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How does agricultural management modify ecosystem services in the argentine Pampas? The effects on soil C dynamics

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ABSTRACT

Crop management modifies the structure and functioning of the ecosystems. C dynamics has been identified as a key intermediate or support ecosystem service that is profoundly altered by agricultural practices. The temperate grasslands of Argentina, the Pampas, are one of the main crop production regions of the world. Crop sequence, tillage and fertilization change inputs and outputs and, consequently the whole C dynamics. Our objectives in this article were (i) to provide a spatially explicit characterization, based on remotely sensed data, of crop sequences and tillage systems in the Rolling Pampas, (ii) to evaluate changes in C gains by computing the absorbed photosynthetic active radiation (APAR) from NDVI data of different crop, (iii) to evaluate the soil organic carbon (SOC) balance of different management schemes (crop sequence, conventional tillage vs. no till and three levels of nitrogen fertilization) using the CENTURY model, and (iv) to estimate the changes in SOC at a regional level. The results showed that 54% of the area was under continuous agriculture, with only two crop rotations occupying 61% of the area, and the main tillage system was no-tillage (73% of the area analyzed). Annual APAR was lower in crops than in rangelands, except for wheat-soybean double crop. Based on CENTURY simulations the crop management which had a most negative SOC balance (SOC reference value (100%) = 79 t ha^{-1}) was crop sequence "maize/soybean" under conventional tillage and with no fertilizer application (37% losses of SOC in 60 years). The management that presented the most positive SOC balance was "soybean/wheat-soybean double crop (6 years) pasture (4 years)" under no till and with high fertilization (10% increase of SOC in 60 years). A positive and linear relationship was found between APAR estimates derived from satellite data and simulated SOC providing basis for a quantitative hypothesis on the importance of C inputs on SOC's dynamics. At regional scale, if crop sequences proportions remain constant, the lost of SOC would average a 15% in 60 years.

1. Introduction

Grasslands, one of the most transformed biomes of the world (Hannah et al., 1995; Hoekstra et al., 2005; Ellis and Ramankutty, 2008), have been considered highly relevant to global carbon (C) sequestration (Scurlock and Hall, 1998; Shuman et al., 2002). Their role as a C sink is associated to a positive carbon balance (inputs–outputs), mainly in soils. Carbon inputs (primary productivity) and outputs (respiration, photodegradation and exports) are controlled differentially by environmental and anthropogenic factors. The primary productivity in grasslands is positively and linearly associated to precipitation (Sala et al., 1988; Paruelo et al., 1999) while heterotrophic respiration/decomposition is mainly related to temperature (Reichstein and Beer, 2008). Consequently, accumulation of soil organic carbon (SOC) at regional scale is positively correlated with the ratio of precipitation/temperature (Álvarez and Lavado, 1998). At local scale, management as crop sequence, tillage or fertilization, are important controls of carbon dynamics affecting differentially both carbon gains and losses (Viglizzo et al., 2004). The crop sequence will set the time, quantity and C/N ratio of plant tissue incorporated to the soil. The time and quantity depend, mainly, on crops phenology (annual/perennial, winter/summer), radiation use efficiency and harvest index. The C/N ratio depends on the species and growing conditions. Generally C/N ratio is higher in cereals than in legumes (Cadisch et al., 1994). Conventional tillage increases soil aeration and incorporates plant residues into the soil. This modifies several controls of decomposition, such as soil temperature, water content, pH and the surface exposure of stubble (Liu et al., 2006). No-tillage

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minimizes soil mechanical disturbance reducing decomposition rate and consequently decreasing soil organic carbon losses (Balesdent et al., 2000). No till system also reduces the loss of organic matter by erosion as it leaves a greater percentage of soil covered with plant residues (Fu et al., 2006).

Carbon inputs and SOC can be characterized, following Fisher et al. (2009), as two key intermediate ecosystem services (IES) in grasslands, i.e. functional and structural aspects of the ecosystem that generate, directly or indirectly benefits for the human beings. Vitousek et al. (1986) estimated that the proportion of the terrestrial net primary productivity (NPP) appropriated by humans worldwide, both directly (consumption) or indirectly (loss), was greater than 15%. McNaughton et al. (1989) identified intra-annual variation in C gains as a main descriptor of ecosystem functioning. Paruelo et al. (2001) showed that the land-use influences the variation of C gains throughout the year (seasonality). The amount of support, provision and regulation ecosystem services (MEA, 2005) may be decreased by NPP seasonality, NPP reductions or a higher proportion of C exported out of the system. Organic matter and SOC are closely and positively related to aggregate stability and erosion resistance (Tisdall and Oades, 1982; Lal, 2007). Furthermore, organic matter increases the availability of nutrients (mainly nitrogen) and improves the fertilization efficiency due to its high cation exchange capacity that prevents nutrient losses (Kramer et al., 2006). For example crops, which have higher seasonality of C gains, increase soil losses by erosion and therefore reduce N retention (Vitousek and Reiners, 1975). Soil organic carbon losses represent, then, a reduction in soil productivity and, additionally, a net increase of the atmospheric CO_2 pool with direct impacts on climate. The IES and final ecosystem services (FES) relationship can be considered as a *production function*. FES, those ES directly related to benefits for the human beings (i.e. C sequestration, fertility or erosion control), may be a function of one or several IES (i.e. SOC stocks and C gains) and of additional variables (climatic and weather conditions, C cost of the agricultural inputs, topography, post-harvest management of the agricultural products).

The Rolling Pampa is the subregion of the Río de la Plata grasslands with the longest agricultural history in Argentina (Soriano et al., 1991; Hall et al., 1992; Viglizzo et al., 2001) (Fig. 1). Before the 16th century, the local hunters and gatherers generated a relatively low impact on the original environment. With the arrival of Europeans and the introduction of domestic herbivores (Giberti, 1954), grazing became the main regulator of the structure and functioning of the native grasslands (Soriano et al., 1991). Due to the lack of fences that protected crops from grazers, manpower and transportation, during the first centuries of colonization crops were performed only at small scales near villages (Sbarra, 1964). In the late 19th century, massive immigration, the spread of wired fences and the railway network promoted changes in land use patterns, increasing the cropped area (Hall et al., 1992). At the beginning of the 90s in the 20th century, the spread of no-tillage, double-cropping and the lower cost of inputs (fertilizers, pesticides, etc.) promoted a further expansion and intensification of agricultural production resulting in an increase of crop yields and a reduction of the area devoted to ranching (Senigagliesi et al., 1997; Viglizzo et al., 2001; Paruelo et al., 2005). The appearance of RR soybean (resistant to glyphosate herbicide) in 1996 simplified the management and increased the area of this crop, reducing the share of wheat, maize and, mainly, sunflower (SAGPyA, 2006). The more intensive use of soils during the previous century changed the C dynamics of the system and therefore the IES they provide. In the Pampas region Guerschman (2005) estimated that human appropriation of NPP varies between 19.7 and 45.2% depending on the type of land use. In the rolling pampas, Álvarez (2001) estimated that SOC decreased 35% in the first 15 cm with respect to its original value. Michelena et al. (1988) reported soil losses of 3–5 cm over the past 100 years in the same area as result of agricultural use. It is difficult to know how much of the observed carbon loss was due to a negative carbon balance or to soil erosion. Álvarez et al. (2006) assigned 58% of the C loss to a negative balance and 42% to soil erosion.

Which is the impact of management practices on these two key IES (NPP and SOC) in the Pampas? A first step to answer this question is to estimate how each possible land use will affect NPP and SOC. Additionally and to generate regional estimates, a spatially explicit description of land use pattern and specifically the crop sequences on the region is needed. Our specific goals in this article were:

(i) To perform a spatially explicit description of land use (crop sequence) and tillage systems on Argiudolls (the most important soil unit) of the Rolling pampas.
(ii) To evaluate changes in C gains by computing the absorbed photosynthetic active radiation (APAR) from spectral indices derived from satellite data for the different land cover units.
(iii) To simulate, using CENTURY biogeochemical model, the effects of the different management practices (land use, tillage and fertilization) on soil organic carbon contents (60 years from a reference value).
(iv) To generate regional estimates of SOC changes (simulated) under the present management scheme. Our aim with the simulations was not to get the actual SOC content of the region but to compare different management schemes.

2. Materials and methods

2.1. Study area

The study area is located in the Rio de la Plata grasslands (Buenos Aires province, Argentina) (Fig. 1A) and occupies an area of 3,114,318 ha. It includes part of 3 phytogeographic districts: the Rolling Pampa, the Flooding Pampa and the Inland Pampa (Soriano et al., 1991) The predominant soil types in the area are: Argiudoll, Hapludoll, Natracuoll, Argialboll and Natracualf (INTA-SAGyP, 1990). Our analysis focused on the Argiudoll soils of the Rolling Pampa (1,294,488 ha), the most abundant cropped soil unit (Fig. 1B). The average annual rainfall in this area is 978 mm and the average annual temperature is 16.5 °C (INTA Pergamino data, average 1967–2004).

2.2. Land cover and land use characterization

The characterization of spatial and temporal heterogeneity of land cover (crop sequence) was performed using Landsat 5 TM and Landsat 7 ETM+ images. Images were geometrically and radiometrically corrected (Chander et al., 2007). We performed five classifications for the period 2000–2005, (one classification per growing season, June–July) using the reflectance values of bands 3, 4 and 5. Classification algorithm Maximum likelihood (Lillesand et al., 1994) was applied on, at least, 3 dates that represents the phenological dynamics of each land cover. Land cover ground truth data corresponds to geo-referenced records registered on the main roads included in the scene. The ground truth was randomly divided into two subsets. The first (70% of the data) were used to train the algorithm, and the second one (30% of the data) to evaluate the classification. The classes defined included the five main land covers: water, rangelands (natural grasslands and perennial sown pastures), wheat–soybean double crop (WS), maize (M) and soybean (S). Finally, a 3 × 3 majority filter was applied to each classified land cover image to reduce the salt-and-pepper effect (Lillesand et al., 1994). Urban areas, occupying an area of 13,993 ha (0.45% of

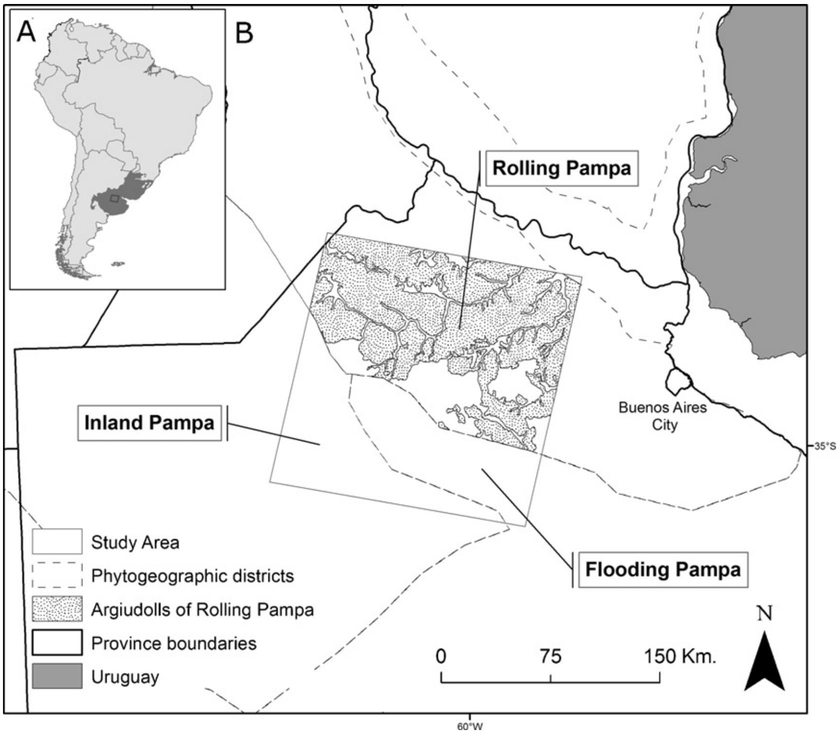

Fig. 1. (A) Geographic location of the Río de la Plata Grasslands (dark gray) and Landsat scene Path 226 Row 084 (line). (B) Study Area—Province boundaries, phytogeographic districts of the Río de la Plata Grasslands and Argiudoll soils of the Rolling Pampa (outlined in inset).

the area analyzed), were masked using the layer of population of the Soil Atlas (INTA-SAGyP, 1990).

The five classifications were overlapped to generate a new layer of crop sequence (Fig. 2). The participation of each crop in the period of 5 years was used to generate crop sequences/rotations schemes based on the standards used in this region (see Table 2). The crop sequences/rotations were then classified in three land use classes: continuous agriculture (crops every year), crop–rangeland rotation (crops during part of the period and the rest rangelands) and cattle grazing (rangelands every year). Continuous sequences of rangelands were assumed to be "grassland" and rangelands in rotation with crops were assumed to be "Pasture" (P). Alfalfa (*Medicago sativa*) is the most frequently used species in pastures.

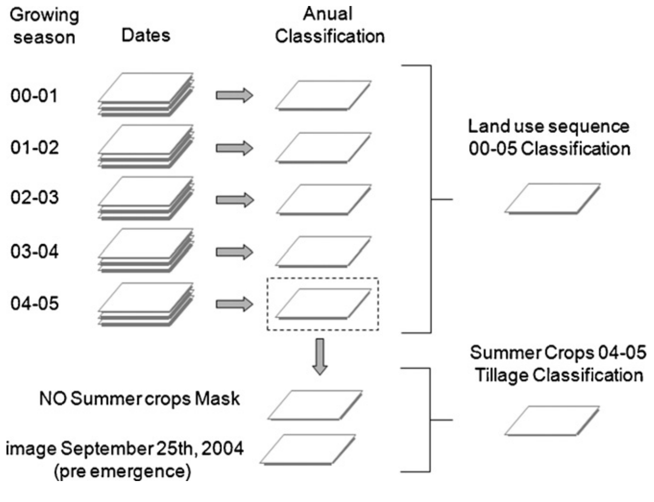

Fig. 2. Methodological scheme to characterize crop sequence and tillage system from LANDSAT TM imagery.

The tillage system was characterized only for the area devoted to maize and soybean crops during the growing season 2004–2005. Such characterization was based on a classification of reflectance values of bands 3, 4, 5 and 7 (duly corrected) of a Landsat 5 TM image from 25 September 2004. According to seeding dates recorded by SAGPyA (2006) for this area and year, at this date maize and soybean had not yet emerged. The ground truth data used to perform the classification were obtained during September and October 2004. As in the land cover classifications, 70% of this information was used to train the algorithm while the remaining 30% was used for evaluation. A mask of the area with no maize or soybean (classification 04/05) was applied and a supervised classification was performed (maximum likelihood) discriminating the classes "conventional tillage" and "no-tillage" (Fig. 2).

The accuracy of the classifications was assessed by constructing a confusion matrix (Congalton, 1991) and calculating the Kappa coefficient and its standard error (Cohen, 1960; Fleiss et al., 1969). The satellite images processing was performed using ENVI 4.1 (ENVI Research Systems, Inc. Copyright © 2004) and ArcGIS 9.1 (ESRI Copyright © 2005).

2.3. *Estimate of absorbed photosynthetic active radiation (APAR)*

We used APAR as an estimator of C gains. Monteith (1972) showed that NPP is a linear function of the amount of radiation intercepted by the canopy. APAR was calculated by the equation:

$$\mathrm{APAR}\,(\mathrm{MJ\ m^{-2}}) = \mathrm{fPAR} \times \mathrm{PAR}\,(\mathrm{MJ\ m^{-2}}) \qquad (1)$$

where fPAR: fraction of the photosynthetically active radiation intercepted by the green tissues of the canopy

PAR: photosynthetically active radiation

fPAR was obtained from the Normalized Difference Vegetation Index (NDVI)). NDVI is calculated from the red and near infrared reflectance recorded by the MODIS sensor. NDVI is a linear estimator of fPAR (Baret and Guyot, 1991; Sellers et al., 1992; Gamon et al., 1995; Myneni et al., 1995). We used the product MODIS MOD13Q1 that corresponded to a 16 days composite of daily values and generated a site specific calibration for the fPAR–NDVI (MOD13Q1) relationship (Fig. A1, Appendix A). The MODIS FPAR product was not used because it is based on Land_Cover_Type maps which showed some serious mismatches for our area. A local based calibration of FPAR from NDVI was, in our opinion, a better approach. The product MOD13Q1 for the period between 2000–2001 and 2004–2005 growing seasons was obtained from https://lpdaac.usgs.gov/lpdaac/get_data. We eliminated NDVI data not labeled as "Ideal" (according to the quality information band provided in the product). The image of crop sequence was vectorized to obtain the limits of management units included in the study area (considering as management unit a spatial unit that had the same crop sequence during the 5 growing seasons). We selected MODIS pixels (250 m) that were completely included within management units. We calculated the average NDVI values at the management unit level to avoid spatial correlation effect in the data. Then the data set was divided by growing season and cover information was assigned to each management unit each year. NDVI values were rescaled from 16 days to monthly composites by calculating the weighted mean. The values of fPAR were calculated by using monthly NDVI values at the management unit level and the site specific calibration specified above.

PAR was obtained from the average value of daily global solar radiation for the study area reported in the monthly charts of the Atlas of Solar Energy of the Argentina (Grossi Gallegos and Righini, 2007). Each value was multiplied by the number of days of the respective month and then by the coefficient 0.49 to obtain PAR (Righini and Grossi Gallegos, 2005). The product of monthly fPAR times PAR was added up to obtain annual APAR estimates at the management unit level. Differences among land covers were evaluated using ANOVA.

2.4. Impact of crop sequence, tillage system and fertilization on SOC content

CENTURY 5.4.3 model (Parton et al., 1987) was used to quantify SOC changes under different crop sequences in Argiudolls of the Rolling Pampa. The model does not consider the SOC changes by erosion so the results must be considered as conservative. CENTURY was parameterized and evaluated for the Pampas by Piñeiro et al. (2006). They also performed a sensitivity analysis of CENTURY for fire frequency, species composition and atmospheric CO_2 content observing that model results were not substantially affected by changing these factors (Piñeiro et al., 2006). The model simulates carbon, other nutrients (N, P and S) and water dynamics for forests, savannas, steppes, grasslands and agroecosystems. The organic matter submodel includes three pools of soil organic matter: active, slow and passive with different potential rates of decomposition, and turnover times of 1–5, 20–40 and 100–1000 years, respectively. The model runs with a monthly time step and its inputs are information of the site (climate and soil) and management (crop, tillage, fertilizer, stocking rate, etc.). More information on model characteristics is available at http://www.nrel.colostate.edu/projects/century5/.

Soil parameters were obtained from the Soil Map of the Buenos Aires Province (INTA-SAGyP, 1990) and corresponded to the most common Argiudoll in the study area (Argiudol Típico fino (Cartographic Unit M_{17}tc2)). Climatic data corresponded to the average of 38 years (1967–2004) recorded in INTA Pergamino. Land use data were obtained from the image classification analysis and two tillage systems were considered, conventional tillage and no till. Only N fertilization was considered, assuming no P and S limitations. Three levels of fertilization were used for crops: (i) no fertilization, (ii) the average fertilization reported by FAO for the crops of the Pampas in the 2002/2003 growing season (wheat: 40 kgN ha^{-1}, maize: 28 kgN ha^{-1} and soybeans: 2 kgN ha^{-1}) (FAO, 2004) and (iii) high fertilization (2 × average). Fertilization was not simulated for rangelands or for soybean in double cropping. Herbivore consumption was computed following the approach used by Piñeiro et al. (2006) yielding values ranging from consumptions of 4% of aboveground net primary productivity (ANPP) for systems grazed by native herbivores to 67% of the ANPP for current grazing conditions. No crop-stubble grazing was considered so all residues, in both tillage systems, were returned to the soil. The crop parameters used were those provided by the model for current genotypes and yields.

Based on Piñeiro et al., 2006, simulations were conducted in three steps: (1) native herbivores grazing, until SOC stabilization (6000 years; SOC: 95.94 t C ha^{-1}); (2) 300 years of cattle grazing with stocking rate adjustments every 100 years, reaching a value of SOC of 79.32 t C ha^{-1} (considered here as the reference value); and (3) 60 years of the different management practices to be evaluated.

2.5. Regional estimates of SOC changes

The spatial explicit estimates of current SOC loss at regional level was derived from the land cover classifications (crop sequence layer), the tillage system classification and the output values of CENTURY model considering average fertilization. When there was no information about tillage system (areas under wheat soybean double crop or rangelands during 2004/2005 growing season) no-tillage was assumed. The magnitude of current SOC loss was spatially represented in a grid of hexagonal cells, each one of 6495 ha. It is important to point out that this estimation is only vertically spatial explicit because no mass transfer between cells has been considered.

3. Results and discussion

3.1. Land cover and land use characterization

All land use classifications had an accuracy higher than 90% (Appendix B). In the Rolling Pampa Argiudolls the two main land covers were rangelands and soybean crop. Rangelands were the main land cover during the first three growing seasons (2000–2001 to 2002–2003), being the soybean crop the main land cover in the last two (2003–2004 and 2004–2005). Maize was the crop with lowest area during all the growing seasons except the last one. The area occupied by water was lower than 1% along all the studied period.

Based on remotely sensed data we found that eleven crop sequences occupied more than 90% of the area under study. Six sequences corresponded to continuous agriculture, four to crop–rangelands rotation and one to rangelands, representing an area of 54%, 16.3% and 29.7% respectively. The two main crop sequences in continuous agriculture were soybean/wheat soybean double cropping/maize (19%), and soybean monoculture (14%), participating the remaining crop sequences with less than 10% each one (Fig. 3). Soybean/wheat soybean double crop/maize corresponds to the basic crop sequence recommended for the area (CREA, 1996), while soybean monoculture had the highest economic return in the short term (Lorenzatti, 2004).

The total accuracy of the tillage system classification was 96%. No-tillage was the dominant system in summer crops and it was used in 76% of the area occupied by soybean (without considering the soybean that was part of double cropping systems) and in 66% of the maize fields. Based on official data (SAGPyA, 2006) the area under no-tillage during that growing season (2004–2005) was 68%

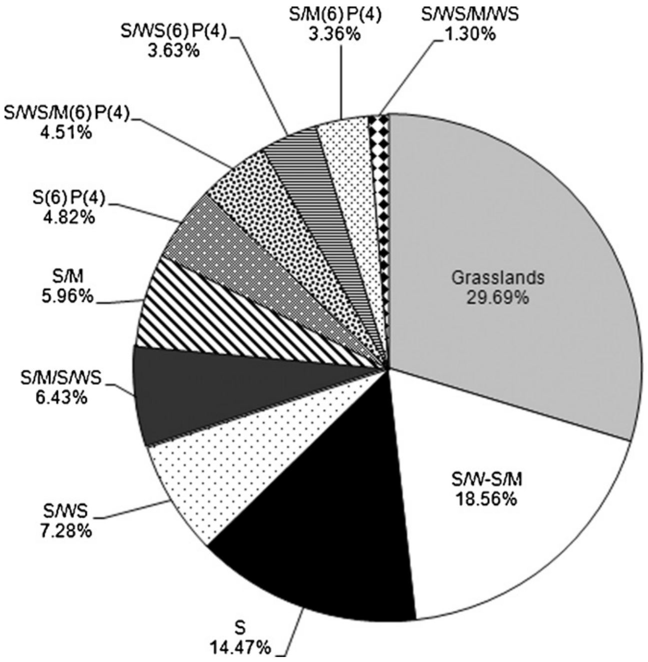

Fig. 3. Percentage of the study area under different crop sequence. Crop sequences were derived from the temporal analysis of land cover classifications (5 years). The numbers in brackets represent the number of years in a 10 years sequence. S: Soybean; WS: double crop Wheat-Soybean; M: Maize; P: Pasture.

for soybean and 53% for maize for the whole Buenos Aires province. The differences in the estimates could be related to the different scales of analysis since the study area of this work covered the portion of the Buenos Aires province where no-tillage has the highest adoption (Studdert et al., 2008).

3.2. Estimate of absorbed photosynthetic active radiation (APAR)

Different land covers presented a particular seasonal NDVI dynamics. The average NDVI values for different crops and dates ranged from 0.33 to 0.90 (Fig. 4). Rangelands showed the lowest variability among dates being the coefficient of variation (CV) the same for pastures and grasslands (0.10). Crops displayed a more markedly seasonality with a higher intra annual variability (CV maize: 0.34; soybean: 0.33; wheat soybean double crop 0.31). Soybean had the highest NDVI peak (0.90) during the period February 2–17, followed by the soybean in double crop (0.86) in the period 6–21 March, maize (0.82) in the period December 19–31 and wheat (0.82) in the period September 30–October 15.

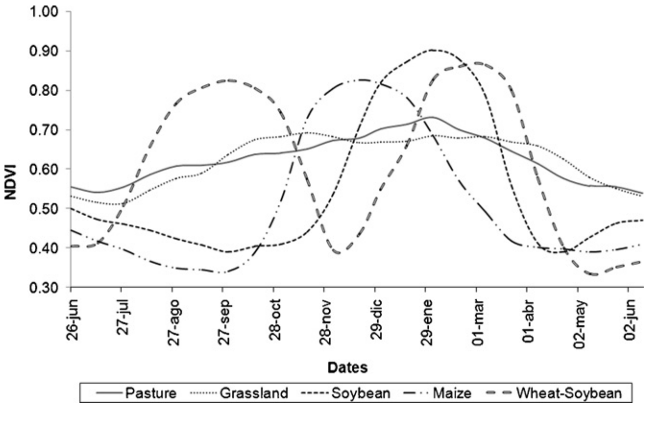

Fig. 4. Average MODIS-NDVI seasonal dynamics for each land cover in the study area (management units average of 5 campaigns (2000–2001 to 2004–2005)).

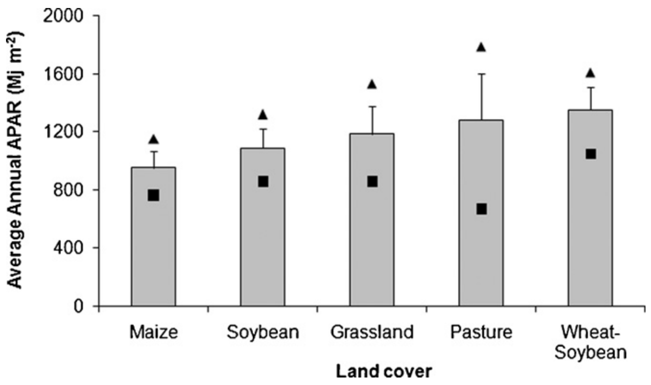

Fig. 5. Average annual absorbed photosynthetic active radiation (management units average of 5 campaigns (2000–2001 to 2004–2005)) for the different land covers analyzed (vertical bars). Different letters indicate significant differences ($p < 0.01$; Tukey's test). Squares: percentile 10, Triangles: percentile 90.

Wheat–soybean double crop had the highest average annual APAR values ($1353\,\mathrm{MJ\,m^{-2}\,year^{-1}}$) and maize the lowest ($953\,\mathrm{MJ\,m^{-2}\,year^{-1}}$) (Fig. 5). These values of APAR corresponded to 50% and 35% of the annual average incoming PAR ($2694\,\mathrm{MJ\,m^{-2}\,year^{-1}}$) respectively. Rangelands intercepted on average $1234\,\mathrm{MJ\,m^{-2}\,year^{-1}}$. At the crop sequence level, average annual APAR (estimated from the average APAR of the 5 growing seasons for each cover and the cover participation in the sequence) varied from 1021 to $1246\,\mathrm{MJ\,m^{-2}\,year^{-1}}$, being the difference among them less than 10% of the annual average incoming PAR (Table 1).

3.3. Impact of crop sequence, tillage system and fertilization on SOC content

Based on CENTURY simulations, continuous agriculture on the Argiudolls of the Rolling Pampas generated, in 60 years, SOC losses ranging from 4 to 37% of the reference value ($79\,\mathrm{t\,ha^{-1}}$) depending on management practices. For the crop–rangeland sequences maximum SOC losses were 16% and SOC increases of 2–10% were observed in some sequences under no till and N fertilization. Cattle grazing had a SOC loss of 9%. (Table 2)

After 60 years of continuous agriculture all the simulations, including those fertilized with high doses (2 × average), showed a reduction in SOC contents. The highest losses were observed in the "soybean/maize" sequence under conventional tillage and no fertilization (37%) and the lowest in the "soybean/wheat soybean double crop/maize/wheat soybean double crop" under no-tillage and high fertilization (4%). Grain exports in agricultural systems

Table 1
Average annual absorbed photosynthetic active radiation calculated for different crop sequences and the percentage each represents of the Average Annual PAR.

Crop sequence[a]	Average Annual APAR (MJ/m^2)	% PAR
S/M	1021	37.88%
S	1089	40.41%
S/M/S/WS	1121	41.59%
S/M (6) P (4)	1126	41.78%
S/WS/M	1131	41.99%
S (6) P (4)	1166	43.29%
Grassland	1185	43.96%
S/WS/M/WS	1187	44.05%
S/WS/M (6) P (4)	1192	44.24%
S/WS	1221	45.31%
S/WS (6) P (4)	1246	46.24%

[a] Crop sequences were derived from the temporal analysis of land cover classifications (5 years). The numbers in brackets represent the number of years in a 10 years sequence. S: Soybean; WS: double crop wheat–soybean; M: Maize; P: Pasture.

Table 2
Simulated changes in SOC (%; SOC reference value (100%) = 79 t ha^{-1}) after 60 years with different management (crop sequence, tillage system and fertilization) in Argiudolls of the Rolling Pampa (North of Buenos Aires province, Argentina).

Land use	Crop sequence[a]	Conventional tillage			No tillage		
		Without fertilization	Average fertilization	Average fertilization × 2	Without fertilization	Average fertilization	Average fertilization × 2
Continuous Agriculture	S	−34%	−34%	−34%	−28%	−28%	−28%
	S/WS	−29%	−17%	−7%	−26%	−15%	−7%
	S/M	−37%	−26%	−18%	−31%	−22%	−14%
	S/M/S/WS	−35%	−26%	−17%	−29%	−19%	−10%
	S/WS/M/WS	−31%	−16%	−5%	−27%	−11%	−4%
	S/WS/M	−34%	−24%	−15%	−29%	−16%	−5%
Crop (6 years) Rangelands (4 years) rotation	S (6) P (4)	−12%	−12%	−11%	−4%	−4%	−4%
	S/WS (6) P (4)	−7%	−5%	−3%	−1%	4%	10%
	S/M (6) P (4)	−16%	−12%	−9%	−6%	−1%	3%
	S/WS/M (6) P (4)	−13%		−5%	−4%	2%	9%
Cattle Grazing	Grassland				−9%		

[a] Crop sequences were derived from the temporal analysis of land cover classifications (5 years). The numbers in brackets represent the number of years in a 10 years sequence. S: Soybean; WS: double crop Wheat-Soybean; M: Maize; P: Pasture.

remove large amounts of nutrients. Soil nitrogen is a key factor in the organic matter formation due to the stable C/N ratio. Therefore, the nitrogen lost must be restored through fertilization or legumes cultivation (both generate a positive balance of nitrogen in the soil) to maintain the levels of organic matter. Several authors warn that despite the higher amount of fertilizer applied since the 1990s these volumes do not reach the amount of nutrients exported by the grains, producing chemical and physical degradation of soils (Flores and Sarandón, 2002; Díaz Zorita, 2005).

The low amount of nitrogen applied to soil as fertilizer in soybean cultivation, which generally derives from the application of diammonium phosphate fertilizer (DAP) at sowing (FAO, 2004; Austin et al., 2006), did not reduce the losses of SOC under none of the two tillage systems. Nitrogen fertilization is not a widespread practice in the soybean cultivation because it reduces the biological fixation of nitrogen, a low cost source of N, but that only covers 20–50% of the nitrogen exported in the grain. The N negative balance resulting from these practices in the Pampas was estimated between 42 and 126 kg ha^{-1} (Austin et al., 2006). Possible options to reduce losses of soil nitrogen during the soybean cultivation include fertilization with slow release products below the zone of nodulation and/or nitrogen application during the reproductive stages in high-yielding cultivars (>4500 kg ha^{-1} for soybean yield) (Salvagiotti et al., 2008).

In the simulations, unfertilized maize crops had a higher negative effects in the carbon balance than soybean monoculture, since C losses in crop rotations including maize were greater than the same rotations including soybean (Conventional tillage: 37% vs. 34%; No till: 31% vs. 28%). The results contrast with field observations where the inclusion of maize in the sequence generally increases SOC due to higher residue biomass returned to soil (Studdert and Echeverría, 2000). Maize showed the lowest annual average APAR (Fig. 5) suggesting lower carbon gains. Even though Maize is a C_4 species with higher radiation use efficiency than the other crops considered (C_3 species) and therefore higher PPN (C input to the system), its lower humification rate due to higher lignin content (Andriulo et al., 1999) could reduce the C inputs to the soil. Huggins et al. (1998) reported that although aboveground C returned to the soil from maize was in average 40% higher than C returned from soybean, SOC did not differ from crop sequence. In our simulations, when maize was fertilized with N, soybean monoculture lost higher amounts of SOC than the soybean/maize sequence.

There was a positive effect (less SOC losses) of the wheat–soybean double cropping presence in the sequence, particularly with higher levels of fertilization. This positive effect would be due to a higher APAR (Caviglia et al., 2004) and to the higher doses of fertilizer applied to wheat with respect to other crops (FAO, 2004).

Both losses and gains of SOC were observed under crop–rangeland rotations. The highest losses were in the soybean/maize (6 years) pasture (4 years) sequence under conventional tillage and no fertilization (16%), being the highest gains obtained in soybean/wheat soybean double crop (6 years) pasture (4 years) sequence under no-tillage and high fertilization (10%).

The losses observed in grasslands are associated with changes in the outputs and inputs of nitrogen in the system. Cattle grazing increased N emissions reducing soil nitrogen pool (Piñeiro et al., 2006). A lower soil N pool constrains organic matter accumulation and consequently reduces SOC, making the system more dependent on external N inputs (Piñeiro et al., 2006). Nitrogen fertilization or inter-seeding of legume species that incorporates nitrogen to the soil may potentially contribute to reduce SOC losses in these systems.

Our data showed a positive and direct relationship between APAR estimation derived from satellite data and simulated SOC (Fig. 6) suggesting the importance of C inputs on the dynamics of SOC. Each point in Fig. 6 corresponds to the simulated values of SOC losses and to the average APAR for the different sequences.

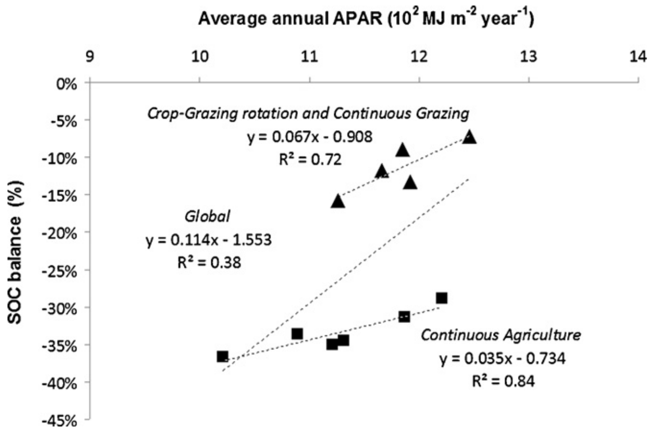

Fig. 6. Relationships between the average annual APAR (5 years) and SOC simulated balance (60 years under conventional tillage and no fertilization (SOC reference value (100%) = 79 t ha^{-1})). Each point represents a crop sequence. Squares: Continuous agriculture; Triangles: Crop–rangeland rotation and continuous grazing.

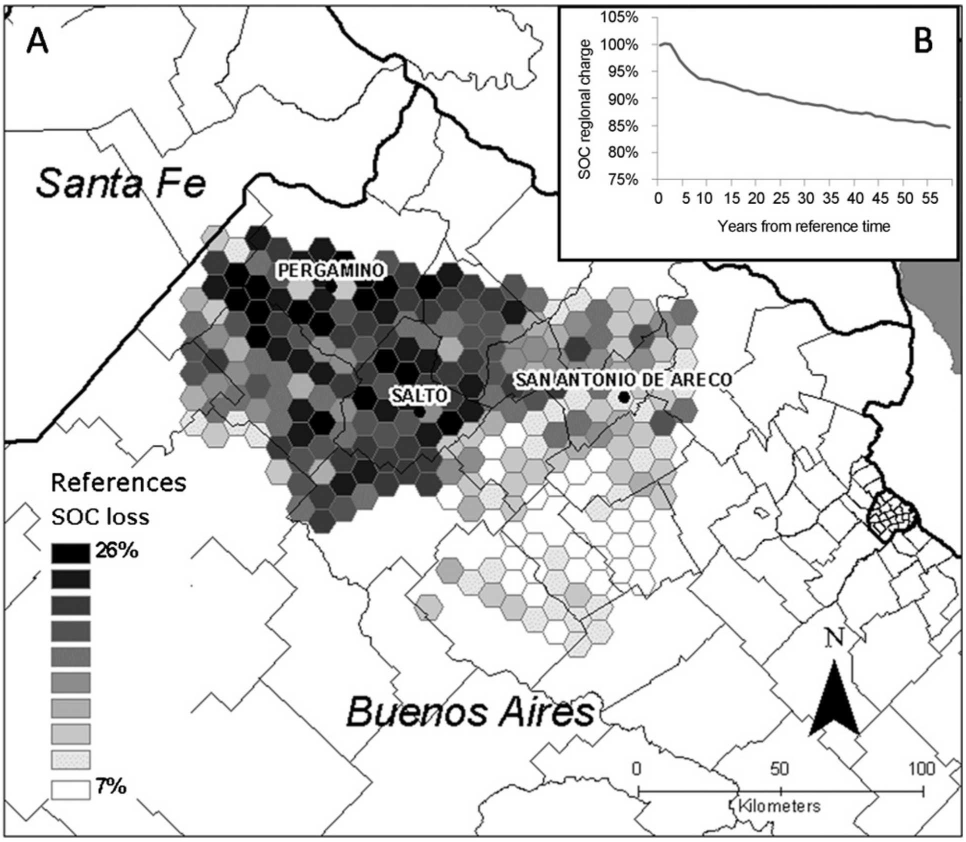

Fig. 7. (A) Simulated loss of SOC in 60 years, as % of the reference value (79 t ha^{-1}), in the Argiudolls of the Rolling Pampa. The value of each cell summarizes the effect of the observed management (crop sequence and tillage system with average fertilization). Santa Fe and Buenos Aires are provinces, Pergamino, Salto and San Antonio de Areco are towns and solid lines correspond to county limits. (B) Simulated loss of regional SOC, as % of the reference value, along 60 years.

Fig. 6 showed that SOC losses for crop–rangeland rotations were not only lower (three times in average) but also more responsive to changes in APAR (higher slope for the model fitted to the APAR-SOC loss relationship for crop–rangeland rotations than for continuous agriculture). Crop sequences under conventional tillage and without fertilization included in a crop–rangeland rotations showed C losses 2–4 times lower than their equivalent under continuous agriculture showing, once again, the positive effect of the legume pastures in the rotation in the absence of N additions through fertilizers (Casanovas et al., 1995; Studdert et al., 1997; Díaz Zorita et al., 2002; Miglierina et al., 2000). Crop sequences under no-tillage and without fertilization included in a crop–rangeland rotations showed C losses 5–26 times lower than their equivalent under continuous agriculture (Table 2). By adopting no-tillage, applying fertilizers and including alfalfa in the crop sequence farmers would be able to increase SOC. Fig. 6 is a good example of the relationship between an IES (APAR) and a FES directly related to several human benefits (C losses as a descriptor of C sequestration or soil fertility). As in many production functions used in agriculture (i.e. APAR vs. grain yield), additional factors need to be considered (i.e. level of fertilization, soil texture, etc.). Further exploration of the production functions of FES from IES derived from remotely sensed data appears as a promising way to improve the use of the ES concept in land planning and management.

3.4. Regional estimates of SOC changes

Considering current land use, the observed proportion of different tillage system and assuming an average fertilization level, the simulated SOC losses in the studied area (1,294,488 ha) were 15.9 Tg C in 60 years (0–20 cm depth). This represents a reduction of C stocks of 15.5% according to the reference value (79 t ha^{-1}). Considering that 300 years of grazing had reduced SOC by 14.7%, total losses with respect to the original situation (96 t ha^{-1}) would be 30.2%.

Even though carbon loss has not a linear behavior these values would represent an average decrease rate of 204.7 kg ha^{-1} year^{-1} or 265,025 Mg year^{-1} for the study area (about 13,000 km^{2}). This annual value is equivalent to 0.6% of C emissions from fossil fuel consumption at the country level (41,679,000 Mg C year^{-1} 2005—CDIAC, 2008). If the rate in other agricultural areas were only half the one observed in the Rolling Pampas (a conservative estimation), emissions from the agricultural sector would represent more than 12% of the emissions associated with fossil fuels.

The map shows lower SOC losses on the eastern portion of the studied area than in the west (Fig. 7). These patterns results from differences in land uses, being continuous agriculture the most widespread use near Pergamino and crop–rangeland rotations and cattle grazing more common in the south of San Antonio de Areco.

4. Conclusions

(i) Continuous agriculture is the main land use in the Rolling Pampas and only two crop sequences (soybean monoculture and soybean/wheat soybean double crop/maize) represents the 61% of its area. This two crop sequences have very different C dynamics response to management such as tillage or fertilization. The particular arrangement of land uses through time has a large impact on the level of two key IES, C gains and soil C losses. A proper characterization of the pampas agroecosystems requires the description of, not only, the spatial distribution of land cover and/or land uses, but also, the temporal distribution of them.

(ii) Compared to the less modified land cover (grasslands grazed by cattle) agricultural use may either increase or decrease the amount of PAR absorbed (APAR) by green tissues, a linear indicator or NPP or C gains. We showed that land covers may differ by 15% in the proportion of the incoming PAR which represent differences up to 30% among them. Differences in APAR among land covers were associated mainly to differences in the annual dynamics of PAR absorption. Crop sequences with a large wheat soybean double crop and/or rangelands participation had the greatest average annual APAR.

(iii) SOC losses were directly associated to the N balance and to the C inputs. A proper management of N balance (fertilization and pastures including legumes) may even increase SOC stocks. The magnitude of the effect of N balance was higher that the effect of C inputs, i.e. those rotations that include legume pastures had SOC losses three times lower than continuous agriculture sequences (Fig. 6). The effect of C inputs (quantified through changes in APAR) was lower but highly significant (Fig. 6). The reduction in C losses per unit of increase in APAR was higher in crop–rangelands rotations suggesting a positive interaction of N balance and C gains on SOC losses.

Our analyses allow us to derive *impact functions* for these two IES. Tables 1 and 2 summarize the quantitative effect of the most frequent management on the level of provision of “C gains” and “C losses” services. A particular management can be evaluated in terms of physical production, economic outputs and impact on IES. Of course the analysis cannot state the level of reduction of ecosystem services to be accepted. Such decision needs to incorporate the opinions, values and interests of stakeholders and the society as a whole. However, the availability of *impact functions* as those presented here may set quantitative boundaries to the discussion.

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Appendix A.

A.1. Relationship between field based NDVI and MODIS NDVI

A.1.1. Samples

Six management units, each of them big enough to include at least 4 pixels MODIS of 250 m, were selected in the northern part of Buenos Aires province (Pergamino). The management units were occupied by maize (3), soybean in double crop (2) and soybean (1).

A.1.2. ASD measurements

In four dates throughout the growing 2008–2009 season (14 November 2008, 05 December 2008, 24 December 2008 and 21 January 2009) we measured the surface reflectance signatures using a hyperspectral sensor FieldSpec® 3 (Analytical Spectral Devices; 1 nm spectral resolution). Six to eight subsamples were obtained per management unit, each of them in turn were the average of three measurements. NDVI values were calculated averaging reflectance values for the portion of the spectrum that corresponds to red and near infrared bands of MODIS (620–670 nm for the red band (band 1) and 841–876 nm for the infrared band (band 2)) (NDVI ASD).

A.1.3. MODIS product

Images corresponding to the MOD13Q1product were obtained from https://wist.echo.nasa.gov/api/. Each image corresponded to a 16 days composite of NDVI at 250 m. The composites used matched the dates of field measurements. The information of the 250 m pixels was averaged to obtain a NDVI value per management unit (NDVI MODIS). Only NDVI data flagged as “Ideal” were used.

To analyze the correspondence between ground and satellite NDVIs a regression was done with both estimates:

$$\mathrm{NDVI}-\mathrm{MODIS} = 0.7751\,\mathrm{NDVI}-\mathrm{ASD}+0.1339 \quad (R^2 = 0.83) \quad \text{(A1)}$$

A.2. Calibration of the NDVI-MODIS and fractional photosynthetic active radiation (fPAR) relationship

A.2.1. Samples

Fourteen management units were selected in northern Buenos Aires province (Pergamino, Hurlingham): maize (5), soybean in double crop (2) and soybean (7).

A.2.2. ASD measurements

In six dates throughout the growing season 2008–2009, 14 November 2008, 05 December 2008, 24 December 2008, 29 December 2008, 9 January 2009 and 21 January 2009 measurements were taken with a hyperspectral sensor FieldSpec® 3 (Analytical Spectral Devices; 1 nm spectral resolution) to obtain each management unit surface reflectance signature. Six to eight subsamples were obtained per management unit, each of them in turn were the average of three measurements. NDVI values were calculated averaging reflectance values for the portion of the spectrum that corresponds to red and near infrared bands of MODIS (620–670 nm for the red band (band 1) and 841–876 nm for the infrared band (band 2)) (NDVI ASD).

A.2.3. fPAR measurements

Simultaneously with ASD measurements we recorded photosynthetically Active Radiation using a linear quantum sensor (©Cavadevices) that measures the photon flux between 300 and 1000 nm, and up to 3000 μmol m^{-2} s^{-1}, over a 1 m linear surface. The fraction of PAR intercepted by the canopy was calculated as:

$$\mathrm{fPAR} = \frac{\mathrm{PARi}-\mathrm{PARt}}{\mathrm{PARi}}$$

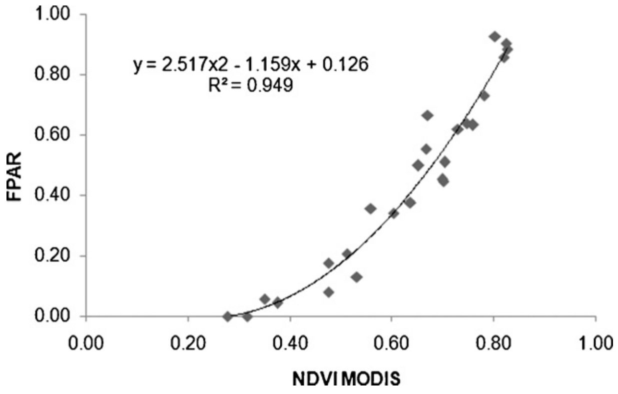

Fig. A1. NDVI-FPAR relationship. Soybean and maize crops; North of Buenos Aires province, Argentina; Growing Season 2008–2009.

where PARi is the incoming PAR measured locating the quantum linear sensor just above the canopy and PARt is the transmitted PAR registered underneath the canopy. Six to eight subsamples were performed per management unit, averaging them to obtain the management unit fPAR.

The NDVI ASD was transformed to NDVI MODIS using Eq. (A1). A non-linear model was fitted to the relationship NDVI MODIS-fPAR (Eq. (A2) and Fig. A1):

$$\mathrm{fPAR} = 2.517\,\mathrm{NDVI}^2 - 1.159\,\mathrm{NDVI} + 0.126 \quad (R^2 = 0.95) \tag{A2}$$

Appendix B. Confusion matrixes of land cover classifications – Landsat Path-226 Row-084 (North of Buenos Aires province, Argentina) – Growing Seasons 2000–2001 to 2004–2005

Growing Season 2000–2001

Dates: 17/11/2000, 12/01/2001, 09/03/2001 (total $N = 254$)	
Overall Accuracy	0.91
Kappa Coefficient	0.89
Kappa Variance	0.02

Class	Prod. Acc. %	User. Acc. %
Water	1.00	1.00
Forage resources	0.96	0.89
Wheat–Soybean	0.79	1.00
Maize	0.78	0.78
Soybean	0.88	0.89

Growing Season 2001–2002

Dates: 09/09/2001, 22/12/2001, 23/01/2002 (total $N = 302$)	
Overall Accuracy	0.96
Kappa Coefficient	0.95
Kappa Variance	0.03

Class	Prod. Acc. %	User. Acc. %
Water	1.00	1.00
Forage resources	0.96	0.97
Wheat–Soybean	1.00	0.90
Maize	0.91	1.00
Soybean	0.90	0.94

Growing Season 2002–2003

Dates: 17/12/2002, 18/01/2003, 23/03/2003 (total $N = 354$)	
Overall Accuracy	0.94
Kappa Coefficient	0.93
Kappa Variance	0.02

Class	Prod. Acc. %	User. Acc. %
Water	0.91	1.00
Forage resources	0.96	0.90
Wheat–Soybean	0.93	0.92
Maize	0.92	0.99
Soybean	0.95	0.96

Growing Season 2003-2004

Dates: 03/05/2003, 09/10/2003, 04/01/2004, 14/02/2004 (total $N = 695$)	
Overall Accuracy	0.91
Kappa Coefficient	0.88
Kappa Variance	0.00

Class	Prod. Acc. %	User. Acc. %
Water	0.99	1.00
Forage resources	0.88	0.87
Wheat–Soybean	0.85	0.83
Maize	0.91	0.92
Soybean	0.92	0.93

Growing Season 2004-2005

Dates: 25/11/2004, 30/12/2004, 04/03/2005 (total $N = 1026$)	
Overall Accuracy	0.92
Kappa Coefficient	0.90
Kappa Variance	0.00

Class	Prod. Acc. %	User. Acc. %
Water	0.99	1.00
Forage resources	0.89	0.55
Wheat–Soybean	0.89	0.98
Maize	0.89	0.96
Soybean	0.95	0.95

Appendix C. CENTURY evaluation

C.1. *Objective*

To evaluate CENTURY model SOC results with SOC of long term experiments in the study region.

C.2. *Materials and methods*

We used yield and SOC data of a long term experiment in Pergamino (Andriulo et al., 1999). Also information about soil, crops, management and climate of this experiment was gathered.

1. *Soil*
   (a) SOC time variation (specifying depths)
   (b) Texture, layers depth, SOC initial condition, filed capacity, wilting point, pH.
2. *Crops*
   Grain and biomass yields (or yield index) along the experimental period.
3. *Management*
   Information on crop sequence, fertilization, tillage, sowing date, etc.
4. *Climate*
   (a) Climate data along the experimental period: daily or monthly precipitation, maximum temperature, minimum temperature.
   (b) Historic climatic data of the site.

This information was obtained from Andriulo et al. (1999) or provided by the authors. This experiment was done in the INTA Pergamino station. The site has not been plowed or grazed for 80 years. The experiment consisted in cultivating soybean for 13 years.

The CENTURY simulation consisted in 4000 years of grassland and native grazing to get the SOC stabilized, 300 years of domestic grazing (adjusting stocking rate, see Piñeiro et al., 2006), 80 years of no grazing and finally the experiment of 13 years of soybean

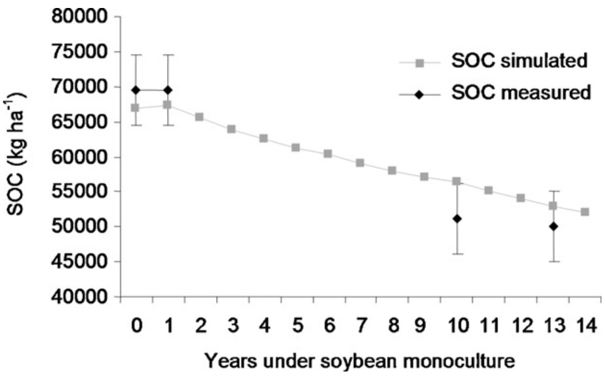

Fig. C1. Variation of SOC, measured and simulated by CENTURY model, along 13 years of soybean monoculture, in a Rolling Pampa's Argiudol (Pergamino).

monoculture. The SOC data were converted to kg ha^{-1} for the first 20 cm of depth as it is simulated by the model. Model simulations were performed with the available data.

The SOC content simulated was compared with the SOC content recorded in the experiment.

C.3. Results

The decrease of the SOC simulated by the CENTURY model was similar to the one reported in the experiment, being the simulated values inside the confidence level of the values measured by Andriulo et al. (1999) (Fig. C1).

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