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Exploring land use scenarios by long-term simulation of soil organic matter in central Argentina

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Abstract

Frequently, agriculture intensification by means of high-input technologies and agroecosystem simplification led to unsustainable farming systems. Increasing spatial-temporal diversity in agroecosystems has been shown as a promising alternative for restoring degraded land. A methodological approach is discussed here, based on preliminary results of experiences in a region of strong biophysical gradients. The CENTURY model is validated under local conditions and used as monitoring tool. The impact of an increased agrodiversity on soils with contrasting inherent properties is exemplified by running three land use scenarios for two case-study sites for the next 50 years and evaluating trends in soil organic matter (SOM) contents. Field survey and simulation results suggested that: (1) reference values for SOM levels for monitoring soil health should be defined considering main agroecological factors; (2) simulation models may help identifying adequate ranges of variation for them; (3) and model outputs may complement experimentation and represent a didactic tool to be used for decision-making and knowledge-transfer processes.

Additional key words: Century model, crop rotation, soil health and quality, soil resilience, sustainability.

Resumen

Explorando escenarios de uso de la tierra por medio de simulaciones de materia orgánica edáfica de largo plazo en el centro de Argentina

Frecuentemente, la intensificación de la agricultura, en términos de la utilización de tecnologías de altos insumos y la simplificación de los agroecosistemas, conduce a la inestabilidad del sistema agrario. El incremento de la diversidad espacio-temporal en agroecosistemas se ha mostrado como una alternativa promisoria para la restauración de los suelos degradados. En este trabajo se discute un enfoque metodológico basado en resultados preliminares de experiencias en una región de fuertes gradientes biofísicos. El modelo CENTURY es validado bajo condiciones locales y usado como herramienta de monitoreo. El impacto del incremento en la agrodiversidad sobre suelos con propiedades inherentes contrastantes es ejemplificado corriendo tres escenarios de uso de la tierra en dos sitios de estudio para los próximos 50 años y la evaluación de la tendencia en los contenidos de materia orgánica del suelo (MOS). Las observaciones de campo y los resultados de las simulaciones sugieren que: (1) los valores de referencia de los niveles de MOS para el monitoreo de la salud del suelo deberían ser definidos considerando los principales factores agroecológicos, (2) los modelos de simulación podrían ayudar a identificar los rangos adecuados de variación para ellos, y (3) las salidas del modelo podrían complementar la experimentación y representar una herramienta didáctica para ser utilizada en la toma de decisiones y en el proceso de transferencia de conocimientos.

Palabras clave adicionales: calidad y salud del suelo, modelo Century, resiliencia del suelo, rotación de cultivos, sustentabilidad.

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Introduction

Intensive agricultural production systems based on large-scale, commercial production of commodities, and relying on high-input technologies, are currently displacing traditional, diversified and smaller scale systems in many areas of the world (Altieri, 2002). Such intensification leads to an important loss of agro(bio)diversity, affecting the productivity and stability of the resulting systems and having negative consequences for the environment and society. Such a situation constitutes a common picture in many agroecological zones of Argentina, as described e.g. for the inland Pampas (Alessandría *et al.*, 2001; Ghersa *et al.*, 2002). Additionally, in the transitional areas between the Pampas and the surrounding forest ecosystems (i.e. the Gran Chaco and the Espinal), deforestation has been taking place at alarming rates to gain land for agricultural production (Bucher and Huszar, 1999). The mid- and long-term consequences of agricultural intensification includes various forms of physical and chemical soil degradation (e.g. soil erosion, compaction, acidification-depletion, etc.) and important losses of soil biodiversity (Michelena *et al.*, 1988; Constantini *et al.*, 1999).

Several process-based technologies for designing sustainable agricultural production systems rely on an increased agrodiversity (Vandermeer *et al.*, 1998), such as the strategic rotation of crops and livestock activities in a certain field, which concomitantly results in an increased spatial diversity at farm scale. As indicated by previous studies (e.g. Gómez *et al.*, 1996), it is possible to «restore» land that underwent a certain degree of soil degradation by accomplishing an increased diversity of agricultural production with minimum tillage, crop-livestock rotation and/or crop residue management. Designing sound rotational schemes of production activities, suited for the particular agroecological conditions in each case, appear an interesting initial approach to restoring quality attributes of degraded land in central Argentina, as suggested by preliminary evidence (Viglizzo *et al.*, 1997). However, the benefits of an increased spatial-temporal diversity would also depend on the biophysical characteristics of the system, i.e. its resilience: the capacity to restore its life support processes or its ability to rebound or heal itself following a perturbation (Ludwig *et al.*, 1997). Such potential for restoration of a certain land class is tightly bound to the various soil health and quality attributes (Doran, 2001).

Soil organic matter (SOM) content has been frequently proposed as a robust indicator to monitor soil health and hence agroecosystem sustainability (FAO, 1997; Bosshard, 2000; Bouma, 2002). Several biological, chemical and physical processes essential to soil functioning take place in the organic fraction, which plays also a key role in the flows and cycles of energy and materials of the ecosystem, and hosts an enormous diversity of living forms. Thus, SOM content may be used to monitor/indicate the rate of land restoration when different technological interventions are adopted. However, evaluating the impact of alternative technologies on SOM requires long-term experimentation, particularly when different crop rotation systems are considered. The use of computer-based simulation models, able to accurately represent the processes that govern SOM dynamics, may help (i) identifying technological alternatives with a potential for restoration of degraded land in the long-term and (ii) evaluating them while considering the inherent properties of different soil types.

Among the many organic matter models currently available, with their different computational and conceptual assumptions, the model CENTURY (Parton *et al.*, 1987) has been widely used for both temperate and tropical conditions around the world (e.g. Kelly *et al.*, 1997; Zingore, 2002). It simulates the flows of C and macronutrients through the organic fraction of the soil, as affected by the various agroecosystem processes. Plant residues are discriminated into «metabolic» and «structural», depending on their lignin to N ratio. Different «pools» of soil C are defined, according to their turnover rate, with characteristic C:N ratios and rates of CO_2 release as a consequence of the microbial reactions (see the above-cited sources for further details on model structure and assumptions). Scenarios of both long-term land use systems (grassland, cropland, forest) and short-term management practices (crop rotation, grazing intensity, tillage, organic matter addition, etc.) can be analysed with CENTURY. The soil properties and the climate of the site can be modified to represent the variable biophysical conditions (chiefly soil texture and rainfall). The model outputs include biomass production, CO_2 release and soil C, N, P and S content for the different organic pools.

The recovery rate of degraded soils may be faster or slower depending on the type and degree of degradation, on the technologies applied to restore its quality and on its inherent properties. The aim of this work was to evaluate alternative land use scenarios for redesigning agroecosystems in central Argentina, where important variability in agroecological conditions can be observed.

Material and Methods

This work presents an approach of research undertaken to evaluate alternative land use scenarios for redesigning agroecosystems in central Argentina, where important variability in agroecological conditions can be observed. The organic matter model CENTURY was validated under local conditions and then used to generate different land use scenarios, fed with data gathered in representative fields. The impact of an increased agrodiversity on the long-term evolution of SOM was analysed for a number of different land use scenarios, and considering several sub-locations within the region; such methodological approach is illustrated here for two case-study sites and three land-use scenarios encompassing the full range of options evaluated. This was seen as a necessary step towards the selection of promising alternatives to be tested in field experiments, fine-tuning crop rotation strategies for the various soil types and agroecosystems in the region.

The study area

The central region of Argentina (ca. 10 million ha; approximately from 32°30' to 35°00' S and from 63°00' to 66°00' W) offers interesting gradients of biophysical conditions and land use systems. They range from intensive cropping in the sub-humid flat and gently undulating lands on loess soils, to several crop-livestock combinations on sandy plains and/or on the foothills of the Comechingones mountain range, to a virtually pure livestock system in the lower wetlands and in the higher mountain grasslands (Table 1). However, the climate is quite homogeneous all over the region, despite the local variability associated with the mountains. Figure 1 presents monthly average rainfall and mean temperature values for four meteorological stations representing the extremes of the climatic gradients in the region. Almost similar rainfall and temperature regimes can be observed across extended areas including widely different, contrasting soil types. This situation allows for the study of the inherent potential of soils for land restoration, and offers wide ranges of variation in soil properties that are of interest for validating SOM models.

Input data and model validation

The model CENTURY (version 5.0) (Parton, 1996) was validated for the region using data from sampling points that included soils under «natural» conditions and soils with a different degree of degradation by agricultural use. The land use history of each site (i.e. sampling point) has been re-constructed from interviews

Table 1. Characterisation of the four sub-regions defined for the study area

Characteristic	Sub-region[a]			
	Poorly-drained plains	Well-drained plains	Sandy plains	Foothill and mountain range
Average altitude	~120 m	~320 m	~450 m	~1,000 m
Landscape	Flat to concave plains, with scattered lagoons	Gently undulating to fairly flat; slopes 0.5 to 5%	Generally undulating, presence of dunes (1 to 10%)	Abrupt slopes and alternating fairly flat valleys
Sediments and soils	Fluvial and aeolic sediments (silt-fine sands); saline and saline-sodic soils	Dominating aeolic sediments (loess and fine sands); silt loam to sandy loam soils	Aeolic sands, in dunes and extended plains; loamy sand to sandy soils	Volcanic and loessoid sediments, high organic matter contents; shallow soils
Original vegetation and land use	Halophitic grasslands, with vegetation patterns highly affected by drainage; livestock keeping	Highly fragmented agricultural landscape (originally savannah-like vegetation)	Psammophitic grasslands and scattered spiny trees; livestock keeping and grain crops	Alternating grasslands and open forests; livestock keeping at high altitudes and grain crops in the foothills

[a] This sub-division agrees with the one used by the regional research and extension organisms.

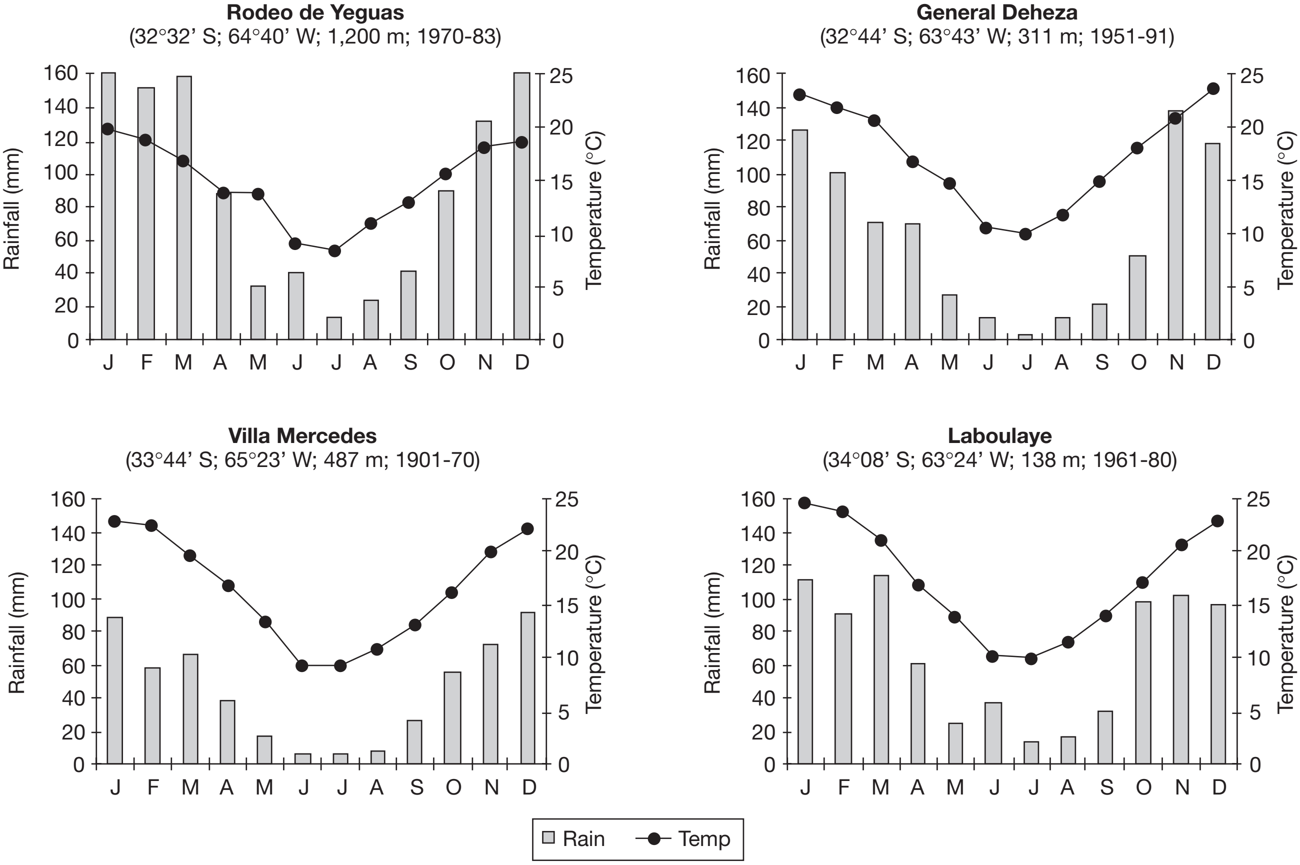

Figure 1. Monthly average rainfall and mean temperature measured at four meteorological stations in central Argentina. Four sub-regions are represented: the foothills of Comechingones mountains (Rodeo de Yeguas), the well-drained plains (General Deheza), the sandy plains (Villa Mercedes) and the poorly drained plains (Laboulaye). Figures between brackets next to the name of the stations indicate latitude, longitude, altitude (above see level) and period of measurements considered.

held with farmers and other key informants, and simulated with the model. The «natural» conditions were those in which the original vegetation was still present. In some cases, the vegetation had been cleared away in the past, but the land was later abandoned and a semi-spontaneous vegetation grew instead. At each site, ca. 1 m-deep pits were dug and soil profiles were described; that information was matched with regional soil maps to identify soil types (Great Groups of Soil Taxonomy - USDA) (Soil Survey Staff, 1960). Topsoil texture was determined with the hydrometer method after removing organic matter with H_2O_2. Soil C content (g kg^{-1}) in topsoil samples was chemically determined by the Walkley & Black method, and converted to g C m^{-2} soil by using bulk density (kg m^{-3}) measurements and considering a default depth for the topsoil of 0.2 m - similar to that assumed by CENTURY. The accuracy of the model to predict the current level of soil organic matter in the sampled soils was quite high (Fig. 2).

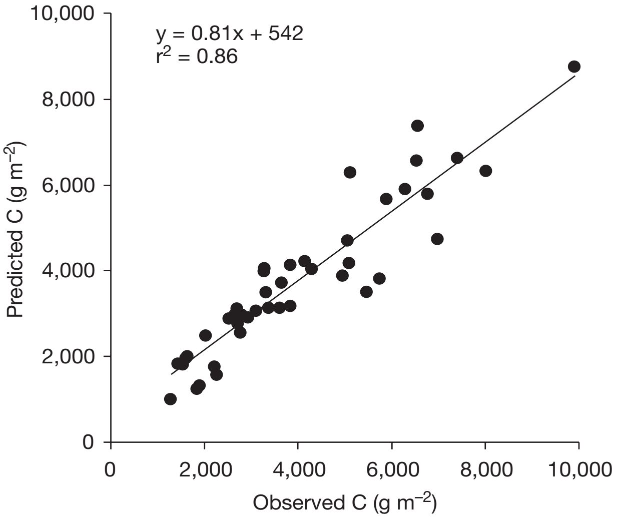

Figure 2. Relationship between the soil C level predicted with the simulation model and the observed by soil sampling and laboratory analysis, for 45 topsoil (0-15 cm) samples from undisturbed and/or minimally disturbed soils of central Argentina.

Table 2. Main biophysical characteristics of the two case-study sites selected for the development of land use and management scenarios

Site attributes	Las Selvas	Sarmiento
Clay content, %	13.2	6.0
Sand content, %	47.8	79.3
Topsoil depth, m	0.21	0.19
Current SOM, g kg^{-1a}	21.0	10.2
Bulk density, kg m^{-3}	1,270	1,310
Annual rainfall, mm[b]	762	693
Max. average temperature, ºC	24.7	25.8
Min. average temperature, ºC	9.7	8.8

[a] Current soil organic matter content in the topsoil. [b] Average values over more than 30 years.

Case-study sites and land use scenarios

Two representative sites were considered to exemplify the interaction of soil type and land use scenarios: «Las Selvas» (well-drained plains; silt loam soils) and «Sarmiento» (sandy plains; loamy sand soils), which main site attributes are presented in Table 2. The model was fed with measured data and first run with the historical land use and management system for each site (with a monthly time step), yielding an estimation of the present status of the different soil properties. Then, these values were used as starting points to run the scenarios for the future. In this simplified case, the climate was assumed to remain unchanged for the next 50 years. For both sites, the data from the nearest meteorological station were used to feed in the model (average values in Table 2).

Three land use and management scenarios were simulated. The «current» scenario simulates the continuation of the historical management system for the next 50 years, assuming no technological changes (fertilization level, crop yields, etc.). From 1990 onwards, however, the frequency of the double crop wheat-soybean was increased in the rotational scheme, reflecting the actual intensification of such practice. The «improved» scenario assumes an increased agrodiversity in time by rotating crop and livestock activities suited for each particular site. Table 3 presents the rotational scheme representative for each case study site and the improved rotations to be implemented by simulation. Some assumptions were necessary to simulate these rotations, as e.g. groundnuts or sunflower are not available by default in CENTURY. In such cases, the effect of each crop type on the C flows in the system was considered: forage rye was simulated as wheat and changing harvesting parameters, sunflower was simulated as maize and modifying patterns of residue incorporation, etc. Finally, the «untouched» scenario simulates a situation in which the land is abandoned and the wild vegetation re-colonises the land.

Results

Reference ranges for soil organic matter in the region

For the three sub-regions of major economic importance, the average SOM content varied for different soil types and tended to be higher in soils of finer texture (Table 4). Coarser soils showed also a greater variability in SOM content, as reflected by the coefficients of variation (CV ~ 70-80%), which led also to

Table 3. Simplified crop sequences representing the land use scenarios used for simulating long-term evolution of soil organic matter

Case-study site	Land use and management scenario	
	Current rotation	Improved rotation
Las Selvas	Ground nuts-short fallow Wheat-soybean[a] Maize-fallow (grazing maize residues)	Maize-fallow Sunflower-fallow Wheat-soybean Fallow-forage rye Five years of pasture[b]
Sarmiento	Ground nuts-fallow Soybean-fallow Maize-fallow (grazing maize residues) Forage rye-pasture (3 years)	Soybean/groundnuts-fallow Wheat-fallow Maize-fallow Forage rye-pasture (6 years)

[a] Climatic conditions in the region allow double cropping, which increased notably from 1990 onwards. [b] Livestock stocking rates were set in 1.2 grazing units per ha for Las Selvas and 0.9 for Sarmiento.

Table 4. Average values, confidence intervals (CI) and coefficients of variation (CV) for topsoil depth, clay plus silt and soil organic matter content; calculation of the amount of organic C in the first 0.2 m of the soil profile; and average soil organic matter (SOM) content under «natural» conditions for two types of vegetation, for three sub-regions of central Argentina. Observations were grouped according to soil type (i.e. Great Groups of the USDA Soil Taxonomy)

Sub region/ Great group of soils	Topsoil depth (m)			Clay + silt ($g\ 100^{-1}\ g$)			Soil organic matter ($g\ kg^{-1}$)			Organic C in 0.2 m ($g\ m^2$)	SOM under natural conditions ($g\ kg^{-1}$)	
	Mean	CI $P < 0.05$	CV (%)	Mean	± CI $P < 0.05$	CV (%)	Mean	± CI $P < 0.05$	CV (%)		Monte[c]	Grassland
Well drained plains												
Hapludolls	0.23	0.02	24	42.6	7.1	41	31.4	8.3	60	4,550	48.1	33.9
Haplustolls	0.21	0.01	15	33.0	5.6	35	22.1	5.2	57	2,900	40.0	19.2
Ustorthents[a]	0.19	0.05	25	17.8	2.9	17	11.2	5.0	45	1,100	—	10.1
Poorly drained plains												
Haplustolls[b]	0.25	0.03	15	29.4	1.5	12	18.0	4.0	27	2,720	—	18.9
Haplacuolls[b]	0.22	0.04	21	42.3	5.7	14	16.2	4.5	33	3,240	—	24.1
Natracualfs	0.21	0.04	15	53.0	5.2	24	22.4	17.2	68	4,570	—	39.0
Duracualfs	0.17	0.03	17	55.1	2.9	6	19.0	13.1	79	4,310	—	44.5
Sandy plains												
Haplustolls	0.21	0.04	17	21.9	2.1	9	20.1	18.0	78	2,680	38.1	12.1
Ustorthents	0.19	0.03	26	26.9	3.3	22	18.9	7.8	71	2,720	32.7	—
Ustipsaments	0.19	0.03	24	16.6	2.3	24	15.4	6.4	67	2,100	28.2	10.1
Torripsaments	0.18	0.08	47	12.0	2.7	23	17.8	14.1	83	2,580	30.4	—

[a] This Great Group was not widely represented in this sub-region. [b] Includes also polygenetic soils (e.g. Thapto Natric Haplustoll). [c] Represents a savannah-like vegetation, with scattered spiny trees and shrubs with less that 10% of canopy overlapping in the densest stands.

confidence intervals that resulted too wide (e.g. 20.1 ± 18.0 g kg^{-1}, $P < 0.05$). The important heterogeneity in soil types observed in the poorly-drained plains, reflected in Table 4 by soil texture, affected the average SOM contents and their variability. When only those situations close to the natural equilibrium were considered (i.e. undisturbed or minimally disturbed sites), SOM contents were much higher for the sites where woody vegetation grew, both in the well-drained and in the sandy plains. However, the differences between vegetation types were wider for soils or coarser texture. Since less basic soil information was available for the mountainous sub-region, accurate soil classification was not possible; average SOM values at high altitudes were 108 and 91 g kg^{-1}, under woody or grassy vegetation, respectively (average clay plus silt content: 44.3%).

Simulation results

Figure 3 shows the results of the modelling exercise for the two case study sites. The natural savannah-like vegetation was cleared and agriculture started at the beginning and at the middle of the 20th century for Las Selvas and Sarmiento, respectively. The simulated original amount of soil organic C was higher in Las Selvas, though the difference with Sarmiento was not very important, and was above the reference levels for both sites (Table 4). However, when agriculture started, the coarser soils of Sarmiento lost organic C at a notably faster rate, showing an important difference with respect to Las Selvas for the year 2000. The organic C levels in the topsoil by that year (3,188 and 1,251 g m^{-2}, respectively) were around the reference level for Las Selvas but much below than for Sarmiento. Considering average bulk density values for both sites (Table 2), a conversion factor of 1.725 for soil C to SOM, and adjusting for the actual topsoil depths, the simulated amounts of soil C represent SOM contents of 20.6 and 6.4 g kg^{-1}, respectively.

If the current land use and management continues for the next 50 years (Fig. 3), the amount of soil C remains somewhat steady for Sarmiento, whereas it keeps on decreasing for Las Selvas until it reaches its

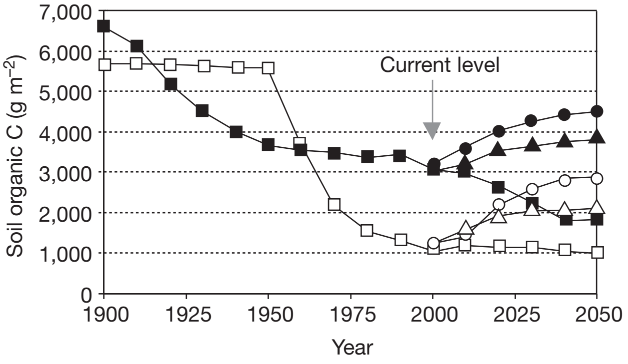

Figure 3. Simulation of the soil organic matter dynamics for two soils of central Argentina under different land use and management situations. Square markers indicate the evolution under the historical system and the continuation of the current situation. Triangular markers indicate the «improved» management scenario and circular markers indicate the «untouched» situation, both from the year 2000 onwards. The black markers correspond to Las Selvas (silt loam) whereas the white ones correspond to Sarmiento (loamy sand).

lower limit by the year 2040 (i.e. the lower limit to land degradation, in terms of the amount of organic C in the topsoil, varied with soil type). Note also in Fig. 3 that the rate of decrease in soil C for Las Selvas was accelerated during the 90's, reflecting the «intensification» process described in the introductory paragraphs. If agriculture stops and the land remains «untouched», the amount of organic C in the topsoil recovers at a faster relative rate for the coarser soil (Fig. 3); although it does not recover the original amount of soil C (year 1950), the reference level is reached after ca. 20 years. A similar trend can be observed for the «improved» scenario: the initial recovery rate is faster for Sarmiento. However, the simulated amount of soil C continues to increase for Las Selvas, whereas it reaches a new equilibrium and it does not increase during the last 10 years of the simulation for Sarmiento. Such equilibrium occurs at a soil C level below the reference value (cf. Table 4), implying that the «improved» rotation should be re-considered in this case.

Discussion

Establishing reference values for SOM requires a careful consideration of the main factors controlling C dynamics under different agroecological conditions. The well-established relationship between soil texture (i.e. clay plus silt fraction) and C saturation potential is also likely to vary under different land use patterns and vegetation types (Feller and Beare, 1997), as shown by these results. Climatic control of SOM levels was extendedly documented (e.g. Janssen, 2002) and may be particularly important under the relatively extreme conditions of the mountains, as illustrated by these results as well (note that the average clay plus silt fraction in the mountain soils was similar to that of the Hapludolls in Table 4). Landscape factors of local variation add to these regional gradients in geology, climate and vegetation. Such is the case of the topography in the poorly-drained plains, which was shown as affecting water and solute dynamics in the soil and determining vegetation patterns by previous research in the region (Cantero *et al.*, 1998).

The simulated amounts of soil C are in agreement with previous measurements in the region, for soils under the «common» management systems (e.g. Moreno *et al.*, 1996), and fall near the values measured for each site (cf. Table 2 and confidence intervals in Table 4).

Potentiality and limitations of the approach

This simplified example illustrated the potential of using an organic matter model validated under local conditions as a tool to monitor and/or predict the impact of a process-based technology aimed at restoring degraded land. SOM contents varied for different soil types and agroecological conditions within the region, and the ranges of variation were affected by soil texture, vegetation type and topography (Tables 1 and 4). SOM appeared a sensitive indicator in face of the simulated land use scenarios for the long run, and the model was also able to reflect its evolution from the original to the current levels, under representative land use systems (Figs. 2 and 3). Additional simulation outputs showed that the absolute amount of atmospheric CO_2 released up to the year 2000 was greater for Sarmiento than for Las Selvas; a smaller amount of CO_2 was fixed into soil organic C for Sarmiento, whereas larger amounts of C in the biomass were harvested for Las Selvas under all scenarios (data not shown). These considerations may be of greater importance when analysing environmental and socio-economic aspects of different land use scenarios. In fact, further steps in this methodological approach should consider farmers' perspective and efficiency indicators of physical and economic performance at farm and regional scales, for refining simulations and complementing experimentation in an iterative way.

The land use scenarios proposed here, i.e. the current, untouched and improved, were indeed quite unrealistic. Continuation of the current practice for the next 50 years is rather unlikely, since the performance of certain production activities would be affected as land degradation proceeds. Such an effect is already observed in the region, where the traditional crops such as groundnuts are being displaced to «new» areas (Alessandría *et al.*, 2001) and «less demanding» crops are increasingly grown (Pengue, 2001). However, this assumption allowed illustrating the lower limit to SOM for each case-study site (Fig. 3). The untouched scenario, on the other hand, was meant to show the upper level that can be expected for SOM to recover, i.e. the potential, without organic matter additions or increased fertilisation rates. An important implication of these upper and lower-limit scenarios is that they may be considered to define reference values for soil health and quality (SHQ) indicators. For instance, using the SOM levels under natural conditions as reference values for SHQ does not seem adequate for Sarmiento (Tables 2 and 4, Fig. 3), as that would result in unattainable SOM levels. Instead, the upper level defined by the untouched scenario seems a more realistic figure.

The performance of the «improved» land use scenarios proposed here (i.e. increasing agrodiversity in time) should still be considered with caution; they could be further refined to suit the actual conditions of each site and to include new technological options. Improved crop rotations were designed without considering the introduction of new production activities, but only those already known in the area. Besides, in long term horizons (i.e. 50 years) energy and generally input-use efficiency are also expected to change, as sound technologies for agricultural production continue being developed (van Ittersum and Rabbinge, 1997), affecting C dynamics in the system. Although other complementary natural processes and technology options were not considered in this example (e.g. soil erosion, fertiliser use, no-till systems, etc.), their effect can be readily simulated with CENTURY (Parton, 1996); recent modifications would also allow the analysis of more complex scenarios, such as those representing low-input, small-scale farming (Gijsman *et al.*, 2002). Finally, considerations regarding soil organic matter quality are still lacking. Previous evidence indicates that the organic C accumulated in the coarser soil under the «untouched» scenario would be mainly active C, easily decomposable and therefore non-stable (Six *et al.*, 2002). These quality aspects were not shown in the example but they can be studied with the model as well, by assimilating model C pools to physical SOM fractionation.

Soil organic matter constitutes a sensitive, integrating indicator of soil health and quality to be used for monitoring land degradation and restoration processes. However, SOM levels to be used as reference values of SHQ should consider regional and local variability of the main agroecological factors controlling them. Long-term SOM simulation may help identifying feasible reference values for comparing current SOM levels in SHQ assessments, rather than using reference levels derived from measurements taken in «natural» or minimally disturbed conditions. The example presented here illustrated differences in resistance and resilience attributes of different soil types that should be considered while monitoring SHQ, when defining critical limits for degradation, and for redesigning agroecosystems.

SOM simulation models can be used to save time and resources in research for agroecosystem design; an initial modelling step may help directing and designing the experimental phases. Preferably, their use should be combined with experimentation and field surveys to continually refine their validity and to feed in new data for eventual re-parameterisation. This example also showed the didactic potential of the SOM models to illustrate possible outcomes in terms of achieving land restoration with alternative technology options. The outputs can be used during discussion meetings of relevant stakeholders when collective decisions on land use and management are to be made for a given region, offering also multiple possibilities for their use in processes of knowledge transfer.

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