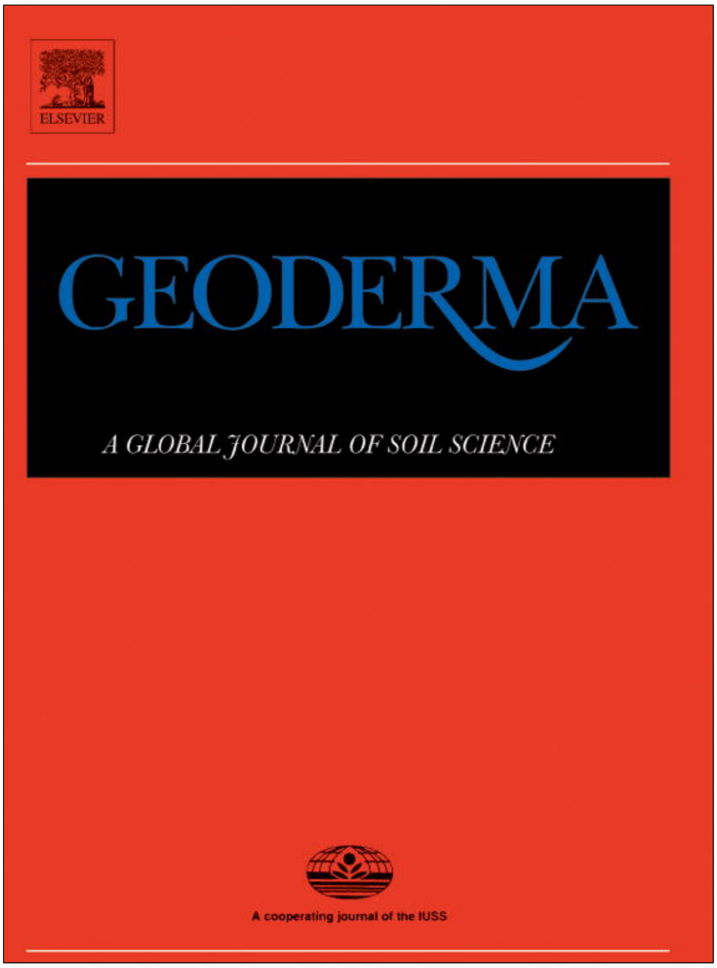
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Land use intensity and cropping sequence effects on aggregate stability and C storage in a Vertisol and a Mollisol

L.E. Novelli [a,b,*], O.P. Caviglia [a,b,c], M.G. Wilson [a,c], M.C. Sasal [a]

[a] INTA EEA Paraná, Ruta 11, Km 12.5 (3100) Paraná, Argentina
[b] CONICET, Argentina
[c] Facultad de Ciencias Agropecuarias—Universidad Nacional de Entre Ríos, Ruta 11, Km 10 (3100) Paraná, Argentina

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ABSTRACT

The relevant change in land use due mainly to the rapid expansion of soybean cropping towards areas traditionally occupied for livestock purposes or with native grasslands of South America may have negative consequences on soil organic carbon (SOC) storage and aggregate stability, although the effect may be different between soils with contrasting aggregation agents. The aim of our work was to assess the impact of the land use, measured as the intensification and/or frequency of a given crop, on SOC storage and aggregate stability in two soils differing in their main agents of aggregation. The study was conducted in a Mollisol and a Vertisol of Argentina. Eleven cropped fields (agricultural and crop–pasture rotation) under no-tillage and one uncropped situation (pristine native grassland) were selected in each soil type. The fraction of annual time with plant cover (as a measure of the intensification in the land use) and the frequency of a given crop in the cropping sequence over a 6-year period were calculated. Undisturbed soil samples were collected from each soil at 0–5, 5–15 and 15–30 cm depths. The SOC stocks in equivalent soil mass were calculated using the native grassland as the baseline system. Aggregate stability was evaluated using a method that involved three pretreatments: fast wetting, stirring after prewetting and slow wetting. The intensification improved the aggregate stability in the Mollisol, whereas a low impact of land use on aggregate stability was recorded in the Vertisol. Overall, both the intensification sequence index and the soybean cropping frequency were the best indexes to evaluate the impact of land use on aggregate stability and SOC storage, mainly in the Mollisol. The stirring after prewetting pretreatment was mainly associated with SOC concentration in the Mollisol, appearing as a method with high potential capacity to discriminate land use in the Mollisol, in which the SOC is the main aggregation agent. In contrast, the slow wetting pretreatment was more appropriate to evaluate the impact of land use in the Vertisol. The approach used to evaluate the land use, which included agricultural lands, crop–pasture rotation and native grasslands, evaluated through indexes of occupation with plant cover, was more suitable for the Mollisol than for the Vertisol. This reveals that the evaluation of land use through several indexes should be based on the soil type.

1. Introduction

In recent years, the lands of South America have experienced an important change in crop sequence composition, mainly due to the rapid expansion of soybean cropping on areas traditionally occupied with livestock or native grasslands (Baldi and Paruelo, 2008; Paruelo et al., 2006). This process has been encouraged by the adoption of no-tillage management, due to its operative simplicity and low costs (reduction in the use of fossil fuels), as well as by the advent of genetically modified soybean varieties, which have allowed simplifying weed control, and the favorable international soybean price (Satorre, 2005).

Because the change in the land use influences the chemical, physical and biological properties in the soil (Doran and Safley, 1997; Lal, 1993; Wilson and Paz-Ferreiro, 2012), the rapid expansion of cropped lands toward more environmentally fragile areas may have negative consequences on soil organic carbon (SOC) storage (Novelli et al., 2011; Studdert and Echeverría, 2000), aggregate stability (Novelli et al., 2011; Wright and Hons, 2004) and productivity of the crop sequence (Caviglia et al., 2011).

The intensification of cropped lands, defined as the increase in the intensity of the environmental resource use (Boserup, 1965; Caviglia and Andrade, 2010), including sequential double-crops (i.e. wheat/soybean or other winter crops/soybean) and crop–pasture rotation, is one of the feasible options to increase the efficiency and productivity of the systems mentioned (Caviglia et al., 2004).

Indexes that include the fraction of annual time with plant cover or the frequency of a particular crop in the cropping sequence may help to characterize systems with different intensities in the land use (Caviglia and Andrade, 2010; Farahani et al., 1998; Franzluebbers et al., 1994; Novelli et al., 2011). Accordingly, native grasslands or fields with

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[*] Corresponding author at: INTA EEA Paraná, Ruta 11, Km 12.5 (3100), Paraná, Argentina. Tel.: +54 343 4975200 237; fax: +54 343 4975200 275.
E-mail address: lnovelli@parana.inta.gov.ar (L.E. Novelli).

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crop–pasture rotation can be characterized by a high intensification index in the land use as compared to the sequences with high frequency of fallows, based on annual crops (Sasal et al., 2010).

It has been demonstrated that the intensification of cropped lands increases the input of crop residues returned to the soil (Caviglia et al., 2011; Shaver et al., 2003), improves SOC storage (Álvaro-Fuentes et al., 2009; Bowman et al., 1999; Luo et al., 2010; Peterson et al., 1998; Sherrod et al., 2003; Wood et al., 1990, 1991) and other soil physical properties such as effective porosity, bulk density, and the formation and stabilization of soil aggregates (Álvaro-Fuentes et al., 2008; Shaver et al., 2003), due to a more continuous activity of root and soil microorganisms than systems under frequent fallow (Álvaro-Fuentes et al., 2008; Franzluebbers et al., 1994).

Aggregate stability is a key issue for soil functioning and system productivity, due to its influence on soil porosity, root growth, and water and air movement, which directly affect crop yields (Kasper et al., 2009). In addition, the aggregation is an important process for SOC preservation and storage, because it plays an important role as a physical barrier between decomposers and SOC (Chung et al., 2009). However, the capacity of SOC protection in aggregates depends on the stability provided by the kind of aggregation agent involved (Oades, 1993; Six et al., 2000; Tisdall and Oades, 1982). In fact, it has been suggested that, in many soils, SOC is a major agent responsible for stabilizing aggregates (Tisdall and Oades, 1982), whereas in others, inorganic agents of aggregation such as clay, iron or aluminum oxides may drive this process (Denef et al., 2004; Fabrizzi et al., 2009; Novelli et al., 2011). Thus, the effect of land use on aggregate stability and SOC storage may be quite different in soils that differ in aggregation agents such as Mollisols and Vertisols, typical of many cropped lands of South America.

While the impact of intensification on SOC sequestration, soil physical properties or aggregate stability have been extensively reported for cropped lands (Álvaro-Fuentes et al., 2008; Bowman et al., 1999; Peterson et al., 1998; Wood et al., 1990, 1991), the relationship between aggregation and SOC sequestration in soils with different aggregation agents and intensity in the land use has been scarcely explored considering both cropped and uncropped lands (native grasslands).

Native grasslands have a high stability in the primary productivity which is a consequence of their biological and trophic complexity. Intensification may restore some complexity in cropped lands, being the comparison between different land uses, particularly useful because the clues for the improvement of agricultural systems may be found within native grasslands (Doré et al., 2011).

We hypothesized that the intensification in the land use has a more important role than the frequency of a given crop in the sequence on SOC storage and aggregate stability, and that the impact of intensification in the land use or the frequency of a given crop in the sequence on aggregate stability is more important in a Mollisol than in a Vertisol, due to the effect of clay type as an agent of soil aggregation.

The aim of our work was to assess the impact of the land use, measured as the intensification index and the frequency of a given crop, on SOC storage and aggregate stability of two soils differing in their main agents of aggregation.

2. Materials and methods

2.1. Study site and index calculation

The study was conducted in the Entre Ríos province in the Northeastern Pampas of Argentina, in two sites with different soil types. The region has a humid and temperate climate, with a mean annual rainfall of 1000 mm and a mean annual temperature of 18.3 °C. The Vertisol was located in Las Tunas (31°51′ S, 59°45′ W) and was classified as a fine, smectitic, thermic Typic Hapludert (Soil Survey Staff, 2010), with silty clay loam texture in the A1 horizon (0–19 cm) (41 g kg^{-1} sand, 609 g kg^{-1} silt and 350 g kg^{-1} clay) and silty clay texture in the B21t horizon (19–47 cm) (45 g kg^{-1} sand, 535 g kg^{-1} silt and 420 g kg^{-1} clay) (Plan Mapa de Suelos, 1998). The Mollisol was located close to the Experimental Station INTA Paraná (31°51′ S; 60°32′ W) and was classified as a fine, mixed, thermic Aquic Argiudoll (Soil Survey Staff, 2010), with silty clay loam texture in the Ap horizon (0–17 cm) (45 g kg^{-1} sand, 679 g kg^{-1} silt and 276 g kg^{-1} clay) and silty clay texture in the B21t horizon (17–34 cm) (39 g kg^{-1} sand, 546 g kg^{-1} silt and 415 g kg^{-1} clay) (Plan Mapa de Suelos, 1998). Despite some differences in soil texture, it should be noted that both soils fit in the same textural class within each horizon.

Eleven cropped fields (agricultural and crop–pasture rotation) under no-tillage and one uncropped situation were selected in each soil type (Table 1). The production fields were chosen taking into account that: i) they belonged to the same series and erosion phase, ii) they had been under a similar crop management and productivity, and iii) they had been under no-tillage for at least the previous ten years. For the uncropped situation in each soil, we selected pristine native grasslands close to the production fields. Information of the crop sequences was gathered from the farm record from a 6-year period (2002–2008) previous to the time of soil sampling, and different indexes (Table 2) were calculated: i) the intensification sequence index (ISI), based on the number of months with growing crops in relation to the total number of months (Sasal et al., 2010) in the previous 6 years; and ii) the frequency of a given crop, based on the number of months cropped with soybean (SCF, Novelli et al., 2011), wheat (WCF), or cereals (CCF), including maize, wheat or sorghum (*Sorghum bicolor* L. Moench) in relation to the total number of months with growing crops in the previous 6 years.

For the calculation of these indexes (Table 2), we used an annual average land use of 6 months for maize and wheat and of 5 months for soybean. In some cases, other crops, such as white sweet clover (*Melilotus albus* Medik), sorghum, or flax (*Linum usitatissimum* L.), were present within crop sequences (Table 1). For white sweet clover we used an annual average land use of 8 months, for sorghum of 5 months, and for flax of 5.5 months. For the native grassland and the period with alfalfa (*Medicago sativa* L.) in crop–pasture rotation, we used a land use of 12 months.

Table 1
Crop sequence for the 6 years preceding the soil sample for eleven cropped fields and one uncropped field, in pristine situation, in a Mollisol and a Vertisol from the Northeastern Pampas of Argentina.

Soil	Site	Year					
		2002–2003	2003–2004	2004–2005	2005–2006	2006–2007	2007–2008
Mollisol	1	Uncropped					
	2	W/Sb	W	P	P	P	P/Sb
	3	P/C	Sb	W/Sb	C	C	W/Sb
	4	W/Sb	C	W/Sb	C	W/Sb	C
	5	W/Sb	C	Sb	W/Sb	C	C
	6	C	Sb	W/Sb	C	W/Sb	C
	7	Sb	C	W/Sb	C	W/Sb	C
	8	C	Sb	W/Sb	C	Sb	W/Sb
	9	Sb	C	W/Sb	W/Sb	Sb	C
	10	W/Sb	Sb	W/Sb	C	Sb	W/Sb
	11	C	Sb	Sb	W/Sb	C	Sb
	12	Sb	Sb	W/Sb	Sb	W	F/Sb
Vertisol	13	Uncropped					
	14	P	P	P	P	P	W/Sb
	15	P	P	P	P	P/Sb	W/Sb
	16	W/Sb	C	WSC	Sb	W/Sb	C
	17	W/Sb	Sb	W/Sb	W/Sb	C	W/Sb
	18	C	Sb	W/Sb	W/Sb	C	W/Sb
	19	Sb	W/Sb	C	Sb	W/Sb	C
	20	P/Sb	W/Sb	Sb	W/Sb	C	W/Sb
	21	Sb	W/Sg	Sb	Sb	W/Sb	Sg
	22	W/Sb	W/Sb	Sb	W/Sb	C	Sb
	23	Sb	W/Sb	C	Sb	W/Sb	Sb
	24	W/Sb	Sb	W/Sb	Sb	C	Sb

C: corn; F: flax; WSC: white sweet clover; P: pasture; Sb: soybean; Sg: sorghum; W: wheat.

Table 2
Land uses and soil organic carbon stock in equivalent soil mass (C_{equiv}) for eleven cropped fields and one uncropped field, in pristine situation, in a Mollisol and a Vertisol from the Northeastern Pampas of Argentina.

Soil	Site	Indexes of land use				C_{equiv} (Mg ha^{-1})			
		ISI	SCF	WCF	CCF	0–5 cm	5–15 cm	0–15 cm	0–30 cm
Mollisol	1	1	0	0	0	29.6 ± 1.6[a]	28.4 ± 4.3	58.0 ± 4.9	92.8 ± 13.4
	2	0.88	0.16	0.19	0.19	16.1 ± 0.6	25.4 ± 1.1	41.5 ± 0.7	75.7 ± 1.5
	3	0.67	0.21	0.25	0.63	12.5 ± 0.7	23.9 ± 2.7	36.3 ± 3.0	63.5 ± 8.3
	4	0.71	0.30	0.35	0.70	15.1 ± 1.3	25.3 ± 1.7	40.4 ± 0.4	71.6 ± 3.1
	5	0.63	0.33	0.27	0.67	12.4 ± 0.5	22.3 ± 4.6	34.7 ± 5.0	64.9 ± 5.8
	6	0.63	0.33	0.27	0.67	14.5 ± 2.7	21.2 ± 0.6	34.3 ± 3.0	62.1 ± 3.7
	7	0.63	0.33	0.27	0.67	16.1 ± 1.2	27.4 ± 0.7	43.3 ± 2.9	73.6 ± 2.9
	8	0.61	0.46	0.28	0.54	10.7 ± 0.5	21.9 ± 2.3	32.7 ± 2.4	63.2 ± 5.5
	9	0.61	0.46	0.28	0.54	14.3 ± 0.5	27.6 ± 0.6	41.4 ± 0.4	72.5 ± 2.7
	10	0.68	0.51	0.37	0.49	10.4 ± 0.6	20.6 ± 0.7	30.5 ± 1.1	55.2 ± 1.0
	11	0.57	0.56	0.14	0.44	12.6 ± 0.4	21.9 ± 3.5	34.4 ± 3.8	64.5 ± 8.1
	12	0.62	0.61	0.27	0.27	11.5 ± 0.8	23.7 ± 0.8	35.3 ± 2.9	66.5 ± 4.5
	Mean					14.5	24.0	38.6	68.8
	SE[b]					0.8	0.6	1.3	1.7
Vertisol	13	1	0	0	0	29.7 ± 9.6	40.9 ± 7.9	70.6 ± 15.6	126.1 ± 18.0
	14	0.97	0.07	0.08	0.08	19.7 ± 0.7	25.7 ± 4.0	45.4 ± 3.6	84.7 ± 3.5
	15	0.96	0.15	0.08	0.08	17.1 ± 0.9	24.5 ± 5.4	41.5 ± 5.9	74.8 ± 7.0
	16	0.65	0.32	0.26	0.51	15.7 ± 2.3	21.3 ± 4.4	37.1 ± 4.0	59.8 ± 6.1
	17	0.76	0.37	0.43	0.55	16.2 ± 2.9	23.4 ± 7.2	39.6 ± 6.7	66.4 ± 13.5
	18	0.69	0.41	0.36	0.61	24.4 ± 3.0	26.9 ± 6.6	51.3 ± 8.1	82.5 ± 8.1
	19	0.61	0.46	0.28	0.54	14.8 ± 1.4	19.5 ± 2.1	34.3 ± 1.2	59.6 ± 5.2
	20	0.75	0.47	0.33	0.44	15.5 ± 1.4	19.5 ± 3.8	35.1 ± 4.4	57.3 ± 10.8
	21	0.58	0.48	0.29	0.53	18.2 ± 2.6	27.2 ± 5.1	45.3 ± 2.5	76.3 ± 4.5
	22	0.68	0.51	0.37	0.49	16.8 ± 2.6	23.2 ± 5.2	40.0 ± 6.2	68.8 ± 11.7
	23	0.60	0.58	0.28	0.55	15.7 ± 0.3	26.9 ± 4.8	42.7 ± 4.9	78.6 ± 7.3
	24	0.61	0.59	0.28	0.41	15.6 ± 1.7	26.0 ± 4.8	41.6 ± 4.3	79.2 ± 10.0
	Mean					18.3	25.4	43.7	76.2
	SE					0.9	1.2	1.8	3.2

ISI: intensification sequence index, SCF: soybean cropping frequency, WCF: wheat cropping frequency; CCF: cereal cropping frequency. Indexes were calculated using the fraction of annual time with plant cover in a 6-year period (2002–2008). C_{equiv} was calculated using the uncropped situation in each soil type as the baseline system.

[a] Standard deviation of the mean for each site (n = 3).

[b] SE: standard error of the mean (n = 36).

2.2. Soil sampling and analysis

Soil samples were collected between March and October 2008 after the summer crop harvest and before planting the next summer crop. The sampling sites within each field were on the same soil series and its erosion phase. Sampling areas with obvious erosion or deposition of soil were avoided.

In each field three replicates of soil samples were taken at 0–5, 5–15 and 15–30 cm depth, using a shovel. The replicates were separated by 50 m through a linear transect. Each sample was composite from ten subsamples taken within a circular area with a radius of 3 m.

Bulk density in each field was determined by the core method (height 3 cm, diameter 5.4 cm, volume 68.7 cm^3) (Forsythe, 1975) at 0–5, 5–15 and 15–30 cm depth in each sampling place.

Soil samples were passed through a 10-mm sieve, roots removed, air-dried and stored at room temperature until analysis. An aliquot of each sample was used to aggregate stability, whereas another aliquot was dry sieved by 2 mm and then milled to 0.5 mm to measure C by dry combustion using a LECO autoanalyzer, model TRU SPEC (Leco Corp., St. Joseph, MI, USA). Since there was no carbonate in the samples, the measured C concentration was assumed equivalent to SOC concentration.

Because the uncropped situation (native grassland) had a lower bulk density than the cropped lands, we calculated the SOC stock at each depth and at 0–15 cm and 0–30 cm, in equivalent soil mass (Lee et al., 2009), using the uncropped situation in each soil type as the baseline system. For that, the following equations were used:

$$C_{equiv(0-5cm)} = \left(M_{i(0-5cm)} - M_{i,add(0-5cm)}\right) * \%C_{(0-5cm)} \qquad (1)$$

$$C_{equiv(5-15cm)} = \left(M_{i,add(0-5cm)} * \%C_{(0-5cm)}\right) + \left(\left(M_{i(5-15cm)} - M_{i,add(5-15cm)}\right) * \%C_{(5-15cm)}\right) \qquad (2)$$

$$C_{equiv(15-30cm)} = \left(M_{i,add(5-15cm)} * \%C_{(5-15cm)}\right) + \left(\left(M_{i(15-30cm)} - M_{i,add(0-30cm)}\right) * \%C_{(15-30cm)}\right) \qquad (3)$$

$$C_{equiv(0-15cm)} = (1) + (2)$$

$$C_{equiv(0-30cm)} = (1) + (2) + (3)$$

where C_{equiv} is the equivalent C mass (Mg ha^{-1}), M_i is the dry soil mass (Mg ha^{-1}) for each layer obtained by the product of thickness of the soil layer (m), bulk density (Mg m^{-3}) and a factor conversion 10^4 (m^2 ha^{-1}), and $M_{i,add}$ is the difference between M_i and mass in the baseline system.

The stratification ratio of SOC stock was calculated as the ratio between $C_{equiv0\text{-}5cm}$ and $C_{equiv5\text{-}15cm}$ based on stock in equivalent soil mass from the uncropped situation in each soil type as the baseline system.

In the samples from 0 to 5 and 5 to 15 cm depth, dry aggregates < 10 mm were sieved and separated in six size classes (> 5 mm, 3 to 5 mm, 2 to 3 mm, 1 to 2 mm, 0.2 to 1 mm and < 0.2 mm) with vibration equipment for 5 min. Soil aggregates between 3 and 5 mm, dried at 40 °C for 24 h were used to determine the soil aggregate stability by the method of Le Bissonnais (1996). This method involves three pretreatments (fast wetting, stirring after prewetting and slow wetting), which allow distinguishing three breakdown mechanisms: slaking, mechanical breakdown and microcracking (Cosentino et al., 2006; Le Bissonnais, 1996). We used 10 g of 3 to 5 cm aggregates for each pretreatment. In fast wetting, the aggregates were immersed in deionized water for 10 min; in the stirring after prewetting, the soil aggregates were saturated in ethanol for 30 min, stirring in deionized water in an Erlenmeyer flask and turned end over end 10 times; and in the slow wetting, the soil aggregates were capillary rewetted with deionized water for 60 min. All aggregates were sieved in ethanol at 50 µm, oven-dried at 40 °C for 48 h, and dry-sieved by hand with a nest of six sieves (2000 µm, 1000 µm, 500 µm, 200 µm, 100 µm and 50 µm). The sum of the mass fraction remaining on each sieve after sieving, multiplied by the mean aperture of the adjacent sieves was used to calculate the mean weight diameter (MWD) of the soil aggregates for each pretreatment (MWD_{fw}: fast wetting; MDW_{st}: stirring after prewetting; MDW_{sw}: slow wetting). In addition, the means of the three pre-treatments were calculated (MWD_{mean}).

2.3. Statistical analysis

Correlations and regressions between land use indexes, SOC concentration and stocks, and aggregate stability were performed considering all land uses and lands under crop use in order to study the relationships between variables using INFOSTAT software (Di Rienzo et al., 2011).

We performed a *t*-test to detect differences between soils and uncropped vs. cropped situation in each soil using INFOSTAT software (Di Rienzo et al., 2011).

3. Results

3.1. Soil organic carbon (SOC) stock

The values of SOC stock between soils were similar on the surface in the uncropped situation (sites 1 and 13) ($C_{equiv0\text{-}5cm}$, c.a. 30 Mg ha^{-1}). However, in depth, the SOC stock in the uncropped situation ($C_{equiv5\text{-}15cm}$, $C_{equiv0\text{-}15cm}$ and $C_{equiv0\text{-}30cm}$) was 44, 22 and 36% higher in the Vertisol than in the Mollisol (Table 2). In both soils, the SOC stock ($C_{equiv0\text{-}30cm}$) in uncropped lands was different from that in cropped ones (Mollisol: $P<0.01$; Vertisol: $P<0.001$) (Table 2).

In cropped lands, $C_{equiv0\text{-}5cm}$ and $C_{equiv0\text{-}30cm}$ ranged from 10.4 to 16.1 Mg ha^{-1} and from 55.2 to75.7 Mg ha^{-1}, respectively, in the Mollisol, whereas in the Vertisol $C_{equiv0\text{-}5cm}$ and $C_{equiv0\text{-}30cm}$ ranged from 14.8 to 24.4 Mg ha^{-1} and from 57.3 to 84.7, respectively (Table 2). Pooling all the data for each soil type and depth considered, the Vertisol had on average a SOC stock higher than the Mollisol ($C_{equiv0\text{-}5cm}$: 26%; $C_{equiv5\text{-}15cm}$: 6%; $C_{equiv0\text{-}15cm}$: 13%; $_{Cequiv0\text{-}30cm}$: 11%) (Table 2).

In the Vertisol, pooling all the data, the stratification ratio ($C_{equiv0\text{-}5cm}/C_{equiv5\text{-}15cm}$) was slightly, but significantly higher ($P<0.05$) than in the Mollisol (Fig. 1) due to the high $C_{equiv0\text{-}5cm}$ in cropped lands in the Vertisol (Table 2). On average, the stratification ratio ($C_{equiv0\text{-}5cm}/C_{equiv5\text{-}15cm}$) in the cropped lands of the Vertisol was 0.75, whereas in the cropped lands of the Mollisol it was 0.56 (Fig. 1). However, in the uncropped situation, the stratification ratio was higher in the Mollisol than in the Vertisol (1.06 vs. 0.73, respectively) (Fig. 1).

The SOC stock ($C_{equiv0\text{-}5cm}$, $C_{equiv0\text{-}15cm}$ and $C_{equiv15\text{-}30cm}$) in the Mollisol was positively related to the ISI ($P<0.01$), but SOC stocks were unrelated by ISI in the Vertisol (Table 3). On the other hand, the SOC stock, mainly $C_{equiv0\text{-}5cm}$, was negatively related to the soybean (SCF), wheat (WCF), and wheat plus maize cropping frequency (CCF) only in the Mollisol (Table 3). However, these relationships were driven more by the difference between cropped vs. uncropped lands than by sequence composition. Moreover, within the cropped lands there were no evident differences in SOC stocks in either of the soils or at any of the depths studied (not shown). Although the impact of land use on SOC stock was less evident in the Vertisol, in both soils the lower values of SOC stock were recorded at sites with a low intensification sequence index (ISI) and a high soybean cropping frequency (SCF) (Table 2).

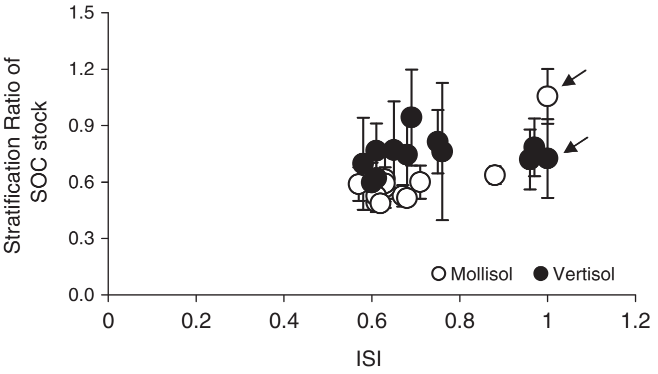

Fig. 1. Stratification ratio of soil organic carbon (SOC) stocks ($C_{equiv0\text{-}5cm}/C_{equiv5\text{-}15cm}$) as affected by the intensification sequence index (ISI). C_{equiv} was calculated using the uncropped situation in each soil type as the baseline system. The open circles represent the Mollisol. The solid circles represent the Vertisol soil. The vertical bars represent the standard deviation of each mean (n = 3). The arrows indicate the uncropped situation in each soil type. Mollisol: linear model ($y = 1.00$ ISI $- 0.08$; $R^2 = 0.69$, $P<0.001$). Vertisol: linear model ($y = 0.11$ ISI $+ 0.66$; $R^2 = 0.04$, $P =$ NS).

3.2. Aggregate stability

The mean weight diameters (MWDs) were different between the pretreatment and the soils (Table 4). Pooling all the data for each soil, we found that the MWD_{fw} and MWD_{sw} were 72 and 28% greater in the Vertisol than in the Mollisol. In contrast, the MWD_{st} was greater in the Mollisol (16%) (Table 4).

In both soils, the MWDs for the different pretreatments were higher at 0–5 cm depth than at 5–15 cm ($P<0.001$), except in the pretreatment stirring after prewetting in the Mollisol, in which the MWD_{st} was higher in 5–15 cm than in 0–5 cm ($P<0.001$) (Table 4). The MWD_{mean} ranged between 0.80 mm and 2.01 mm at 0–5 cm depth of the Mollisol, whereas it ranged between 1.40 mm and 2.21 mm in the Vertisol (not shown). At 5–15 cm depth of both soils, the MWD_{mean} showed a similar range (0.86 mm to 1.87 mm in the Mollisol; 0.83 mm to 1.96 mm in the Vertisol) (not shown).

In the Mollisol, the highest MWD was recorded with the stirring after prewetting pretreatment, whereas the lowest values of MWD were recorded with the fast wetting, the most aggressive pretreatment. In this soil, the site that included a pasture in the rotation (site 2)

Table 3
Correlation coefficients (r) from the relationships between land use indexes and SOC stocks in equivalent mass (C_{equiv}), for eleven cropped fields and one uncropped field, in pristine situation, in a Mollisol and a Vertisol from the Northeastern Pampas of Argentina.

Soil	Variables	ISI	SCF	WCF	CCF
Mollisol	$C_{equiv0\text{-}5cm}$	0.83***	−0.77**	−0.78**	−0.61*
	$C_{equiv5\text{-}15cm}$	0.53 NS	−0.55 NS	−0.44 NS	−0.36 NS
	$C_{equiv0\text{-}15cm}$	0.78**	−0.74**	−0.71**	−0.57 NS
	$C_{equiv0\text{-}30cm}$	0.77**	−0.70*	−0.73**	−0.62*
Vertisol	$C_{equiv0\text{-}5cm}$	0.55 NS	−0.62*	−0.51 NS	−0.48 NS
	$C_{equiv5\text{-}15cm}$	0.46 NS	−0.51 NS	−0.59*	−0.54 NS
	$C_{equiv0\text{-}15cm}$	0.52 NS	−0.58*	−0.58 NS	−0.53 NS
	$C_{equiv0\text{-}30cm}$	0.56 NS	−0.58*	−0.67*	−0.63*

NS indicates not significant. ISI = intensification sequence index, SCF = soybean cropping frequency, WCF = wheat cropping frequency; CCF = cereal cropping frequency. Indexes were calculated using the fraction of annual time with plant cover in a 6-year period (2002–2008). C_{equiv} was calculated using the uncropped situation in each soil type as the baseline system.

* $P<0.05$.
** $P<0.01$.
*** $P<0.001$.

Table 4
Mean weight diameters (MWDs) after the water stability test at 0–5 and 5–15 cm depths for eleven cropped fields and one uncropped field, in pristine situation, in a Mollisol and a Vertisol from the Northeastern Pampas of Argentina.

Soil	Site	0–5 cm			5–15 cm		
		MWD_{fw}	MWD_{st}	MWD_{sw}	MWD_{fw}	MWD_{st}	MWD_{sw}
		mm					
Mollisol	1	1.23 ± 0.19[a]	2.93 ± 0.08	1.87 ± 0.12	0.90 ± 0.00	2.95 ± 0.08	1.57 ± 0.01
	2	1.33 ± 0.22	2.61 ± 0.09	1.92 ± 0.27	1.11 ± 0.23	2.71 ± 0.09	1.79 ± 0.37
	3	0.79 ± 0.34	2.23 ± 0.12	1.19 ± 0.38	0.46 ± 0.08	1.98 ± 0.16	0.72 ± 0.05
	4	0.45 ± 0.07	2.05 ± 0.38	0.77 ± 0.16	0.45 ± 0.01	2.58 ± 0.13	0.71 ± 0.06
	5	0.62 ± 0.06	1.92 ± 0.25	0.99 ± 0.07	0.41 ± 0.05	2.34 ± 0.06	0.64 ± 0.03
	6	0.50 ± 0.11	1.78 ± 0.12	0.84 ± 0.18	0.43 ± 0.10	2.01 ± 0.19	0.60 ± 0.10
	7	0.88 ± 0.30	2.49 ± 0.12	1.56 ± 0.49	0.55 ± 0.30	2.71 ± 0.12	1.03 ± 0.49
	8	0.47 ± 0.12	1.29 ± 0.15	0.70 ± 0.15	0.38 ± 0.02	1.84 ± 0.09	0.50 ± 0.03
	9	0.69 ± 0.22	2.39 ± 0.23	1.08 ± 0.24	0.49 ± 0.04	2.71 ± 0.05	0.71 ± 0.10
	10	0.46 ± 0.11	1.33 ± 0.15	0.75 ± 0.25	0.40 ± 0.08	1.64 ± 0.30	0.54 ± 0.12
	11	0.44 ± 0.05	1.54 ± 0.11	0.73 ± 0.13	0.49 ± 0.05	2.22 ± 0.27	0.69 ± 0.10
	12	0.41 ± 0.03	1.25 ± 0.03	0.74 ± 0.07	0.35 ± 0.01	1.90 ± 0.19	0.52 ± 0.03
	Mean	0.69	1.98	1.10	0.53	2.30	0.83
	SE[b]	0.06	0.09	0.08	0.04	0.07	0.07
Vertisol	13	1.81 ± 0.65	2.62 ± 0.42	2.19 ± 0.78	1.59 ± 0.57	2.36 ± 0.57	1.93 ± 0.63
	14	1.15 ± 0.53	1.80 ± 0.52	1.36 ± 0.63	0.84 ± 0.34	1.42 ± 0.42	1.09 ± 0.36
	15	1.18 ± 0.14	1.67 ± 0.21	1.51 ± 0.20	0.60 ± 0.11	1.15 ± 0.37	0.74 ± 0.24
	16	1.20 ± 0.19	2.00 ± 0.32	1.53 ± 0.17	0.85 ± 0.13	1.72 ± 0.42	0.90 ± 0.11
	17	1.03 ± 0.08	1.78 ± 0.22	1.39 ± 0.22	0.80 ± 0.26	1.73 ± 0.70	0.91 ± 0.33
	18	1.43 ± 0.22	2.24 ± 0.02	1.78 ± 0.12	1.25 ± 0.47	1.97 ± 0.61	1.06 ± 0.15
	19	1.19 ± 0.21	2.06 ± 0.23	1.39 ± 0.26	0.85 ± 0.19	1.60 ± 0.31	0.81 ± 0.10
	20	1.19 ± 0.49	2.03 ± 0.56	1.37 ± 0.41	0.75 ± 0.24	1.38 ± 0.49	0.93 ± 0.20
	21	1.17 ± 0.05	1.86 ± 0.21	1.21 ± 0.20	0.79 ± 0.17	1.60 ± 0.50	0.91 ± 0.20
	22	1.16 ± 0.29	1.87 ± 0.41	1.32 ± 0.34	0.80 ± 0.18	1.65 ± 0.50	0.88 ± 0.15
	23	1.20 ± 0.48	1.96 ± 0.59	1.41 ± 0.52	0.75 ± 0.19	1.38 ± 0.26	0.84 ± 0.16
	24	1.14 ± 0.04	1.94 ± 0.01	1.61 ± 0.24	0.58 ± 0.11	1.43 ± 0.28	0.70 ± 0.07
	Mean	1.24	1.99	1.50	0.87	1.62	0.97
	SE	0.06	0.06	0.07	0.06	0.08	0.06

MWD_{fw}, MWD_{st} and MWD_{sw} are the mean weight diameters from the fast wetting, stirring after prewetting and slow wetting pretreatments respectively.

[a] Standard deviation of the mean for each site (n = 3).

[b] SE = standard error of the mean for each soil and depth (n = 36).

Table 5
Correlation coefficients (r) from the relationships between intensification indexes, SOC stocks in equivalent mass (C_{equiv}) and the aggregate stability test at 0–5 and 5–15 cm depths for eleven cropped fields and one uncropped field, in pristine situation, in a Mollisol and a Vertisol from the Northeastern Pampas of Argentina.

Soil	Depth	Indexes	Mean weight diameters (MWD)			
			Fast wetting	Stirring after prewetting	Slow wetting	Means
Mollisol	0–5 cm	ISI	0.81^{**}	0.68^{*}	0.78^{**}	0.77^{**}
		SCF	-0.81^{**}	-0.84^{***}	-0.80^{**}	-0.84^{***}
		WCF	-0.62^{*}	−0.52 NS	-0.61^{*}	-0.59^{*}
		CCF	−0.57 NS	−0.28 NS	−0.53 NS	−0.45 NS
		C_{equiv}	0.70^{*}	0.76^{**}	0.73^{**}	0.76^{**}
	5–15 cm	ISI	0.84^{***}	0.56 NS	0.86^{***}	0.80^{**}
		SCF	-0.71^{**}	-0.61^{*}	-0.76^{**}	-0.75^{**}
		WCF	-0.64^{*}	−0.51 NS	-0.66^{*}	-0.65^{*}
		CCF	-0.68^{*}	−0.30 NS	-0.66^{*}	−0.56 NS
		C_{equiv}	0.55 NS	0.88^{***}	0.64^{*}	0.77^{**}
Vertisol	0–5 cm	ISI	0.42 NS	0.15 NS	0.45 NS	0.35 NS
		SCF	−0.51 NS	−0.25 NS	−0.50 NS	−0.44 NS
		WCF	−0.54 NS	−0.27 NS	−0.49 NS	−0.45 NS
		CCF	−0.44 NS	−0.15 NS	−0.44 NS	−0.36 NS
		C_{equiv}	0.91^{***}	0.76^{**}	0.82^{**}	0.86^{***}
	5–15 cm	ISI	0.37 NS	0.15 NS	0.58^{*}	0.38 NS
		SCF	−0.50 NS	−0.32 NS	-0.66^{*}	−0.52 NS
		WCF	−0.33 NS	−0.09 NS	−0.55 NS	−0.34 NS
		CCF	−0.26 NS	−0.04 NS	−0.54 NS	−0.29 NS
		C_{equiv}	0.74^{**}	0.65^{*}	0.84^{***}	0.77^{**}

NS, indicates not significant. MWD = mean weight diameters, ISI = intensification sequence index, SCF = soybean cropping frequency, WCF = wheat cropping frequency; CCF = cereal cropping frequency. Indexes were calculated using the fraction of annual time with plant cover in a 6-year period (2002–2008). C_{equiv} was calculated using the native grassland in each soil type as the baseline system.

* $P<0.05$.

** $P<0.01$.

*** $P<0.001$.

(Table 1), had a MWD as high as that in the uncropped land. Similar to that observed in the Mollisol, the stirring after prewetting pretreatment had the highest values as compared to the other pretreatments in the Vertisol (Table 4). In both soils, the MWD decreased sequentially as follows: stirring after prewetting > slow wetting > fast wetting (Table 4).

The MWDs in the Mollisol at the two depths were consistently related to the ISI, mainly with the fast and slow wetting pretreatments (Table 5). However, in the Vertisol, the aggregate stability was not related to the ISI for any pretreatment or depth, except for the slow wetting pretreatment at 5–15 cm (Table 5).

In the Mollisol, the maximum values of MWDs were found with SOC concentration values of c.a. 30 and 20 g C kg^{-1}, at 0–5 cm and 5–15 cm depths, respectively (Fig. 2). In the Vertisol, the maximum values of MWDs, coincident with the uncropped situation, were found with SOC concentration values of 50 and 40 g C kg^{-1} at 0–5 and 5–15 cm depths, respectively (Fig. 2a and b). In the Vertisol, aggregate stability did not increase in the range of 25 to 35 g C kg^{-1} for SOC concentration, which included all cropped lands (Fig. 2a and b). In contrast, considering both depths in the Mollisol, the MWD was closely and positively related to SOC concentration up to 30 g C kg^{-1}(Fig. 2a and b), mainly in the stirring after prewetting pretreatment (not shown).

The relationships between the frequency of a given crop and aggregate stability were more evident in the Mollisol, mainly with the fast and slow wetting pretreatments (Table 5). The SCF was the most closely, although negatively, related to the aggregate stability in the Mollisol. In the Vertisol, in contrast, the SCF was associated only with the slow wetting pretreatment at 5–15 cm (Table 5).

Considering the cropped lands, except the crop–pasture rotation, we found no relationship between the aggregate stability for any pretreatment and depth and the ISI or frequency of a given crop in the Mollisol. In the Vertisol, there was only a weak, negative ($P<0.05$), relationship between CCF and MWD_{fw} and MWD_{st} at 5–15 cm (not shown). These results reflect the strong influence of the uncropped land or crop–pasture rotation on the pooled data.

4. Discussion

Overall, both the intensification sequence index and the soybean cropping frequency were the best indexes to evaluate the impact of land use on aggregate stability and SOC storage, mainly in the Mollisol (Tables 2, 3 and 5).

The close positive relationship between SOC stock and ISI in the Mollisol (Table 3) and the high values of SOC stock at 0–5 cm recorded in lands under crop–pasture rotation and in uncropped lands (Table 2) may be related to the more continuous roots and microorganism activity typical of lands with a high plant cover during long periods. A higher intensity in the use of environmental resources, i.e. solar radiation and rainfall, typical of lands characterized here with a high ISI (Caviglia and Andrade, 2010) may increase the total amount of plant residues returned to the soil (Caviglia et al., 2011). In turn, a more frequent return of residues in lands with high ISI may add organic aggregation agents, particularly temporary and transient types (Tisdall and Oades, 1982), which may contribute to increasing the aggregate stability (Álvaro-Fuentes et al., 2009) and consequently SOC storage (Peterson, et al., 1998; Shaver et al., 2003; Sherrod et al., 2003; Wood et al., 1990, 1991).

It has been suggested that an increase in cropping intensity may increase the stratification ratio (Franzluebbers, 2002), which has been mentioned as a good soil quality index because surface SOC is essential to erosion control, water infiltration and other soil properties (Franzluebbers, 2002). Although the values of stratification ratio were higher in the Vertisol than in the Mollisol, the stratification ratio was related by ISI only in the Mollisol (Fig. 1). The ability to self-structure, typical of the Vertisol, may have minimized the potential impact of intensification on this soil. In accordance, Fabrizzi et al. (2009) have suggested that the self-mixing of the shrink–swell clays may minimize the stratification usually reported under no-till systems, due to a facilitation of a downward movement of SOC.

Our results provided evidence that land use intensity and cropping sequence had an important impact on SOC stock and its stratification, which are dependent on soil type. These results, not previously reported, may provide advice and help to design sustainable cropping systems in our agricultural area, which is under a dramatic simplification process based on a high frequency of soybean as sole crop in the sequences (Caviglia et al., 2011).

The aggregate stability showed a differential behavior between soil types and pretreatments used (Table 4). In both soils, the lowest values of MWD were found with the fast wetting pretreatment, whereas the highest ones were found with stirring after prewetting pretreatment. These results are in agreement with previous reports (Chenu et al., 2000; Gabioud et al., 2011; Le Bissonnais and Arrouays, 1997). In addition, the maximum values of MWDs found in the present work in the Mollisol are comparable to those reported for loamy soils (Le Bissonnais and Arrouays, 1997).

Although the three pretreatments generally gave a similar MWD, the high aggressiveness of the fast wetting pretreatment makes it a less sensitive indicator to assess the impact of land use on fragile soils (Le Bissonnais, 1996). The slow wetting pretreatment seems to be a better indicator to evaluate clay soils, because microcracking by differential swelling increases with the clay content (Le Bissonnais, 1996). Accordingly, in the Vertisol, only the slow wetting pretreatment allowed detecting changes by ISI and SCF (Table 5).

The stirring after prewetting pretreatment of aggregate stability in the Mollisol was more strongly related to SOC than the fast and slow wetting pretreatments (Table 4). These results and the fact that stirring after prewetting pretreatment evaluates the wet cohesion between soil particles (Cosentino et al., 2006; Le Bissonnais, 1996; Robert and Chenu, 1992) suggest that this pretreatment may be the more appropriate method to evaluate the impact of land use on soils such as Mollisols, in which SOC is the main aggregation agent.

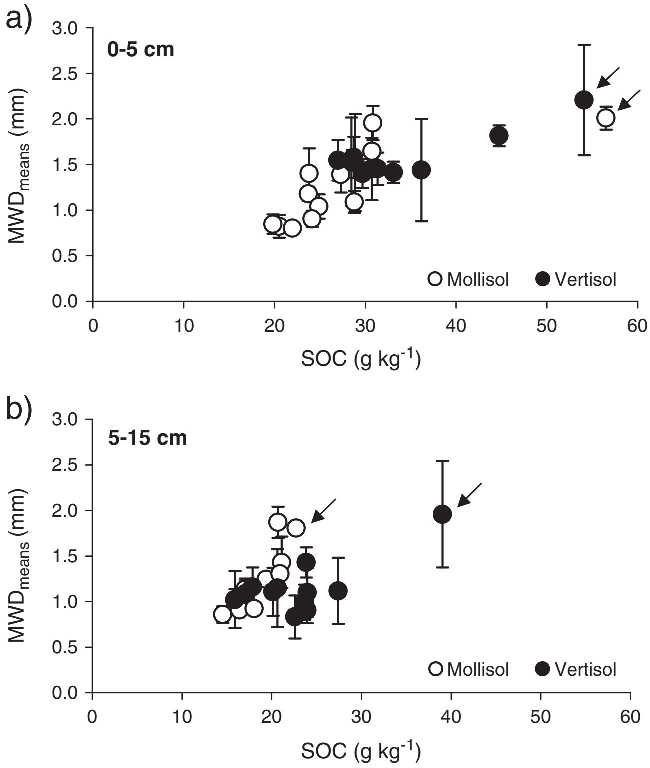

Fig. 2. Mean weight diameter means of three pretreatments (MWD$_{means}$) as affected by soil organic carbon (SOC) concentration, a) at 0–5 cm depth; and b) at 5–15 cm depth. The open circles represent the Mollisol soil. The solid circles represent the Vertisol. The vertical bars represent the standard deviation of each mean (n = 3). The arrows indicate the uncropped situation in each soil type. Mollisol 0–5 cm ($R^2 = 0.59$, $P<0.01$). Mollisol 5–15 cm ($R^2 = 0.74$, $P<0.001$). Vertisol 0–5 cm ($R^2 = 0.74$, $P<0.001$). Vertisol 5–15 cm ($R^2 = 0.52$, $P<0.01$).

We detected a close and positive relationship between ISI and MWDs, although only in the Mollisol at both depths (Table 5). In addition, the high frequency of soybean (SCF), which adds low residue input with high degradability, was negatively associated with MWDs in the Mollisol in comparison with the Vertisol (Table 5).

As we previously suggested, the contrasting difference between the Mollisol and the Vertisol in the relationship between SOC concentration and MWDs (Fig. 2) may be related to the aggregation agents involved in each soil. In fact, the stability of soil aggregates may be driven by other aggregation agents different from SOC, such as clay or iron and aluminum oxides (Fabrizzi et al., 2009; Novelli et al., 2011).

In our work, SOC concentration seems to be an important aggregation agent in the Mollisol up to 30 g C kg^{-1}, without further relevant increases in MWD at higher values. In contrast, SOC concentration appears as an important aggregation agent in the Vertisol with values higher than 35 g C kg^{-1}, but becomes irrelevant at values below that, where clay type may be involved in the apparent higher soil resistance to the land use reported in this soil (Cerana et al., 2006; Fabrizzi et al., 2009).

Although Vertisol showed higher SOC concentration and stock (Fig. 2 and Table 2) than the Mollisol, the poor response of SOC on soil aggregation in cropped land suggests that SOC is not the main aggregation agent in Vertisol. In addition, it has been suggested that the smectitic clays are more efficient than other clays in providing stability to aggregation due to their high specific area (Paz Ferreiro et al., 2009) and high cation exchange capacity, which increase the physical–chemical interaction (Amezketa, 1999).

The role of smectitic clays on the protection of SOC, although still unclear, has been a frequent explanation of higher SOC concentration in the Vertisol than in the Mollisol (e.g. Fabrizzi et al., 2009; Stephan et al., 1983).

Previous reports suggested that the SOC concentration is not important *per se* for the structural development in Vertisols, whereas the labile fractions may have a positive influence (Bravo-Garza and Bryan, 2005; McGarry, 1996). Our results are valuable by showing that the SOC concentration and MWD were highest in sites with high ISI and low SCF (uncropped and crop–pasture rotation), but negligible changes in MWDs were detected in cropped land (Fig. 2). Accordingly, Chan (1997) reported an important reduction in labile fractions of SOC in the transition from native grassland to cropped lands. Thus, labile fractions of SOC could play an important role in the aggregate stability of the Vertisol when values of SOC concentration are higher than 35 g C kg^{-1} (Fig. 2).

The finding of a level of SOC concentration as a possible threshold, for above or below MWDs which remain fairly stable, for the Mollisol and the Vertisol respectively, has not been previously suggested. This finding is useful to acknowledge the differential role of SOC concentration on soil aggregation of each soil and may provide valuable information to develop soil quality index to predict early trends in soil properties.

The approach used in the present study to evaluate the land use, which included cropped (crop–pasture rotation and agricultural lands) and uncropped lands (native grasslands) evaluated through indexes of occupation with plant cover, was more suitable for the Mollisol than for the Vertisol. This reveals that the evaluation of land use through several indexes should be based on the soil type.

5. Conclusions

The improved SOC stock and aggregate stability in the Mollisol was related to the intensification index. In contrast, in the Vertisol, the impact of land use on aggregate stability and SOC was irrelevant.

The stirring after prewetting pretreatment was mainly associated with SOC concentration in the Mollisol, appearing as a method with high potential capacity to discriminate land use in soils where the SOC is a main aggregation agent. In contrast, the slow wetting pretreatment was more appropriate to evaluate the impact of land use in the Vertisol.

Overall, both the ISI and SCF were the best indexes to evaluate the impact of land use on aggregate stability and SOC storage, mainly in the Mollisol.

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