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Short communication

The IPCC Tool for predicting soil organic carbon changes evaluated for the Pampas, Argentina

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ABSTRACT

The Intergovernmental Panel on Climate Change (IPCC) has developed a methodology for predicting soil organic carbon (SOC) stocks and changes known as the IPCC Tool. We tested the use of this tool for soils of the Pampas Region of Argentina by comparing its predictions with results from a soil survey performed on 82 farms widely distributed over the region. The sample comprised soils in uncultivated as well as agricultural fields, both under crops or in the pasture phase of a mixed rotation. Using the default parameters, the IPCC Tool could not predict SOC stocks of uncultivated fields with an acceptable performance ($R^2 = 0.249$; RMSE = 27.7 t ha^{-1} = 48.5% of the mean SOC stock). On average, the methodology estimated SOC decreases on cultivation of 21%, but measured SOC changes were 10–14%. We therefore propose that default parameters values should be calibrated using local data. Using measured SOC stocks from uncultivated fields as reference values and locally calibrated parameters, led to an improvement in the estimation of land use change effect on SOC, but the fit to observed results was still poor ($R^2 = 0.403$; RMSE = 14.9 t ha^{-1} = 31% of the mean SOC stock). Possible causes of this failure of the methodology to capture land-use change effects on SOC are discussed, as well as the performance attained by other methodologies for estimating SOC in the Pampas.

1. Introduction

The impact of land conversion on soil organic carbon (SOC) stocks is one of the most important global change issues. SOC is an important component of the carbon system and increasing SOC is a key process in mitigating increased atmospheric carbon dioxide. Numerous studies have attempted to assess the potential of the soil to sequester atmospheric carbon under different land-use management schemes at local, regional and global scales. It is clear that SOC is an important carbon reservoir that stores more carbon than the global biota and atmosphere together (Janzen, 2004). SOC changes are also the second largest contributor to CO_2 net emission after fossil fuel burning (Houghton et al., 1983). Land conversion from natural ecosystems to cultivation drastically reduces SOC stocks, while afforestation increases SOC stocks (Guo and Gifford, 2002).

Several process-based models have been developed to estimate SOC dynamics (Powlson et al., 1996). While some of these models have been tested under a wide range of environmental conditions (Smith et al., 1997), they can be difficult to apply, especially in developing countries, because they require a number of inputs which are not always available. For this reason, the Intergovernmental Panel on Climate Change (IPCC) has developed a simple methodology to estimate the SOC stocks and changes induced by land-use change; this is referred to as the IPCC Tool. The Tool is distributed as a software package containing the working equations and reference values of the IPCC Guidelines for Greenhouse Gas Inventories (IPCC, 2006). IPCC methods are used worldwide to design environmental policies, but there has been little research to validate the estimates. For example, in Argentina the IPCC Tool has been used to estimate SOC changes after land conversion, but without previous testing the accuracy of the methodology (Gasparri et al., 2008; Viglizzo et al., 2011). The Pampas are main cropping area of Argentina. Because of their extent and productivity, the Pampas are considered as one of the most important grain production regions of the World (Satorre and Slafer, 1999). Starting around the end of the 18th century, the land use of the Pampas was changed, with natural grassland being replaced by seeded pastures and crops (Solbrig and Viglizzo, 1999). This process has continued up to the present-day, and has lead to SOC depletion in some parts of the region (Alvarez, 2001). Process-based models have been successfully used for estimating SOC in pampas grassland soils (Piñeiro et al., 2006) but their use in cultivated soils is limited by the lack of suitable data to parameterize and validate the model.

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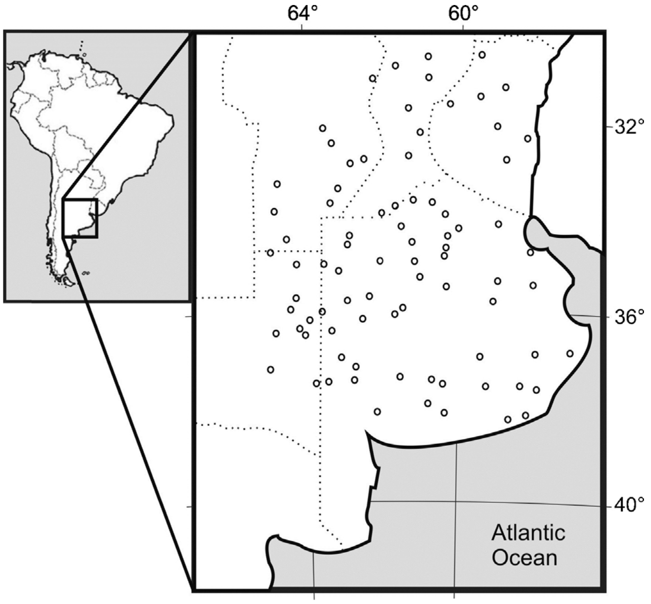

Fig. 1. Location of the sampled farms within the Pampas of Argentina. In each farm we sampled an uncropped field and two long-term cultivated fields (cropland and pasture).

In this paper we evaluate the potential of the IPCC Tool for estimating SOC stocks and changes in the Pampas Region. We compare observed values of SOC stocks measured under different land uses against estimated values and then calculate the impact of cultivation on those stocks.

2. Materials and methods

2.1. Description of the area

The Pampas Region is an extensive prairie of 60 Mha that occupy some 22% of Argentina. It is located (see Fig. 1) in the central east of Argentina between 28° S and 40° S and 68° W and 57° W, and, is bordered on the east by the La Plata and Uruguay rivers and the Atlantic Ocean and on the west by the arid Cuyo eco-region. Mean annual temperature ranges from 19 °C in the north to 12 °C in the south, and mean annual rainfall varies from 500 mm in the west to 1100 mm in the east (Hall et al., 1992; Solbrig and Viglizzo, 1999). Soils of the region were developed over eolian-loessic type sediments, which originated from the southwest, leading to a progressive increase in the proportion of fine textured soils from the southwest to the northeast, correlated with the climatic gradient mentioned above (Hall et al., 1992). The predominant Soil Taxonomy order (USDA, 1975) is Mollisols (Alvarez and Lavado, 1998). Over the last 50 years the region has been subject to extensive land-use change (Viglizzo and Frank, 2006). Grasslands have been replaced by seeded pastures and crops, especially in the wetter east. Between 50 and 75% of the cultivated area is devoted to grain crops. During the last 30 years, the trend has been for pasture and maize to be replaced by soybean as the main component of crop rotation (Alvarez et al., 2011; Viglizzo et al., 2011).

2.2. IPCC methodology description

The IPCC Tool is a simple model for the estimation of SOC changes associated with land-use change (IPCC, 2003), and is included as part of IPCC Guidelines for Greenhouse Gas Inventories (IPCC, 2006). These guidelines propose three levels of accuracy in greenhouse gas inventories: Tier 1, Tier 2 and Tier 3. Moving to a higher tier improves the accuracy of the inventory and reduces uncertainty, but the complexity and resources required for conducting inventories also increases. Tier 1 implies using IPCC equations and default values for all the inputs and parameters; Tier 2 uses IPCC equations, but inputs and parameters are based on local data. Finally, Tier 3 estimates are based on entirely locally developed methodologies. The IPCC Tool is based on the Tier 1 methodology.

Based on annual temperature, precipitation and evapotranspiration, the IPCC Tool identifies eight possible climatic scenarios. Soils are grouped into six categories taking into account genetic and textural characteristics. For different combinations of climate and soil categories, the model uses default reference SOC levels under the native ecosystem for the upper 30 cm of soil, which are based on the SOC profiles integrated according to Bernoux et al. (1998) and Jobbagy and Jackson (2000). The reference carbon content under the native ecosystem is modified by land-use and the level of inputs when cropped. The IPCC Tool assumes that SOC reaches a new equilibrium 20 years after land-use change.

2.3. Data sources

The data used for the model evaluation came from a survey carried out during 2007–2008 on 82 farms spread across the entire Pampas region. The Pampas are mostly farmed as large estates, typically centred on an old farmhouse that is set in extensive never-cultivated parkland. The parkland is periodically mowed and is dominated by graminaceous vegetation; it thus presents similar characteristics to native ecosystems (Berhongaray et al., 2013). Here we term this parkland as ‘uncropped fields’. On each farm the following land-use types were sampled: uncropped fields, seeded pastures, and cropped fields. Seeded pastures were cultivated soils that at the time of sampling were under the pasture phase of a mixed rotation. Cropped fields were sites that at the time of sampling were under the agricultural phase of the rotation or under continuous cultivation. They were selected to be representative of the most common rotation and tillage system used in each area. A detailed description of the land-use types, site properties, sampling and analytical methods for carbon and bulk density determination are given by Berhongaray et al. (2013). The mean annual temperature, mean annual precipitation and clay content of each site are presented in Table 1. As samples were taken from the 0–25 cm soil layer, we corrected measured SOC values to 30 cm depth, using the locally developed power function described by Berhongaray et al. (2013). This allowed comparison with the output of the IPCC Tool estimates. SOC by depth was also transformed to equivalent soil mass (equivalent depth according to Jenkinson et al., 2008). Transformation to cumulative soil mass is used to account for the increases in the bulk density caused by agriculture. The equivalent depth is defined as the depth to which two treatments have the same mass of soil in a layer. The data were transformed to an equivalent soil mass of 3500 t of soil per hectare using the power model presented by Berhongaray et al. (2013).

2.4. IPCC Tool running and evaluation

Land use change effects on SOC stocks were estimated by two different procedures; a Tier 1 and a Tier 2 option. For the Tier 1 option, we used climatic records, soil texture and mineralogy of the sampled sites to estimate SOC for the native ecosystem using the default option of the IPCC Tool. These estimates were compared with SOC measured in the uncropped fields, which were used in this study as a control treatment equivalent to native ecosystems. This comparison allowed us to assess the ability of the model to estimate carbon in undisturbed or minimally disturbed scenarios. We then simulated a land-use change from native ecosystem to agricultural use. The management factors used during the IPCC Tool

Table 1
Climatic characteristics and soil types of the study sites. The sites were grouped according to the IPCC classification of climate and soil.

Climatic region	Soil	Sites	MAT (°C)		MAP (mm)		Soil type
		n	Mean	Range	Mean	Range	Soil taxonomy
Warm temp moist	High clay activity	54	15.6	12.8–17.9	898	690–1081	Argiudolls, Hapludolls, Haplustolls, Argiustolls, Natraqualfs, Natraquolls, Hapluderts
	Sandy	5	15.1	14.7–15.2	849	761–983	Hapludolls
Warm temp dry	High clay activity	10	15.3	14.1–16.4	672	619–729	Haplustolls, Argiustolls, Calciustolls
	Low clay activity	2	15.8	15.3–16.2	641	564–718	Haplustolls, Torripsaments
	Sandy	5	16.6	15.1–16.1	690	655–723	Haplustolls
Trop moist	High clay activity	4	18.5	18.1–19.1	1080	1005–1156	Argiudolls, Hapluderts
Trop dry	High clay activity	2	18.4	18.2–18.5	990	987–993	Argiudolls

Table 2
Soil texture and SOC observed and estimated with the IPCC Tool. The results are grouped according to the IPCC Tool variables inputs. The SOC in the uncropped controls was used as reference carbon in the native ecosystems, average values of cropped lands and seeded pastures were used for the long-term agriculture sites.

Climatic region	Soil	Land use	Sites	Clay (%)		Sand (%)		Observed SOC (t ha^{-1})		Estimated SOC (t ha^{-1})
			n	Mean	Range	Mean	Range	Mean	Range	Mean
Warm temp moist	High clay activity	Uncropped fields	54	14.3	4–31	42.7	17–66	62.8	35–112	88.0
		Long-term agriculture	98	16.5	4–37	41.4	17–70	53.2	12–101	68.7
	Sandy	Uncropped fields	5	3.0	2–5	83.0	76–98	53.6	17–81	34.0
		Long-term agriculture	6	3.8	2–6	82.0	77–87	35.3	22–45	26.6
Warm temp dry	High clay activity	Uncropped fields	10	7.3	2–16	56.7	45–68	42.3	10–87	38.0
		Long-term agriculture	15	10.9	6–22	55.9	39–81	40.9	18–87	34.1
	Low clay activity	Uncropped fields	2	2.0	2	73.5	66–81	35.5	27–44	24.0
		Long-term agriculture	4	3.0	2–4	77.0	72–80	25.5	16–33	21.6
	Sandy	Uncropped fields	5	3.8	3–4	80.6	76–86	36.2	20–54	19.0
		Long-term agriculture	9	3.1	2–5	80.6	71–86	40.9	18–87	17.1
Trop moist	High clay activity	Uncropped fields	4	26.5	26–27	29.5	26–35	59.0	44–81	65.0
		Long-term agriculture	8	27.1	20–32	29.5	25–34	42.3	19–57	37.7
Trop dry	High clay activity	Uncropped fields	2	22.5	22–23	27.0	25–29	56.0	47–65	38.0
		Long-term agriculture	4	25.0	22–28	25.0	18–34	45.5	30–68	26.4

calculation were the options: "reduced tillage" and "high inputs without manure"; these descriptions best characterize agriculture on the Pampas during the last few decades (Solbrig and Viglizzo, 1999). SOC estimates from the IPCC Tool for cultivated soils were then compared with the SOC content measured in cropped fields and seeded pastures. For the Tier 2 option we used measured SOC stock data of uncropped fields as the reference level and simulated the impact of cultivation on these SOC stocks using the default IPCC management factors. A third assessment was carried out using different management factors. These new management factors were calculated for each climate region using the average of the SOC change due to cultivation. Only measured and estimated SOC for cultivated sites were contrasted in the Tier 2 option for model evaluation.

Model estimates were statistically compared with measured data using linear regression methods. The performance of the Tool was evaluated by computing the R^2 and root mean squared error (RMSE). The intercept and the slopes of the observed vs. measured values were tested for deviation from a null hypothesis of 0 and 1, respectively, by a *t*-test.

3. Results

Average measured SOC was higher in uncropped fields (57.1 ± 2.16 t C ha^{-1}, mean ± SE) than in seeded pastures (49.5 ± 2.49 t C ha^{-1}) or cropped lands (46.2 ± 1.96 C t ha^{-1}). When taking into consideration the climatic classification of the IPCC Tool, SOC content measured in uncropped fields varied between climatic regions (Table 2). In the uncropped fields of the Pampas, the IPCC Tool had a tendency to overestimate SOC content in high carbon soils, whereas the model underestimated SOC in soils with a low SOC content (Fig. 2). The intercept of the regression line of observed vs. estimated values was higher than zero and the slope lower than unity ($P < 0.05$), with a generally poor fit between both data sets. The error of the model was equivalent to 48.5% of average SOC stock. Averaged over all the sites, the IPCC Tool overestimated the SOC content by 23.5%.

The IPCC Tool also failed to estimate the SOC of croplands when run using the default parameters, and the SOC stock estimated for uncropped fields as the pre-cultivation SOC stock (Fig. 3A). The poor prediction potential of the methodology

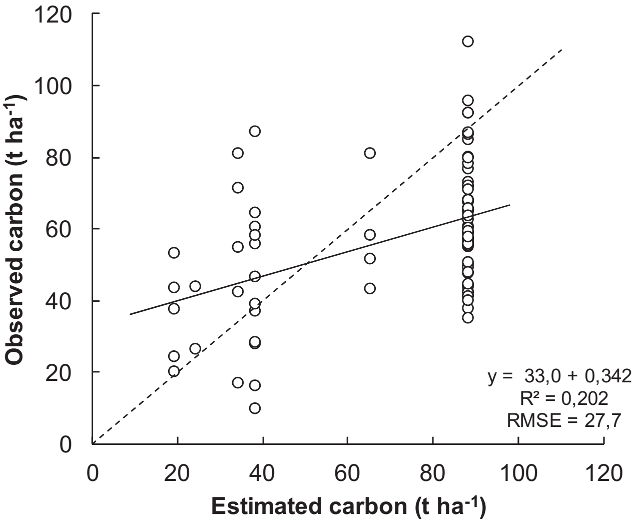

Fig. 2. Observed vs. estimated soil organic carbon (SOC) in the upper 30 cm of the profile using the IPCC Tool in uncropped fields of the Pampas. The estimated values correspond to the default values of SOC for native ecosystems and the observed SOC was measured in uncropped fields. The estimated regression intercept was greater than 0 and the slope lower than 1 ($P < 0.05$).

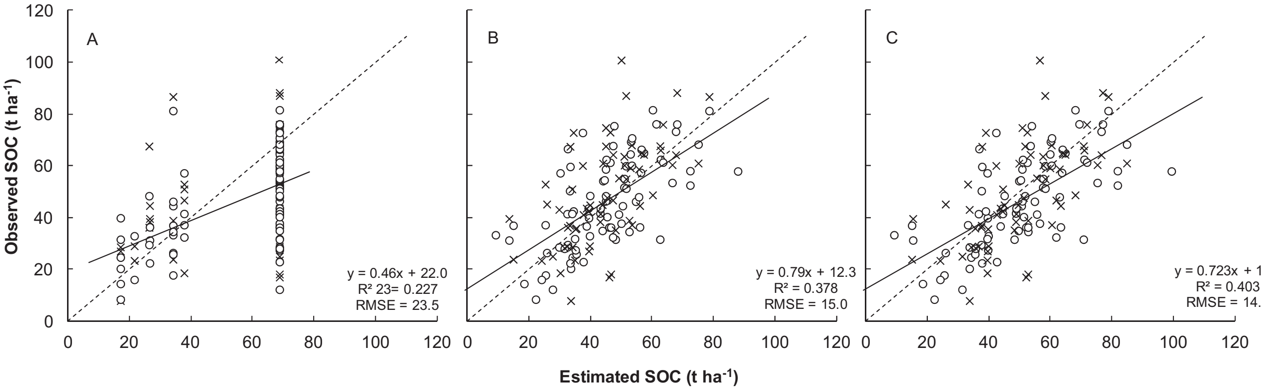

Fig. 3. Soil organic carbon (SOC) in the upper 30 cm of the profile observed in cropped fields (circles) and seeded pastures (crosses) of the Pampas vs. estimated SOC by the IPCC Tool using: (A) default values of SOC for uncropped fields (native ecosystems) and default parameters, (B) SOC measured in uncropped fields and default parameters for cultivation effects, and (C) SOC measured in uncropped fields and parameters based on local data. In all cases estimates of regression intercept were greater than 0 and slopes lower than 1 ($P = 0.05$).

was observed both in sites under annual cropping and in those under the pasture phase of the rotation. The tool overestimated mean SOC losses by cultivation from 2% to 87%, depending on the climate, with an average of 71% for the whole Pampas (Table 3). This overestimation was equivalent to an average error in SOC stock depletion of 6.6 t C ha^{-1}. The soil survey revealed that changes produced by cropping ranged from −79% to +227%. At sites from areas with low SOC, agriculture tended to increase SOC, but decreases were produced in medium to high SOC soils. Analyzing cropping effects on SOC at site level in 32 sites, the soil survey revealed that agriculture produced no depletion or even increases of SOC. These results were not predicted by the IPCC Tool, that estimated SOC losses at all sites. Based on soil survey data the average depletion of SOC in the Pampas was 14% for cropped fields and 10% for seeded pastures relative to the uncropped fields' stocks. On average, the model estimated losses of 21% for all cultivated soils. In higher rainfall conditions the SOC losses estimated by the model were larger than in dry climates (30% vs. 20%). Those losses were independent of soil texture and mineralogy.

The analysis of the data in equivalent mass of soil showed higher effects of cultivation on SOC than the ones detected up the fixed depth of 30 cm (Table 3). When compared to uncropped controls, the decrease of SOC by cultivation averaged 16.2% in the 0–3500 t ha^{-1} layer. The range of differences in SOC between uncropped controls and cultivated soil was −79% to +204%. SOC looses in the warm-temperate sites were 47% higher than in the temperate sites.

The performance of the IPCC Tool for predicting the effect of agriculture on SOC was improved when using measured SOC in uncropped fields as the precultivation SOC stock rather than the IPCC Tool estimated data (Fig. 3B). A significant overestimation of the effect of agriculture was detected, as observed when using the original version, most likely because we used the same default parameters. The use of locally adjusted parameters combined with a measured base SOC level in uncropped fields led to only a minor improvement (but significant, $p = 0.02$) in the estimates (Fig. 3C). Furthermore, in this last case there was no overestimation of SOC lost under agriculture ($p = 0.99$).

4. Discussion

The present study was designed to determine the accuracy of the IPCC tool for estimating SOC stock and changes in soil of the Pampas Region in Argentina. Using present uncropped sites as the control treatment instead of the prescribed native ecosystem may lead to biased estimation when assessing cultivation effects on SOC because spatial variation is used instead of temporal variation. Pre-cultivation soil samples are not available for the Pampas but a previous study showed that our sampled uncropped sites are representative of the present condition of native ecosystems (Berhongaray et al., 2013). Soil and climate properties are similar to adjacent cropped sites, only differing in land-use history. Consequently, uncropped sites are the only possible control treatment when evaluating cultivation effects on soils in the Pampas. Uncropped sites' SOC stock may even be a better control treatment than past native ecosystems' SOC stock data because during the last few decades profund climate change has occurred in the Pampas. Rainfall has increased markedly, especially in the western portion of the region (Viglizzo et al., 1997), and this change would invalidate the use of pre-cultivation SOC stock as an adequate control for assessing the impact of cropping on soils.

Table 3
Average soil organic carbon depletion in the upper 30 cm or 3500 t ha^{-1} of the soil profile produced by cropping at 144 sites located throughout the Pampas region. Observed data were obtained from a soil survey and estimated data were calculated with the IPCC Tool. Results are presented as percentage of the pre-cultivation carbon stock of each site. The climatic region classification corresponds to the IPCC tool categories.

Climatic region	*Sites*	Observed		Estimated
	n	Fix depth (%)	Eq. mass (%)	Fix depth (%)
Warm temp moist	104	11.7	15.6	21.9
Warm temp dry	28	9.9	15.5	10.1
Trop moist	8	24.0	25.0	41.9
Trop dry	4	20.3	21.0	30.6
Total	**144**	**12.3**	**16.2**	**21.0**

The IPCC methodology failed to adequately predict the SOC levels of uncultivated fields which are used as starting values for estimating the impact of land-use change on SOC. The uncertainty of the estimates for these uncropped fields was quite high; with an RMSE equivalent to 48.5% of the mean SOC. The lack of fit of the IPCC Tool estimates to the SOC under uncropped scenarios may be due to the inflexible grouping criteria applied in the methodology. Extremely wide ranges of conditions for defining each category by climate and soil environment are used. As a consequence, soils with very different water, temperature, texture and mineralogical conditions fall into one single category while, on the other hand, soils with similar characteristics close to the threshold values of the classification, may fall into different groups. For example, in the Pampas a site with a mean annual precipitation (MAP) of 705 mm, a mean annual temperature (MAT) of 14.5 °C and 8% clay content was grouped in the same category of 'warm temperate moist with high activity clay' as a site with MAP = 1080 mm, MAT = 17.7 °C, and 29% clay. In contrast, a site very similar to the first one mentioned above (MAP = 653 mm, MAT = 14.1 °C and 16% of clay), was grouped in 'warm temperate dry with high activity clay', which has 67% less carbon than the 'moist' category. Since the IPCC Tool predicts a single SOC level for each group, this may produce a serious bias in estimates of this Tier 1 method. The IPCC tool could be improved by changing the way sites are assigned to the climate by soil–environment matrix.

Average SOC losses due to cultivation estimated by the IPCC tool were much higher than those measured, especially in the wetter sites. We detected a high impact of temperature on measured SOC losses, and a small effect of the moisture condition (Table 3).

In general, the methodology had a very low capacity to estimate land-use change effects on SOC when using estimated SOC levels for uncropped fields for comparison with cultivated soils (Tier 1 option). Improvement of the methodology by using measured SOC stock of uncropped sites (Tier 2 option) also led to an overestimation of SOC losses. Two main reasons may explain these results. In the Pampas, technological improvements have led to a huge increase in crop productivity during the last few decades leading to increases in carbon inputs from crop residues to cropped soils (Alvarez et al., 2011). Parallel to this process, climate change has led to increases in rainfall and soil water content, especially in the semiarid portion of the region with low SOC soils (Viglizzo et al., 1997). Both these reasons may have caused relative changes in the return of residues to the soil between cultivated and non-cultivated situations, affecting the expected impact of land-use change on SOC predicted by the IPCC Tool, which is based on research from other regions of the World. In 50% of the Pampas increases or minimum changes of SOC had been estimated during the last 40 years (Berhongaray et al., 2013), despite a considerable expansion of agriculture in the same period (Viglizzo et al., 2011). This highlights a limitation of the IPCC Tool which, due to its specification, will never accurately predict SOC increases resulting from conversion of natural ecosystems to agriculture in this context. Beyond the stability that can be reached in time using the IPCC Tool, SOC contents can be modified both by land-use change (pasture, crops stubble, tree plantation) and technology adoption (no-till, fertilization, irrigation).

The use of equivalent mass for the comparisons allowed us to detect that the SOC losses were higher than when using a fixed depth, especially in the temperate sites. This correction took into account the changes in the bulk density caused by agriculture. Significant increases in bulk density due to agriculture were reported previously for the Pampas Region (Berhongaray et al., 2013). This effect can be driven by a combination of processes, for instance: disruption of soil aggregates by tillage (Carter, 1990), machinery transit (Richard et al., 1999), and SOC decrease (Rawls, 1983). The higher losses detected, suggest that corrections to an equivalent mass of soil are needed to compare effects of land use change on SOC.

A Tier 2 (with modified SOC and management parameters) or a Tier 3 option must be applied in the Pampas for evaluating the ecological impact of different management practices on SOC and to guide policy makers in developing strategies for resolving the conflict between conserving natural resources and advancing agriculture. A first step in this direction was achieved by generating an artificial neural approach that explained two-thirds of SOC variability in the region using easily obtainable soil and climate information (Berhongaray et al., 2013).

5. Conclusion

The use of the IPCC Tool without previous validation may lead to substrantial errors in SOC estimation and the evaluation of land-use change impacts on carbon fluxes from agroecosystems. This must be avoided. Our study was limited to the Pampas Region and care should be taken if the results are extrapolated to other sites or conditions.

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