results from the inherent error in estimating the parameters of their past statistical distributions. We quantified the effect of this type of uncertainty through the range of variation (maximum to minimum) of the CENTURY model output SOMTC using 25 stochastic simulations of the climate regime as model input.

Type 2: Sensitivity of C-model Output Related to Regional Variations in Soil Texture

In studies at semiarid areas, estimates of soil C stocks with the CENTURY model have been found to be sensitive to changes in the input soil texture (Poussart and others 2004). Soil texture influences many processes in the CENTURY model, such as SOM turnover, field capacity, wilting point and soil water evapotranspiration (Cerri and others 2004; Poussart and others 2004). This suggests that extending the model results obtained with soil data collected at the intensive study sites near EPRA requires taking into account regional variability in soil texture.

We made this estimation based on soil subgroup maps of the study area (see also Table 1). We wrote computer code to randomly sort textural soil classes based on weighed averages of the proportions of soil subgroups in the area and constructed 25 soil textural inputs to the CENTURY model representing the expected ranges of regional variation. We quantified the uncertainty related to soil texture through the range of variation (maximum to minimum) in the corresponding SOMTC model outputs.

Type 3: Variability in C-model Output Derived from Regional Variability of Precipitation and Temperature

The CENTURY program was initialized with long-term ground meteorologic data obtained at the EPRA station during the period 1975 to 2003. The extension of its results to infer that regional conditions in the Patagonian Monte (see Fig. 1) might be affected by the local variations in the precipitation and thermal regimes in the region. The Patagonian Monte is a low-populated area, and continuous, reliable meteorologic data, other than those assembled at the EPRA, are scarcely available. Alternatively, we quantified this type of variability by estimating maximum-to-minimum ranges of variation based on remotely sensed data (Appendix 1).

Type 4: Uncertainty in C-model Derived from Estimates of Future Climate Anomalies Obtained with Various AOGC Models

Available deterministic AOGC models constitute complex hypotheses about future climate variation. Their

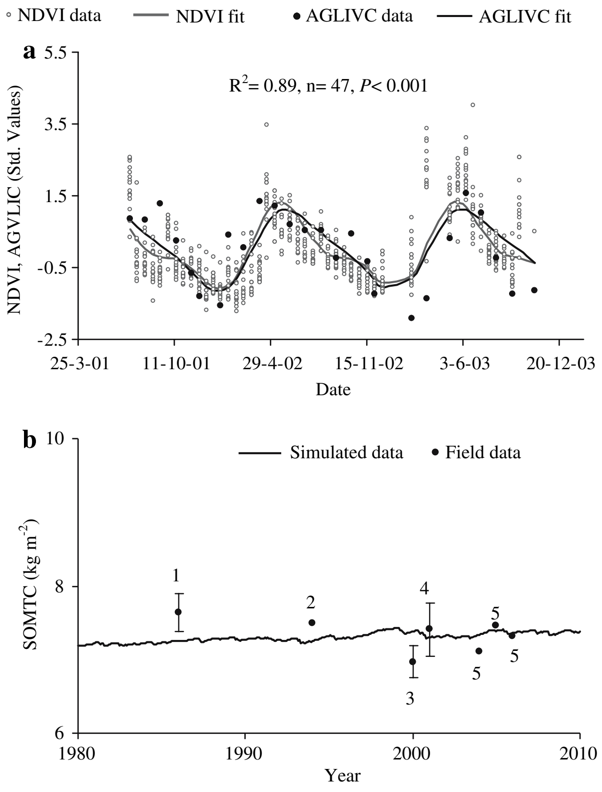

Fig. 2 CENTURY model validation. (**a**) Comparison between time series (July 2001 to September 2003) of MODIS-Terra standardized values of NDVI and CENTURY baseline output AGLIVC under MG intensity. R^2 corresponds to the correlation between NDVI and AGVLIC fitting functions. (**b**) Simulated (MG conditions) and field data values (±1 SD) of SOMTC. Data recalculated from **1** Rostagno and del Valle (1988) and Rostagno and others 1991; **2** Mazzarino and others 1996; **3–4** Carrera and others 2005; and **5** this study

complexity is further enhanced by the lack of certainty about how the world economy (and resulting anthropogenic C emissions) will grow during the current century. Because considerable variation exists between the AOGC models presently available, the usual approach is to average predictions obtained using a set of the most-tested available models (Giorgi and Francisco 2000), and this is also the one followed by this study.

Results

CENTURY Model Validation

Significant fits ($p < 0.05$) of standardized average AGLIVC and local MODIS-Terra NDVI values during the period July 2001 to September 2003 were attained with summed harmonics of length 365 and 182.5 days, corresponding to the fall + spring vegetation growing cycles. Mean NDVI and AGLIVC values were significantly correlated (Fig. 2a). SOMTC output (Fig. 2b) did not differ ($p < 0.05$) from reported field values.

C-model Output Uncertainty and Regional Variability

The average range of variation of monthly values of 25 iterations of SOMTC output correspond to uncertainty in the simulation of baseline precipitation (type 1) was 0.36 kg m^{-2}. The value varied with the time at which the SOMTC scenario was predicted (Fig. 3a). Variability of soil texture (type 2 uncertainty) within the ranges observed at the scale of the Patagonian Monte also produced variations in the SOMTC output that increased with the projected time (average max-min range: 0.26 kg m^{-2}) (Fig. 3b). The intraregional variability of climate parameters also defined additional ranges of (type 3) variability (Fig. 3c). This later summarized the range of variation in SOMTC that would be expected at the Patagonian Monte during this century if no climate change occurred (baseline conditions).

The AOGC models produced varying estimates of climate anomalies expected during this century that also depended on the expected world-development scenario (Fig. 3d). CSIRO Mk2 produced the highest and CCSR/NIES the lowest estimates in the A2 scenario, whereas the reverse occur in the B2 scenario. These extreme estimations were adopted as uncertainty boundaries in AOGC model estimates in each scenario.

Effects of Predicted Climate Change and Grazing Management on Soil C Stocks

AOGC models predicted increasing trends of SOMTC slightly higher than the 2000 to 2100 average baseline, close to the upper bound of the predicted baseline variability at a regional scale. Estimates under MG management were coincident in estimating 7.1 to 7.6 kg m^{-2} SOMTC by the end of this century under scenario A2 and 7.3 to 8.0 kg m^{-2} SOMTC in the B2 scenario (Fig. 4a). The uncertainty range caused by the various AOGC models was nearly always within those corresponding to regional variation across the Patagonian Monte. These results do not supply sufficient evidence to support hypothesis 1, which might not hold in either of the previously mentioned scenarios.

Both baseline SOMTC values and those eventually resulting from climate changes would further increase during the current century under a (so-far-hypothetical) regional policy to decrease MG to LG intensities during this period. Decreasing the intensity of grazing would increase baseline SOMTC to an extent comparable with

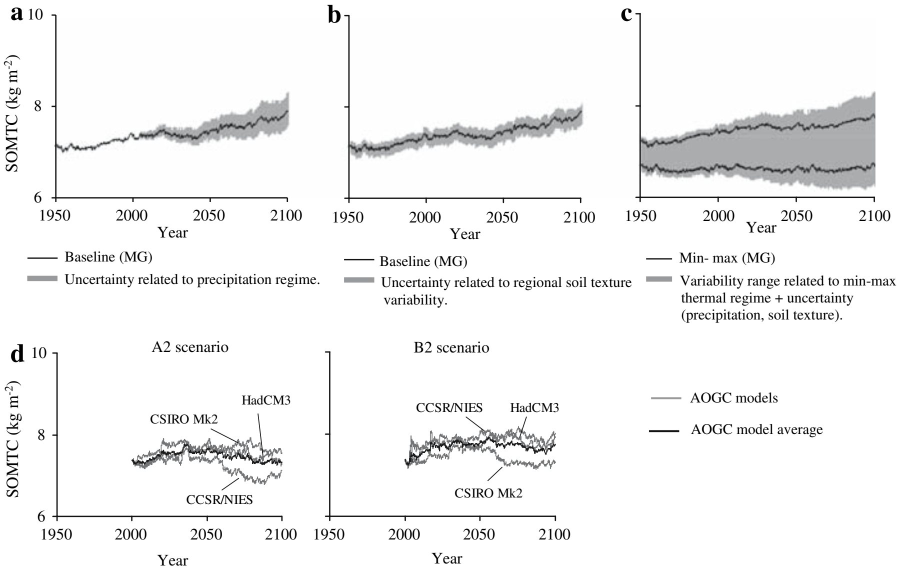

Fig. 3 Baseline uncertainty and regional variability ranges observed in SOMTC related to (**a**) climate variability and (**b**) regional texture variability; (**c**) min and max descriptors of the regional thermal regime and modal values of regional soil texture; and (**d**) SOMTC as predicted by inputting CCSR/NIES, CSIRO Mk2, and HadCM3 models to CENTURY carbon model; the average of these under the A2 and B2 scenarios is shown. All soil C estimates correspond to MG intensity

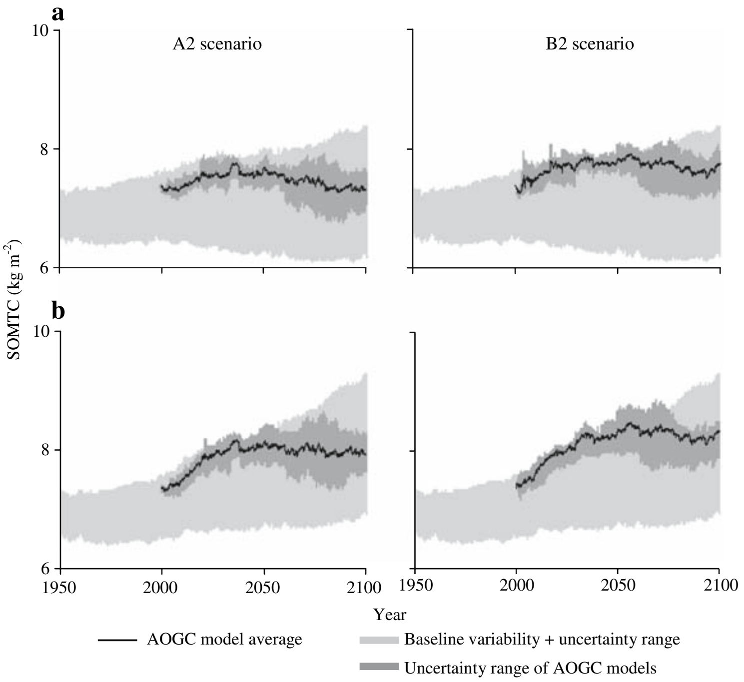

Fig. 4 Mean baseline uncertainty plus variability trends of SOMTC and AOGC model uncertainty ranges during 2000 to 2100 (see also Fig. 3c). (**a**) MG intensity. (**b**) LG intensity

that corresponding to predicted climate changes. If grazing pressure were diminished to a low intensity during this century, average SOMTC values would reach 8 kg m^{-2} and maximum regional values would reach 9.4 kg m^{-2} by the end of the century, even if climate changes did not occur (see baseline value area, Fig. 4b). If this latter scenario were the case, however, AOGCs predict that SOMTC decreases lower than baseline values by the end of this century (but values would still remain higher than those under MG; see Figs. 4a and 4b). In summary, whether climate change would occur or not, a decrease in grazing pressure would result in higher C storing in the soils of the Patagonian Monte by the end of this century.

Discussion

Storage of C in terrestrial ecosystems has been proposed as being relevant in mitigating increases in atmospheric CO_2 resulting from anthropogenic activity (Keller and Goldstein 1998; Olsson and Ärdo 2002; Schrag 2007). In recent studies in northwestern Patagonia (aridity index 0.4), studies on C sequestration have been developed in the context of afforestation paradigms (Nosetto and others 2006; Laclau 2003, 2004). In northeastern Patagonian Monte, where this study was conducted, afforestation has not been proposed as a feasible C sequestration policy, and soil constitutes the most relevant C sink.

This study confirms that an increase in atmospheric CO_2 concentration, in combination with changes in temperature and precipitation as expected in the Patagonian Monte, would produce increases in C sequestration in SOM. Eventual changes in management practices would also have similar effects.

Validation of the CENTURY model through comparison of its AGLIVC output (C in above-ground live plant biomass) with the MODIS-Terra NDVI composite band seems preferable with respect to other validation procedures based on estimates of soil C pools, as done in previous uses of the model (Hill 2003; Kemp and others 2003). C in above-ground live biomass is a much more dynamic indicator of model behavior than soil C pools and is directly coupled to C input into the soil system. Validation of this model output conveyed information about the periodic behavior of the system, both on amplitude and phase components, which cannot be identified in more stable outputs such as SOMTC. We propose that the procedure used in this study be adopted as a preferable alternative to validate CENTURY and similar C-balance models.

It has been recognized that various AOGC models can produce a relatively wide range of predicted climate changes. Covey and others (2003) indicated that the difference between a typical AOGC model simulation and a baseline set of observations is not much greater than the difference between equally reliable observed datasets. Although current AOGC models simulate well the observed global pattern of surface temperature, substantial regional-scale biases are evident. Giorgi and Francisco (2000) compared modeled and observed seasonal mean temperatures and precipitations averaged for several regions around the world, including southern South America. The AOGC experiments they took into account included the models considered in the present study (i.e. CCSR/NIES, CSIRO Mk2, and HadCM3) and produced regional monthly temperature biases in the range of –0.5°C to +0.8°C and monthly precipitation biases of –15% to +35%. The variability observed in the simulation of baseline (i.e. no climate change) regional conditions during this century produces deviations that are lower than those generated by most AOGC models.

In the Patagonian Monte, simulations with either baseline or AOGC model climate regimes predicted a moderate increase of C stocks in above-ground live biomass under LG intensities (results not shown). Increments of C in above-ground biomass expected from climate change would be smaller than those generated by a decrease in grazing intensity. This is consistent with the low response to increasing resource inputs in slow-growing species characteristic of nutrient-poor arid ecosystems (Golluscio and others 1998; Tilman 1998; Chesson and others 2004). However, in other subhumid and semiarid ecosystems, CO_2 enrichment can promote primary productivity (Riedo and others 2000) and enhance production of fine-root biomass (Gorissen and Cotrufo 2000), total amount of litter return, and degree of rhizodeposition (Wardle 2002). Furthermore, Smith and others (2000) reported that new-shoot production of a dominant perennial shrub of the Mojave Desert ecosystem was doubled by a 50% increase in atmospheric CO_2 concentration during a high-rainfall year. All of these responses would result in higher C stocking in the soil.

As in those from Jones and others (2004), our results also predict a slight increase in soil C during the current century. Soil C losses caused by eventual regional warming would be compensated by corresponding increases in C inputs to the soil subsystem. It has been speculated that accumulations of SOM could occur when other factors (*e.g.*, temperature, moisture, litter quality) would limit the activity of decomposer organisms (Schlesinger and Andrews 2000).

Mean soil organic carbon density and its distribution by depth are affected by vegetation, climate conditions, soil texture, and landscape position among other factors (Lal 2004; Reeder and others 2004). SOMTC values found in this study were within the range of variation reported for other arid ecosystems. Schlesinger (1997) measured a mean soil organic carbon content of 5.6 kg m^{-2} in the Arizona desert. Other studies in arid environments showed a wide range of variation in SOM density to a depth of 1 -m depth as reported by Gile and Grossman (1979) for southwestern United States soils (from 0.9 to 11.0 kg m^{-2}) and by Feng and others (2002) for sandy soils of China (from 0.02 to 12.52 kg m^{-2}). Soil texture, mainly the clay and loam content, has a great impact on modeled soil organic C (Gile and Grossman 1979; Poussart and others 2004; Bronick and Lal 2005).

Desertification processes in arid lands produce losses of soil organic C (Ojima and others 1995; Lal and others 1999; Lal 2004). Cole and others (1996) suggested that two thirds of C losses could be sequestered through desertification control and adoption of recommended land use (Lal 2004). In accordance, our study showed that the intensity of domestic grazing to be applied in the region is important in forcing C sequestration in the soil. Even if a “twentieth-century climate” scenario would be expected, decreasing grazing intensity would increase soil C stocks by approximately 11% to 12% by year 2100—(7.0 to 6.3

kg m^{-2})/7.0 kg m^{-2} × 100 (9.4 to 8.4 kg m^{-2})/8.4 kg m^{-2} × 100— considering the upper and lower values of the expected ranges in Figs. 4a and 4b, respectively. In the tested AOGC scenarios, a moderate increase of soil C stocks respective to baseline conditions would be expected if regional grazing intensities persist at moderate levels. Increases would be higher if a policy of LG intensity were adopted.

The high extension of grazing lands where similar trends to those herein reported could occur, motivating an analysis of the effect of grazing management at the scale of global C stocks. Grazing lands compose one third of the land surface of the world (Office for Interdisciplinary Earth Studies 1991) and store approximately 15% of global C stocks (Tate and Ross 1997), and their potential as source sinks of the C cycle has been recognized (Keller and Goldstein 1998; Körner 2002). A 1% change in soil organic C content of the upper 10 cm of soil of United States grazing lands would be equivalent to the total C emission of all United States cropland agriculture (Follet 2001). In agreement with these findings, our results point out that in the Patagonian Monte ecosystems, the benefits of decreasing grazing pressure, as measured in terms of conservation and sequestration of soil C, would exceed the effect of eventual regional climate change.

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Appendix 1

Baseline Precipitation and Temperature Simulation Algorithm

A simulation algorithm was used in this study to generate expected monthly precipitation and air temperature series at the Patagonian Monte during the current century under the assumption that no climate change would occur. This represented a baseline condition for comparison of the various changes predicted by the AOGC models. The algorithm uses EPRA meteorologic station data gathered during 1900 to 2003 to infer the characteristics of their Probability Distribution Functions (PDFs.) Then the PDFs were convoluted to derive data realizations that mimic the observed time series.

Baseline monthly precipitation (P, mm) series were constructed (Equation 1) with the function:

$$P = a_0 + a_1 \sin(2\pi x/a_3 - a_2) + a_4 \sin(2\pi x/a_6 - a_5), \tag{1}$$

(x = 1,.. 12: month no.), which was fitted to EPRA data. We wrote computer code to generate realizations of baseline P series by selecting normally distributed random values of the parameters $a_0 - a_6$ within their $p \leq 0.05$ confidence intervals. Furthermore, the relative frequencies (f) of single monthly precipitation log values were fitted to the function:

$$f = a_7 - a_8 y + a_9 \, exp(-0.5\,(y - a_{10})/a_{11})^2 \tag{2}$$

(y : frequency of ln (P) class in data), and expected stochastic baseline realizations of monthly precipitation were obtained by convoluting Equation 2 (Press and others 2004).

Baseline estimates of monthly minimum average air temperature (T_{min}) were also based on EPRA data (1982 to 2002). Series were fitted to a single annual harmonic (Equation 3):

$$T_{min} = a_{12} + a_{13} \sin(2\pi x/a_{14} + a_{15}). \tag{3}$$

Maximum average monthly air temperature (T_{max}) was then estimated based on the relation between the average minimum temperature (T_{min}) and the monthly average amplitude ($A = T_{max} - T_{min}$) (Equation 4):

$$\begin{aligned} T_{max} = {} & 10.88\,(\pm 0.37) + 0.10\,(\pm 0.02)\,T_{min} \\ & + 0.18\,(\pm 0.03)\,A,\ (p < 0.05,\ n = 240), \end{aligned} \tag{4}$$

and stochastic realizations of the temperature regime were then generated through Equations 3 and 4.

Regional Variability of Precipitation and Temperature

We used NOAA-AVHRR 1-km, 10-day composites of the area (Kidwell 1995) obtained during the period April 1992 to April 1996 to estimate regional spatial fields of average air temperature (T_{air}). The radiance values at Band 4 (T_4) were rescaled with respect to the average values of 20 image pixels encircling the area of coverage of EPRA data, corrected to °C, and correlated to EPRA air temperature data. Altitude correction was achieved based on reported regional temperature–altitude profiles (Coronato 1992) and a 1-km Digital Elevation Model (EOS Data Gateway; http://edcdaac.usgs.gov/gtopo30/gtopo30.asp). These resulted in a time series of 65 regional thermal images during 1992 to 1996. Time profiles of the image series were obtained at 73 grid-corner points covering the region, and each profile was fitted to a sinusoidal trend (wavelength 365 days). Maximum (max) and minimum (min) fitted average, amplitude, and phase

(*Av, Am, Ph*, respectively) values of the sinusoidal trends were used to construct combined estimates of minimum (min*Av*, min*Am*, min*Ph*) and maximum (max*Av*, max*Am*, max*Ph*) values of the regional thermal ranges of variation. Similarly, regional time-serial fields of precipitation (P) over the Patagonian Monte were calculated through a series of NOAA-AVHRR images by applying the procedure described by Andersen (1996). This uses the zenithal instantaneous position of the AVHRR sensor (Zenith Band) and the recorded radiances at Bands 4 to 5 to generate images of the amount of atmospheric precipitable water (P_{Water}). The procedure resulted in 65 regional P_{Water} image 16-day composite images during 1992 to 1996. These were rescaled to P values at ground level by calibration with 20 pixels surrounding the area of coverage of EPRA P ground data. The image-based P fields were then transformed to precipitation-ratio (P_r) fields by dividing all pixel values by the average P at the 20 EPRA-calibrated pixels. This produced P_r maps describing the magnitude of regional anomalies of P with respect to simultaneous precipitation events at the EPRA site. The ranges of P anomalies were further stochastically sampled to generate an estimate of the regional variability of precipitation events.

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