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Resilience of humification process to evaluate soil recovery in a semiarid agroecosystem of Central Argentina

Resiliencia del proceso de humificación para evaluar la recuperación edáfica en un agroecosistema semiárido del centro de Argentina

Resiliência do processo de humificação para avaliar a recuperação do solo num agroecossistema semi-árido da região central da Argentina

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ABSTRACT

Resilience has become a key concept in agricultural management for sustaining soil quality and preventing soil degradation. Land use is a factor that affects soil organic matter (SOM) concentration, distribution and dynamics. In consequence, several recovery practices have been proposed in order to maintain or enhance SOM contents in agroecosystems, such as zero soil disruption (no-till), farm enclosures and crop rotation. We evaluated the efficiency of recovery practices (after a 5-yr period) in reversing SOM losses in a Typic Haplustoll of the central semiarid region of Argentina. A comparative assessment of the resilience of SOM synthesis (humification process) was performed between the recently adopted restorative management and traditional systems (45 years of plow-tillage) using a native woodland as a baseline. In soil samples (0-20 cm), total SOM, its fractions (non-humic substances, humic substances, humic acids, and fulvic acids), and structure (humification index and polymerization index) were analyzed. Degradation rates, recovery rates and soil resilience classes were calculated. Results showed that in our semiarid environment, plowing has significantly affected the resilience of the humification parameters by high degradation rates, whereas the adoption of recovery practices did not reverse ongoing degradative processes. All the analyzed land uses were included in the same resilience class, suggesting that soils have established a new equilibrium (at low values) with high resistance in front of short-term changes. However, a small tendency of minor degradation rates in the farm enclosure site may indicate the beginning of recovery processes.

RESUMEN

La resiliencia se ha convertido en un concepto clave en el manejo agrícola para mantener la calidad del suelo y prevenir procesos de degradación. Debido a que el uso de la tierra afecta el contenido, distribución y dinámica de la materia orgánica (SOM), diversas prácticas de recuperación como siembra directa, clausuras agrícolas y rotaciones de cultivos han sido propuestas para preservar o elevar el contenido de SOM en agroecosistemas. Nosotros evaluamos la eficiencia de prácticas de recuperación (tras un periodo de 5 años) para revertir las pérdidas de SOM en un Haplustol Típico de la región semiárida central de Argentina. Se realizó una evaluación comparativa entre el recientemente adoptado manejo de recuperación y 45 años de prácticas convencionales (labranza convencional). Un suelo de un bosque nativo fue utilizado como referencia. En las muestras de suelo (0-20 cm) se determinó el contenido total de SOM, sus fracciones (sustancias no húmicas, sustancias húmicas, ácidos húmicos y ácidos fúlvicos) y estructura (índice de humificación e índice de polimerización). Se calcularon tasas de degradación y recuperación y clases de resiliencia. Los resultados mostraron que en nuestro ambiente semiárido, sistemas bajo labranza convencional han afectado de manera significativa la resiliencia del proceso de humificación con altas tasas de degradación, mientras que la adopción de prácticas de recuperación no revirtió el curso del proceso de degradación de la SOM. La totalidad

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de las situaciones analizadas quedó incluida en una misma clase de resiliencia, lo que sugiere el establecimiento de nuevo equilibrio (a valores inferiores) con alta resistencia frente a cambios a corto plazo. Sin embargo, una tendencia a menores tasas de degradación en la clausura agrícola podría indicar el comienzo de procesos de recuperación.

RESUMO

A resiliência tornou-se um conceito-chave na gestão agrícola para garantir a qualidade do solo e evitar processos de degradação. Os efeitos do uso da terra afectam o teor, distribuição e dinâmica da matéria orgânica do solo (MOS); em conseqüência, práticas de recuperação como plantio direto, pousio e rotação de culturas têm sido propostas para manter ou melhorar os teores da MOS. Neste estudo avaliamos a eficiência de práticas de recuperação (após 5 anos) para reverter as perdas da MOS num solo Haplustol Típico na região semi-árida central da Argentina. A avaliação comparativa foi realizada entre a recentemente adoptada gestão agrícola e 45 anos de práticas convencionais. Em amostras de solo (0-20 cm) analisou-se o teor total de MOS, suas frações (substâncias não humificadas, substâncias húmicas, ácidos húmicos e fúlvicos) e estrutura (índice de humificação e índice de polimerização). Calcularam-se igualmente ss taxas de degradação, taxas de recuperação e classe de resiliência. Os resultados mostraram que em ambiente semi- árido, os sistemas convencionais têm afetado de forma significativa a capacidade de resiliência do processo de humificação com altas taxas de degradação, enquanto que a adoção do práticas de recuperação não reverteu o curso da degradação da SOM. Todos os usos do solo analisados foram incluídos na mesma classe de resiliencia, o que sugere o estabelecimento de um novo equilíbrio (com valores baixos) com alta resistência de mudanças a curto prazo. No entanto, uma pequena tendência de menores taxas de degradação em pousio pode indicar o início dos processos de recuperação.

KEY WORDS
Humic substances, farm enclosure, no-till cropping systems, degradation rate

PALABRAS CLAVE
Sustancias húmicas, clausura agrícola, siembra directa, tasa de degradación

PALAVRAS-CHAVE
Substâncias húmicas, pousio, plantio direto, taxa de degradação

1. Introduction

Soil is a dynamic and living entity used to produce goods and services of value to humans but not necessarily with a perpetual ability to withstand degradative processes (Tenywa et al. 2001). Land use is one of the human interventions that induce substantial changes on soil quality maintenance, frequently leading to soil degradation especially in sub-humid, semiarid, and arid environments (Lal 1997; Lal and Stewart 2013).

The magnitude and direction of a degradative process relies on the degree of soil resilience. According to Seybold et al. (1999), soil resilience can be defined as the ability of soils to return to original stages after a disturbance. Since soil resilience relies on geomorphological and climatic conditions, there is no general pattern to predict this edaphic property and results may vary according site-specific conditions (Beeby 1995; Seybold et al. 1999), relationships between ecological processes, and soil dynamic properties (Tugel et al. 2005).

Soil resilience is expressed by means of two properties: the rate of recovery and the degree of recovery, which together represent the time demanded by a soil to recover pre-disturbance conditions and the magnitude of recovery reached (Seybold et al. 1999). Much of the interest in resilience and sustainable soil management comes from first world organic agriculture in addition to a more recent focus on poor developing world farmers (Walker et al. 2010). There is abundant research addressing such topics, mainly from a theoretical perspective (Tugel et al. 2005; Folke 2006; Walker et al. 2010; Tenywa et al. 2013); however, relatively little research deals directly with the impact of extensive agriculture on the degree and rate of soil resilience.

Consequently, several authors have proposed the evaluation of soil resilience based on the variation of key soil processes between agricultural and undisturbed sites (Lal 1997; Sá et al. 2014; Tenywa et al. 2013), such as the recovery of SOM (Tugel et al. 2005; Zhao et al. 2005).

Soil organic matter (SOM) is of pivotal importance in defining soil fertility and nutrient cycling. Thus, the synthesis of SOM (known as humification process) has direct and indirect effects on agronomic productivity, global C balance and soil behavior against degradative processes (Hevia et al. 2003; Six et al. 2006; Paul 2007). It is widely known that SOM is a heterogeneous substance, which includes low and high molecular weight compounds of different cycling periods (Abril et al. 2013a; Prentice and Webb 2010). Non-humic substances, mainly formed by soluble carbohydrates, are easily decomposed by microorganisms and can undergo leaching (Abril et al. 2013a). Contrarily, humic substances (recalcitrant fractions) are mainly composed of polymerized aromatic molecules of high stability that are strongly associated with soil mineral components (Sherstha et al. 2008; Pikul et al. 2009; Marinari et al. 2010). Moreover, humic substances can be divided into different fractions according to their solubility in either an alkaline or acidic pH (Aranda and Oyonarte 2006; Marinari et al. 2010). Fulvic acids are composed of low molecular weight organic materials soluble in both alkaline and acidic environments; conversely, humic acids are high weight molecules extracted from soil by dilute alkali but precipitated at a pH of 2 (Marinari et al. 2010; Paul 2007).

During the last decades, because of the critical role of SOM on agronomic productivity and CO_2 sequestration, several studies have documented the effects of land use on SOM contents and distribution in the soil profile, particularly tillage and crop rotation practices (Hevia et al. 2003; Steinbach and Álvarez 2006). Most recently, a more holistic understanding of soil functioning by means of soil quality evaluation has driven some researchers to approach changes induced by land use from the resilience perspective (Tugel et al. 2005; López et al. 2013; Tivet et al. 2013; Sá et al. 2014). As a result, several recovery practices have been proposed in order to maintain or enhance SOM contents around the grain production areas of the world. Farming systems with reduced or zero soil disruption (no-till), enclosures or with intensified crop rotations have shown a potential to reduce the footprint of agriculture on the environment (NRC 2010).

The central semiarid region of Argentina is a fragile environment with a surface area of about 4.5 million ha (Díaz-Zorita et al. 2002), characterized by coarse textured soils with a low SOM content and a monzonic precipitation regime with irregular drought periods. Local crop and pasture productivity is highly related to the timing and amount of available water, typical of subhumid and semiarid environments (Díaz-Zorita et al. 2002). In Argentina, a combination of market policies and environmental issues has expanded the surface of agricultural lands under no-till systems to avoid soil degradation promoted by 50-yr of traditional agricultural production (plow-tillage) (Bongiovanni and Lobartini 2006; Bono et al. 2008; Duval et al. 2013). However, local studies that evaluated the effects induced by a shift on tillage practices or crop rotations on SOM dynamics did not take into account soil resilience and ecosystem thresholds to address the sustainability of current agricultural practices.

A combination of current and historical management characteristics of this agricultural region provides an opportunity to study soil resilience aspects with a focus on the humification process: a) patches of native woodlands remain undisturbed, b) the region is considered the principal peanut (*Arachis hypogaea* L.) growing area of Argentina with plow-based tillage systems, c) farmers frequently attempt to recover soil fertility by means of farm enclosure, and d) the no-till system has not been completely adopted yet.

The present study was conducted to evaluate the efficiency of recovery practices in reversing soil degradation in the central semiarid region of Argentina. A comparative assessment of the resilience of the humification process was performed between recently adopted (5-yr) restorative management (no-till/crop rotation and farm enclosure) and 45-yr of traditional systems (plow-tillage) using a native woodland as a baseline. For this aim, soil organic matter fractions (non-humic substances, humic substances, humic acids, and fulvic acids), and structure (humification index, and polymerization index) were analyzed. Degradation rates, recovery rates and soil resilience classes were calculated in order to determine the effectiveness of recovery practices.

2. Materials and Methods

The study was conducted in the central semiarid region of the Córdoba province, Argentina (29º 54´ S, 63º 41´ W) at an altitude of about 342 m above the sea level. The area corresponds to the Espinal eco-region, which is mainly characterized by woodlands whose tree layer is dominated by *Prosopis alba, Celtis tala* and *Geoffroea decorticans*, with an abundant shrub layer of *Berberis rustifolia* and *Cestrum parqui*, and presence of grasses, mainly perennial Poaceae C4 species (genera *Trichloris* and *Chloris*). Currently, the Espinal presents extensive cultivated flat fields and scarce mosaics of native vegetation. Soybean (*Glixine max* (L.) Merr.), corn (*Zea mays* L.), sorghum (*Sorghum* L.) and peanut (*Arachis hypogaea* L.) are common field crops in the area. Soils are alluvial forms related to loess-like materials, classified as Typic Haplustoll, Mollisol (Soil Taxonomy, USDA 2014) with a high content of sand. Intrinsic levels of SOM are low to medium (Díaz-Zorita et al. 2002). The climate of the region is temperate with continental characteristics (Díaz-Zorita et al. 2002) with a mean annual temperature of 17 ºC and a mean annual rainfall of 760 mm concentrated in summer (Jarsun et al. 2003).

The study was carried out following a fully randomized factorial design. Sites were selected according to four types of land use: plow tillage (PT), no-tillage (NT), farm enclosure (FEn) and native woodland as a control site (Ct). Agronomic management of the PT site includes plowing to a 20 cm depth using the disc plow 3 months before sowing, and using a harrow disk to refine the seedbed for growing summer gramineous and leguminous crops with winter fallow (**Table 1**). This management has been applied for 45 years. Agronomic management of the NT site consists of a biannual cropping sequence involving one crop per year with soybean and sorghum in the summer alternating with winter fallow (3 mo). The sorghum residue is removed for forage use (**Table 1**). No-till has been applied for 5 years, and the site was previously managed under plow-tillage systems for peanut production. The FEn site was previously (5 years ago) an agricultural plot with a plow-tillage system and is currently occupied by natural vegetation and devoid of trees and woody species, such as *Cestrum parqui, Sorghum halepense, Silybum marianum, Chenopodium álbum, Ipomea purpurea, Tagete minuta and Chloris berroi*. The Ct site is an undisturbed area with typical Espinal woodlands.

Table 1. Typical agronomic management of the study sites of semiarid central region of Argentina. NT: no-till site; PT: plow tillage site

Land use	Rotation phase	Seeding date	Harvesting date	Average crop yield	Weed control	Fertilization
PT	Peanut/ Sorghum	October	March-April	Peanut 1.9 Mg ha^{-1} Sorghum 3.0 Mg ha^{-1}	Mechanical/ Chemical	None
NT	Soybean/ Sorghum	October	March-April	Soybean 1.7 Mg ha^{-1} Sorghum 2.7 Mg ha^{-1}	Chemical	P:S (20:12) 80 kg ha^{-1} N:P:S (20:20:12) 80 kg ha^{-1}

On each site, soil samples (0-20 cm) were taken on August 2012 (winter fallow) on three 500 m linear transects. On each transect, one composite sample (ten sub-samples) were collected. Soil samples were homogenized, and transported in plastic bags to the laboratory.

2.1. Sample analysis

Soil samples were air-dried for 24 h and sieved through a 2 mm mesh. Soils were characterized according to the following physical variables: soil water content (gravimetric), conductivity, and pH (1:2.5 soil/water extract) following Klute (1986). Soil textural analyses were performed by settling soil mineral fractions (LaMotte Company, Chestertown, MD). To evaluate the humification process, we measured SOM content by the wet method of Walkley and Black (Nelson and Sommers 1982), and the humic substances content (HS) by alkali extraction (NaOH) (Bongiovani and Lobartini 2006). From the alkaline extract, humic (HA) and fulvic acids (FA) were separated by acid precipitation (H_2SO_4) following Marinari et al. (2010).

2.2. Calculations and Statistical Analysis

The following calculations were made with soil data: a) NHS, non-humic substances, calculated as the difference between SOM and HS (Marinari et al. 2010; Abril et al. 2013b); b) HI: humification index (HS/SOM) (Abril et al. 2013b); and c) PI: polymerization index (HA/FA) (Abril et al. 2009; Marinari et al. 2010). According to Sa et al. (2014), for the total SOM and each SOM fraction, we calculated the degradation rate (DR) and the recovery rate (RR) (g kg^{-1} y^{-1}) by using equations (1) and (2):

$$DR = \frac{SOM\ Ct - SOM\ PT}{t} \quad (1)$$

$$RR = \frac{SOM\ NT; FEn - SOM\ PT}{t} \quad (2)$$

where SOM Ct, SOM PT, SOM NT, SOM FEn refers to the total SOM or SOM fraction content in the control, plow-tillage, no-tillage and farm enclosure sites, respectively.

Resilience classes were established by means of the variations (%) of each parameter between traditional system/recovery practices and Ct site, modified from Lal's scale (1997): a) Class 0 (variation range: 0-25%), highly resilient soils; b) Class I (26-5%), moderately resilient soils; c) Class II (51-75%), slightly resilient soils; and d) Class III (76-100%), non-resilient soils. The 75% of variation is considered the resilience threshold.

Soil data for each variable were subjected to analysis of variance (ANOVA). Means were compared using the least significant difference test (LSD) ($P < 0.05$). Principal component analysis (PCA) was performed in order to identify patterns of variations. All statistical calculations were carried out using the software program INFOSTAT (Di Rienzo et al. 2013).

3. Results

Local soils show pH values near neutrality with a sandy-loam texture for the NT site and loamy-sand textures for the remaining situations. Conductivity values indicate that salinity was not a restricting condition for local soils. Water contents were low, in accordance with the sampling date (dry season) (Table 2).

Total SOM and all SOM fractions were significantly higher under Ct than in the remaining sites. SOM, NHS, HS and HA contents did not differ between NT, PT and FEn sites (Table 3), while the FA contents were lower in the NT site, although without differing from the FEn site. Intermediate FA contents were registered under the PT site. Both HI and PI values did not present significant differences among all the analyzed land uses (Table 3).

Table 2. Soil physical and chemical characteristics at the analyzed sites. NT: no-till site; PT: plow tillage site; FEn: farm enclosure site; Ct: control site

	NT	PT	FEn	Ct
Water content (g kg^{-1})	28.71	24.11	29.74	28.21
pH	6.62	6.93	6.96	6.13
Conductivity (dS m^{-1})	0.127	0.118	0.118	0.497
Texture	Sandy- loam	Loamy- sand	Loamy- sand	Loamy-sand

Table 3. Soil organic matter content, fractions and structure (means ± standard deviation) of the analyzed sites. SOM: soil organic matter; HS: humic substances; FA: fulvic acids; HA: humic acids; NHS: non-humic substances; HI: humification index; PI: polimeraxion index; NT: no-till site; PT: plow tillage site FEn: farm enclosure site; Ct: control site. Letters in the row indicate significant difference at p ≤ 0.05 by LSD Fisher test

	NT	PT	FEn	Ct	p
SOM	14.0b	17.2b	15.2b	37.7a	0.0001
(g kg^{-1})	(±0.44)	(±0.62)	(±2.74)	(±0.61)	
HS	5.3b	6.0b	5.3b	13.8a	<0.0001
(g kg^{-1})	(±0.11)	(±0.16)	(±1.69)	(±0.35)	
FA	2.1c	2.7b	2.3bc	5.7a	<0.0001
(g kg^{-1})	(±0.04)	(±0.04)	(±0.72)	(±0.26)	
HA	3.2b	3.3b	3.0b	8.1a	0.0001
(g kg^{-1})	(±0.11)	(±0.14)	(±0.96)	(±0.61)	
NHS	8.7b	11.2b	9.9b	23.9a	0.0041
(g kg^{-1})	(±0.49)	(±0.50)	(±0.19)	(±0.65)	
HI	0.42	0.37	0.35	0.37	0.1042
	(±0.20)	(±0.09)	(±0.07)	(±0.08)	
PI	1.55	1.27	1.32	1.43	0.2832
	(±0.58)	(±0.51)	(±0.05)	(±0.18)	

Principal component analysis (PCA) yielded two components that explained 98.5% of the total variance. The first component (PC1), explaining 71.7% of the data variance, showed high loading for SOM and FA (0.45). The second component (PC2), accounting for 26.8% of the total variation, loaded heavily on IH (0.70) and PI (0.71). This analysis clearly separated Ct from the remaining sites, but not FEn from the agricultural sites (**Figure 1**).

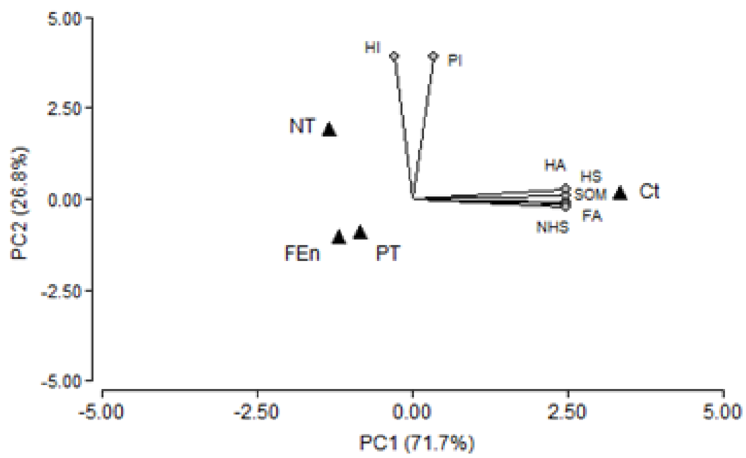

Figure 1. Principal component analysis of humification process parameters. NT: no-till site; PT: plow-tillage site; FEn: farm enclosure site; Ct: control site. HI: humification index; PI: polymerization index; HA: humic acids; HS: humic substances; SOM: soil organic matter; FA: fulvic acids; NHS: non-humic substances.

Degradation rates (DR) were significantly high for the humification parameters under study, reflecting important losses of soil organic compounds (-54.55%) in the 45-yr transition period from the conversion of native woodlands to plow-tillage based systems. Likewise, RR were negative for all the analyzed land uses, including the FEn site (Table 4). This observation indicated that recovery practices did not reverse ongoing degradative processes. However, DR differences between PT and recovery practices showed a tendency to reduce DR values for most parameters in the FEn site. In contrast, DR reduction in NT accounted only for SOM stable fractions (Figure 2).

Table 4. Degradation and recovery rates of humification process parameters. SOM: soil organic matter; HS: humic substances; FA: fulvic acids; HA: humic acids; NHS: non-humic substances

	SOM	HS	FA	HA	NHS
DR: Degradation rate (45 years) (g kg^{-1} y^{-1})	0.45	0.17	0.06	0.10	0.28
RR: Recovery rate (5 years) (g kg^{-1} y^{-1})					
Non-tillage site (NT)	-0.64	-0.14	-0.12	-0.02	-0.50
Farm enclosure site (FEn)	-0.40	-0.14	-0.08	-0.06	-0.26

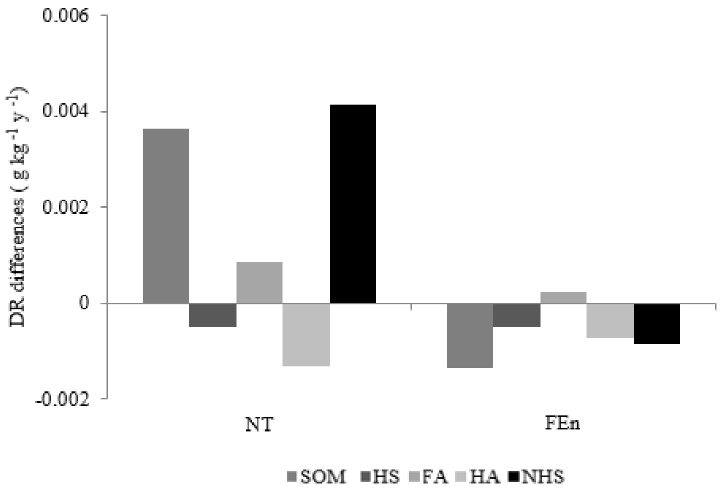

Figure 2. Degradation rate (DR) differences between plow tillage system and recovery practices (no-till and farm enclosure), for humification process parameters. NT: no-till site; FEn: farm enclosure site; SOM: soil organic matter; HS: humic substances; FA: fulvic acids; HA: humic acids; NHS: non-humic substances.

None of the analyzed parameters of the humification process were included in resilience class 0 or I. Surprisingly, all land uses showed the same resilience class for SOM and SOM fractions (Class II), and none of the parameters overcome the resilience threshold (75%) (Figure 3).

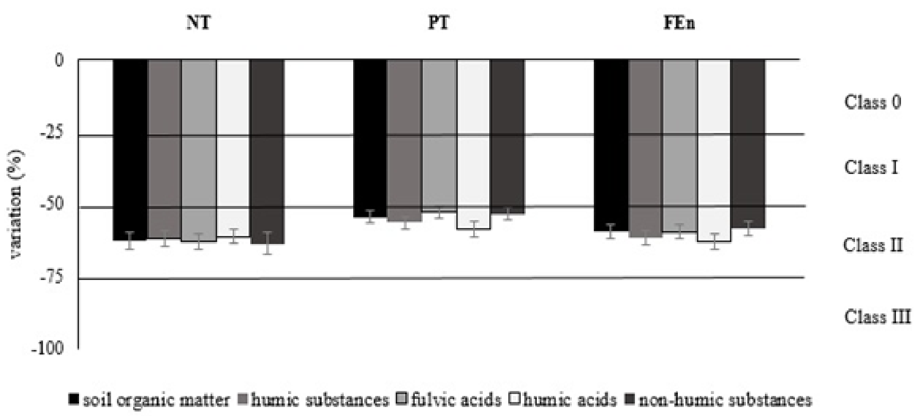

Figure 3. Resilience classes of humification process parameters. Variations (%) between traditional system/recovery practices and control site. NT: no-till site; PT: plow-tillage site; FEn: farm enclosure site. Bars indicate standard error.

4. Discussion

4.1. Soil Organic Matter Contents

Decreasing SOM levels in agricultural soils is in agreement with the widely accepted fact that extensive farming practices negatively affect the reservoir of soil organic C (Abril and Noe 2007; Vityakon 2007; Potter et al. 2009; Raiesi 2012; Vázquez et al. 2013); mainly because of changes in soil aeration, temperature and water content induced by tillage (Dalal and Bridge 1996; Guimarães et al. 2013) and the amount and type of organic residues returned to the soil (Dick and Gregorich 2004). Contrarily, it has been noted that NT is a factor of C sequestration in agricultural soils (Diaz-Zorita et al. 2002; Melero et al. 2011) but generally with smaller effects in semiarid regions compared to humid environments (Dalal and Bridge 1996). Although soil C losses derived from agricultural use are well reported, dynamics of SOM recovery are divergent and locally specific (Janzen et al. 1998; Zhao et al. 2005).

In our study we detected little change in SOM among PT and NT systems, in agreement with Zhao et al. (2005) and Duval et al. (2013) who commented that soil C losses are fast and sharp whereas gains are slow and unsteady. Watts et al. (2011) suggested that in NT soils SOM reaches its maximum values between 5-10 years from the PT transition but it stabilizes after 15-20 years. Similarly, Lin and Chen (2014) did not report significant changes on SOM contents between crop rotations either in NT or sweep tillage over an experimental period of 6 years in a semiarid region of the United States.

Soil organic matter contents at the FEn site did not differ from agricultural situations. It is well-known that SOM levels do not recover their original state in short periods of time, taking at least several decades without crops (Álvarez and Steinbach 2012). Consequently, C sequestration starts many years after the enclosure of agricultural soils, especially in degraded soils of semiarid environments (Zhao et al. 2005; Raiesi and Riahi 2014). Raiesi (2012) reported a SOM accumulation of 26% in long-term abandoned fields (18-22 years) in a semiarid area of Iran. However, since recovery patterns of degraded ecosystems are related to increasing years of land abandonment (Zhao et al. 2005), results are difficult to compare because of the different enclosure periods and soil types analyzed (Wang and Gong 1998).

The results obtained in NT are contradictory since it is assumed that a soil under NT with a crop rotation that includes a high biomass crop like sorghum tends to accumulate SOM due to a greater contribution of stubble and soil coverage (Casado-Murillo and Abril 2013). Moreover, it is widely accepted that reducing soil disturbance (through the use of NT) and using crop rotations (to increase the amount of plant residue) increases SOM contents in agricultural soils (Duval et al. 2013; Toosi et al. 2012). However, the content of SOM in the NT (14.0 g kg^{-1}) site was the lowest of the analyzed situations; the absence of sorghum stubble incorporation resulted in a negative response of SOM contents. According to Tivet et al. (2013) the magnitude of SOM recovery depends on the input of crop biomass. In this regard, Blanco-Canqui and Lal (2009) argued that the practice of removing stubble, used as an energy source for biofuel production and cattle forage, has caused a strong impact on the stock of C in agricultural soils.

4.2. Fractions and structure of SOM

It has been noted that the study of SOM fractions and its dynamics is relevant for the evaluation of productive impacts and the adoption of sustainable agricultural practices at a regional level (Abril et al. 2013a; Duval et al. 2013; Galantini et al. 2002; Shrestha et al. 2008; Vázquez et al. 2013). In this regard, the humified fractions play a critical role due to their localization in organo-mineral complexes that are highly resistant to microbial degradation (Blanco-Canqui and Lal 2009).

The results of this study showed that HS, despite its recalcitrance, suffered a significant reduction in comparison to the native woodland, but with little change despite tillage practices changes. These finding are in agreement with

Bongiovanni and Lobartini (2006) who found a similar reduction (range: 40-70%) in the central area of the Cordoba province, and Shrestha et al. (2008), who reported an insensitivity of more stable SOM fractions to land use. A probable explanation is that HS recalcitrance and stability does not account once tillage practices broke down aggregates, exposing HS to microbial degradation (Dalal and Bridge 1996).

In agreement with other authors (Zalba and Quiroga 1999; Galantini et al. 2002; Guimarães et al. 2013), FA showed more sensitivity to management practices than HA. Fulvic acids are the least polymerized portion of the HS, being a more important energetic source for microorganisms than HA (Abril et al. 2013a; Vázquez et al. 2013). A significant depletion of FA indicates that stubble removal also affects the beginning of plant residue humification (Blanco-Canqui and Lal 2009).

The HI calculated as HS/SOM reflects the global humification process (Marinari et al. 2010), whereas the polymerization index (HA/FA) indicates the HS maturity degree (Guimarães et al. 2013; Toosi et al. 2012). Higher HI and PI values correspond to a more stable SOM structure (Abril et al. 2013a; Galantini et al. 2002). However, a HA/FA > 1 indicates loss of more labile FA fractions, common in sandy soils (Guimarães et al. 2013).

We found no evidence for differences in HI and PI values between the Ct site and agricultural situations. This observation is contradictory since it is expected that higher index values would be found on soils under native vegetation due to a higher content of HA derived from woody residues like those from the Espinal woodland. Hevia et al. (2003) reported that cultivation decreases SOM contents but does not modify the structure of SOM in agricultural soils of the central semiarid region of Argentina. These results can be explained from an ecological perspective. When soils are frequently exposed to external disturbances for long periods of time, ecosystem stability and functionality can be significantly altered causing a regime shift that forces soils to reach less desirable and degraded conditions (Tugel et al. 2005; Tenywa et al. 2013). The absence of differences between SOM structure index values may indicate the establishment of new climax states on degraded soils where a different regime of processes and structure predominates (Tenywa et al. 2013). Since SOM changes were negative but proportional, it is suggested that after 45 years of cultivation, agricultural soils have reached a new equilibrium level regarding SOM content and structure, but in a threshold beyond the initial conditions. This interpretation agrees with the negative RR values found after 5 years since management changes, reflecting stable conditions of new climax states.

4.3. Humification process resilience

Our results showed that traditional land uses exerted moderate to strong changes on the resilience degree of the humification process. Although these changes cannot be reversed in a 5-yr period, there is a tendency to obtain lower DR under recovery systems, particularly in FEn. The observed differences could be the result of an even annual distribution of plant residues (under the FEn site) that is not observed on agricultural sites due to crop cycles. This observation is in agreement with the higher homogeneity of the humification process founded by Janzen et al. (1998) in a farm enclosure system.

In both recovery practices (NT and FEn), HS and HA have reduced their DR, although this effect did not account for SOM labile fractions. For example, an increment of NHS losses was observed under NT; mainly because of a significant proportion of sorghum stubble that is harvested and not incorporated into the soil profile (Abril et al. 2013a).

The fact that SOM and NHS were included in resilience Class II is probably due to the high sensitivity of local soils to erosion caused by textural characteristics (sandy soils) (Díaz-Zorita et al. 2002). Furthermore, that NHS and SOM exhibited similar resilience patterns in all the analyzed agricultural sites indicates a close relationship between the labile and total organic matter in soils (Marriott and Wander 2006). For some soils, especially those with coarse texture in semi-arid climates and cultivated for a long time, the conversion to NT may have little effect on SOM contents (Lal 1997). Similarly, that the majority of the humification process parameters (HS, HA and FA) were included in resilience Class II (also in FEn site) underlines a high degree of soil degradation and a poor short-term ability of agricultural soils to recover original properties, requiring high inputs of organic materials to enhance SOM contents (Lal 1997). Several studies that evaluate C dynamics showed that C losses are significant during the initial years of agricultural production; however, C pools tend to stabilize within years despite its agricultural use (Lal 1997). In this regard, Folke (2006) highlighted the difficulty of transforming stabilized systems (very resilient) to new states in short periods of time.

The degree of resilience of SOM, NHS and FA were included in resilience Class II for soils under NT. Probably, this effect could be attributed to a scarce crop residue deposition, despite being a NT system, derived from sorghum stubble removal. It is widely known that in semi-arid environments an adequate soil cover is vital to maintain intrinsic low SOM contents (Raiesi 2012) and to prevent wind erosion processes (Zhao et al. 2005; Díaz-Zorita et al. 2002). Residue management, quantity and quality of biomass applied to the soil have a significant impact on soil quality, resilience and agronomic productivity (Lal 1997). Short-term studies in the U.S. Corn Belt region showed that corn residue harvest negatively impacts soil structure and reduces soil resilience (Johnson and Barbour 2012).

As for other soil parameters, the short-term response of SOM to soil management will depend upon soil's initial equilibrium condition (Balesdent et al. 2000; Raiesi and Riahi 2014). A combination between the magnitude and frequency of external disturbances and the stability of an ecosystem will determine its strength and malleability in maintaining an equilibrium (Seybold et al. 1999). Frequently, degraded systems are located in stable climax states where the influence of agricultural practices prevented the ecosystem from developing further (Beeby 1995). According to Seybold et al. (1999), agroecosystems may recover in a hysteretic manner without a complete soil restoration before the following growing season is imposed.

5. Conclusions

In the central semiarid region of Argentina, traditional agricultural systems degraded the soils and significantly affected the soil resilience degree of the humification process, so that a shift to recovery practices (NT or farm enclosure) did not reverse ongoing degradative processes. Humification parameters exhibited poor resilience, suggesting that degraded soils have established a new equilibrium (at low values) that offers high resistance to management changes in the short-term. However, a small tendency of minor degradation rates in recovery systems may indicate the beginning of recovery processes.

Crop residue removal highly affects SOM synthesis so it application should be excluded for fragile environments like semi-arid areas. Farm enclosure might be an alternative management for restoring soil conditions when combined with the implantation of perennial grasses for an overall higher productivity of the system (Walker and Desanker 2004). The evolution of sustainable management principles will require further research effort to integrate advanced soil concepts like resilience and farm-level management of soil properties like SOM from a holistic perspective. Thus, enhancing soil quality to agricultural management impacts may be an initial step to improve soil resilience over the long-term.

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