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Long-term impact of grazing and tillage on soil quality in the semi-arid Chaco (Argentina)

Impacto a largo plazo del pastoreo y laboreo en la calidad del suelo en el Chaco semiárido (Argentina)
Impacto a longo prazo da pastagem e do cultivo na qualidade do solo no Chaco semi-árido (Argentina)

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ABSTRACT

Deforestation of Chacoan native forests and reorientation of land use are transforming the region into agricultural use. The main purpose of this work was to evaluate the impact of different land uses on soil quality in the semi-arid Chaco (Argentina). We assessed the behaviour of soil parameters over four years of experimental conditions: 1) Exclosure pasture (EP) used as reference level, 2) Grazed pasture (GP), 3) Grazed pasture transformed to agriculture with Zero tillage (ZT) and 4) Grazed pasture transformed to agriculture under Conventional tillage (CT). Soil organic carbon, particulate and heavy organic carbon (C), total nitrogen (N), C:N ratio, pH, electric conductivity and soil respiration were measured. Soil samples were taken yearly at 0-5, 5-20 and 20-40 cm of soil depth. Differences among treatments across time were assessed by Analysis of Covariance (ANCOVA) with time (years) as covariate factor, treatments as group factor and individual scores from Principal Component Analysis (PCA) as responses. Correlated changes in the soil characteristics were detected, especially at the top soil layer. Both carbon and nitrogen contents increased in both GP and ZT systems. An opposite trend was found for CT, which also had a negative impact on salinity. Both land use change and management practices in the Chaco region represent the main human activities that modify the landscape; thus, they should be analysed by recognizing heterogeneity on farming practices and identifying their impacts on a specific site. The results of this work reinforce the utility of soil organic carbon as a single parameter for monitoring land management systems, especially for monitoring large region like Chaco that are subject to continuous transformation processes.

RESUMEN

La deforestación del bosque nativo chaqueño y la reorientación del uso del suelo están en camino de transformar la región hacia uso agrícola. El principal objetivo de este trabajo es evaluar el impacto de diferentes prácticas de uso sobre la calidad del suelo en el Chaco semiárido (Argentina). Estudiamos el comportamiento de parámetros edáficos a lo largo de cuatro años de condiciones experimentales: 1) Clausura (EP) usada como nivel de referencia, 2) Ganadería pastoril (GP), 3) Agricultura vía siembra directa (ZT) y 4) Agricultura vía labranza convencional (CT). Se midieron los parámetros de carbono orgánico del suelo, carbono orgánico (C) particulado y pesado, nitrógeno total (N), C:N ratio, pH, conductividad eléctrica y respiración del suelo. Las muestras fueron tomadas anualmente a 0-5, 5-20 y 20-40 cm de profundidad de suelo. Las diferencias entre tratamientos a lo largo del tiempo fueron evaluadas por un Análisis de Covarianza (ANCOVA) con el tiempo (años) como covariable, los tratamientos como factor grupal y los valores de los componentes resultantes del Análisis de Componentes Principales (PCA) como respuestas. Se detectaron cambios correlacionados con las características del suelo, especialmente en la capa superficial del suelo. Los contenidos de nutrientes incrementaron en los sistemas GP y ZT. Una tendencia opuesta fue detectada para CT donde, además, hubo un impacto negativo sobre la salinidad. Tanto el cambio en el

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uso del suelo como en las prácticas de manejo dentro de la región del Chaco representan las principales actividades humanas que modifican el paisaje; de esta forma, estas deberían ser analizadas reconociendo la heterogeneidad en las prácticas de producción e identificando sus impactos en sitios específicos. Los resultados de este trabajo refuerzan la utilidad del carbono orgánico del suelo como parámetro individual para monitorear sistemas de manejo de la tierra, especialmente regiones extensas como Chaco que están sujetas a continuos procesos de transformación.

RESUMO

A desflorestação da mata nativa do Chaco e a reorientação do uso do solo estão a transformar a região no sentido do seu uso agrícola. O principal objetivo deste trabalho é avaliar o impacto de diferentes práticas de uso na qualidade do solo no Chaco semi-árido. Foi estudado o comportamento, ao longo de quatro anos, dos parâmetros edáficos em condições experimentais: 1) Pastagem de exclusão (PE) utilizada como nível de referência, 2) Pastagem Ativa (GP), 3) Pastagem transformada em agricultura com sementeira direta (ZT) e 4) Pastagem transformada em agricultura sob preparação convencional (CT). Determinou-se no solo o carbono orgânico, o carbono orgânico particulado e pesado (C), o nitrogénio total (N), a relação C:N, pH, condutividade elétrica e a respiração do solo. As amostras de solo foram colhidas anualmente a 0-5, 5-20 e 20-40 cm de profundidade. As diferenças entre tratamentos ao longo do tempo foram avaliadas por Análise de Covariância (ANCOVA) com o tempo (anos) como uma covariável, os tratamentos como fator de grupo e os valores dos componentes resultantes de Análise de Componentes Principais (PCA) como respostas. Foram detetadas alterações correlacionadas com as características do solo, principalmente na sua camada superficial. As concentrações em carbono e nitrogénio aumentaram nos sistemas GP e ZT. Uma tendência oposta foi observada para o sistema TC, onde, além disso, houve um impacto negativo na salinidade. A mudança no uso da terra e as práticas de gestão na região do Chaco representam as principais atividades humanas que modificam a paisagem. Deste modo, estas deveriam ser analisadas reconhecendo a heterogeneidade das práticas de produção e identificando os seus impactos em locais específicos. Os resultados deste trabalho reforçam a utilidade do carbono orgânico do solo como um parâmetro individual para monitorizar os sistemas de gestão da terra, especialmente em regiões de grande dimensão como a região de Chaco que estão sujeitas a processos contínuos de transformação.

KEY WORDS
Management practices, soil use change, soil organic carbon, soil indicators, grazing systems, agricultural systems.

PALABRAS CLAVE
Prácticas de manejo, cambio de uso del suelo, carbono orgánico del suelo, indicadores del suelo, sistemas pastoriles, sistemas agrícolas.

PALAVRAS-CHAVE
Práticas de gestão, alteração do uso do solo, carbono orgânico do solo, indicadores do solo, sistemas de pastagem, sistemas agrícolas.

1. Introduction

The major challenge of agricultural production consists of producing food, in terms of both quantity and quality, to support a continuously growing population. At the same time agricultural systems face the productive challenge of increasing production in a sustainable way taking into account environmental parameters such as conservation of soil properties. In recent years South America has experienced an increasing rate of deforestation (Volante et al. 2012), especially in the following ecoregions: the Brazilian Cerrado (Mendes Malhado et al. 2010), the Chiquitano Forests in Bolivia (Müller et al. 2012) and the Gran Chaco in Bolivia, Paraguay and Argentina (Gasparri and Grau 2009). In the Gran Chaco ecoregion large areas of forests were transformed into agricultural land (Hansen et al. 2013). These land-use changes are poorly understood, although they are likely globally significant. The South American Chaco has recently emerged as a spot of agricultural expansion and intensification, as cattle ranching expands into forests, and later agriculture replaces grazing land (Baumann et al. 2017).

The Chacoan region lies in the center of South America and covers about 650,000 km^2 encompassing parts of Argentina, Bolivia and Paraguay. The area is a low-lying plain subject to semi-arid climatic conditions under a monsoon regime (Bucher 1982). The mean annual temperature is 25 °C in the north and 18 °C in the southern area. The rainfall gradient varies between 500 and 700 mm y^{-1}, mainly concentrated between November and April. There is a marked dry season from late autumn to early spring. In particular, the semi-arid Chaco sub-region comprises fragile ecosystems where their edaphic and climatic characteristics make it difficult for recovery processes (Giménez et al. 2011). These aspects stress the relevance of handling accurate and updated information, monitored through soil quality indicators (SQI). Thus, understanding and addressing the state of agricultural soils based on the information of SQI, will help the semi-arid Chaco to minimize its deterioration both favoring its recovery and making the application of sustainable management practices possible.

Soil quality has been defined as the capacity of soil to function within ecosystem boundaries, sustaining biological productivity, maintaining water and air quality and promoting plant, animal and human health (Karlen et al. 1997). However, this concept must deal with a great number of variables to reflect changes or variations in management. Soil quality indicators encompass soil properties and processes that contribute to delineate out a minimal data set for soil quality evaluation (Andrews et al. 2004). Physicochemical and biological soil properties could be good candidates as SQI, but they are not universal at specific site changes are expected to occur due to ambient conditions, soil type (Shukla et al. 2005), management factors and study scale. These variables are measured to monitor soil management effects in a defined period (Astier et al. 2002). Measurements are usually taken at the top layer of soil (0-20 cm) because it is more susceptible to respond to changes in management than deeper layers. Studies carried out there involve the assessment of numerous physicochemical and biological variables (Ferreras et al. 2009; Campitelli et al. 2010; Imaz et al. 2010). Changes in SQI could help to determine whether a system falls into a situation of stability, improvement or degradation (Shukla et al. 2006).

Since many variables are considered to comply with the requirements of SQI, it is mandatory to recognize those responsible for the largest amount of variability in the data set. Quantitative procedures linked to multivariate statistics could positively assist in such research direction. Unsupervised methods of multivariate statistics take into account the correlations between many variables that are analysed simultaneously, in order to synthesize and interpret information (Campitelli et al. 2010). The use of multivariate statistical techniques has made possible solving many problems, such as the determination of discriminant management properties in semi-arid soils, the evaluation of tillage impacts on soil quality and the relationship between soil compaction and physical and organic properties. Furthermore, multivariate analysis techniques allow the interpretation of potential causes of observed differences in soil properties (Campitelli et al. 2010).

Studies of land use/cover change detection are available for the sub-region of semi-arid Chaco. Many of these studies are aimed at characterizing the transformations experienced in the territory and reflect on the multiple causes and consequences behind the processes of land use change and deforestation (Gasparri et al. 2013; Gasparri and le Polain de Waroux 2014). However, there is no information about "agriculturization" impacts on the conversion of pasture-livestock systems into agriculture in the region. Moreover, little has been published on the impacts of livestock production on soil quality indicators. The main purpose of this work was to evaluate the impact of different land uses and management practices (i.e. ungrazed pasture, grazed pasture and cropping systems) on several soil quality parameters in the semi-arid Chaco sub-region.

2. Materials and Methods

2.1. Study area

This study was conducted at the experimental field of the Animal Research Institute of semi-arid Chaco (IIACS), located in Leales, Tucumán, Argentina (27° 11’ S, 65° 17’ W). The climate is subtropical sub-humid with a dry season. The mean annual precipitation is 880 mm and rainfalls are concentrated between November and April. Annual temperature ranges from

25 °C in January to 13 °C in July and mean annual temperature is 19 °C.

2.2. Experimental design

The experimental area consists of a site that had been under *Chloris gayana* cv Finecut pasture for about 10 years before the start of the study. During this period a beef cattle system (steers) was implemented, involving sequential grazing periods. At the same time, exclosures were established for comparing grazed versus non-grazed rangelands.

After ten years of cattle usage a portion of the area was divided into two zones: 1) C. *gayana* transformed into agriculture using conventional tillage (CT); and 2) C. *gayana* transformed into agriculture using zero tillage (ZT). The rest of the area continued under the same precedent management, i.e. grazed pastures (GP) and exclosure pasture (EP). The study was carried out under a completely randomized design with three replicates and repeated measures in time.

2.3. Soil sampling and analytical determinations

The soil type subsumes into the Sub-group Fluvaquentic Haplustolls from the order Mollisols following the US Soil Taxonomy System (Soil Survey Staff 2014) which is silty loam at the depth of 0-26 cm (sand, 31.75%; silt, 57.04%; clay, 11.21%) and 26-49 cm (sand, 32.84%; silt, 54.00%; clay, 13.16%). Soil samples were collected at 0-5, 5-20 and 20-40 cm depths in March of 2010, 2011, 2012 and 2013. Six subsamples were collected per plot for each depth and combined to obtain a composite sample for chemical and microbiological determinations. Before collecting soil samples, the upper soil layer was scraped off to remove litter. Composite soil samples were stored in sealed plastic bags and transported to the laboratory where they were air-dried and sieved (2 mm mesh size) to remove stones, coarse roots and any other litter material.

Soil organic carbon (SOC) was determined by the wet oxidation method of Walkley-Black (Nelson and Sommers 1982); particulate organic carbon (POC) and mineral associated organic carbon (AOC) were determined by dispersion and sieving according to Cambardella and Elliot (1992) and total nitrogen (TN) by the Kjeldahl method (Bremmer and Mulvaney 1982). Soil pH was measured in distilled water (1:2.5) and soil electric conductivity (EC) using a saturated paste extract (U.S. Salinity Laboratory Staff 1954). Soil respiration (SR) was determined by placing 20 g of soil into 250 mL glass beakers and incubating in the dark at 25 °C along with 30 mL of 0.1 N NaOH. The CO_2-C evolved was measured after 10 days by titration (Anderson 1982).

2.4. Statistical analyses and graphics

Principal Component Analysis (PCA) was performed on the complete dataset to reduce its complexity and get a better understanding of the underlying structure. Conceptually the goal of PCA is to reduce the number of variables of interest into a smaller set of components. PCA redistributes all variance into orthogonal components. Extraction is the process of forming principal components as linear combinations of the measured variables. Here, variables include pH, EC, TN, SOC, C:N ratio, POC, AOC, and SR. The first two components were retained for further study since they account for a large amount of the variance in the original dataset. The loading for each variable is the correlation between it and the component (i.e. the underlying shared variance). Interpretation of the principal components is based on finding which variables are most strongly correlated with each component.

After projection of data points onto the first two principal components (where the variances are the highest), we drew confidence ellipses around a set of points classified by their membership to the different soil layers. Soil depth was hypothesized as the main factor behind variability in data set even greater than treatment effects across time. If hypothesis is confirmed, then clear separation between dot clouds should be observed. To assist better in the comprehension of overall multivariate data structure, we also produced a parallel coordinates plot. Parallel coordinates is a technique of data visualization in which a single line in a graph connects a series of values - each associated with a different variable - that represents multiple physicochemical aspects of samples.

For each meaningful subset of data points, we ran secondary and independent PCAs and used the two main components therein as new and synthetic variables. To assess statistically the differences in treatment effects across time we performed an Analysis of Covariance (ANCOVA) with time (years) as covariate factor, treatments as group factor, and individual PCA scores as response. Since exclosure was adopted as the reference level, the model parameters (regression coefficients) represent the difference between this reference level and the other treatments. All graphics and statistical analyses were performed with the R software (R Core Team 2016).

3. Results

The first two principal components of the PCA applied on the entire dataset (samples taken at different soil depths, treatments and times) captured 83.88% of total variance. **Figure 1a** shows the projection of data points onto the reduced subspace of PCA. The overall set of points was separated into clusters using the soil layer as classifier. All variables, except the C:N ratio, load highly into the first component (**Figure 1b**). The top soil layer can be distinguished from the remaining layers by its higher content of nutrients, increased microbial activity, lower pH and less salinity. The opposite behavior of C:N ratio separates the points belonging to the intermediate layer from those of the deep layer, being greater in the deep layer. Even though the content of both nitrogen and carbon increases when moving from the deep layer to the topsoil, the relative increase in nitrogen outweighs that of carbon for the intermediate layer, explaining thus the low C:N ratio achieved by this layer (**Figure 2**). The parallel coordinates plot (**Figure 3**) reinforces the striking physicochemical distinction between layers of soil depth, beyond any putative treatment effect, justifying their analyses separately.

For the subset of data concerning to the upper soil depth (top soil layer), the first two components of the respective PCA accounted for 70.67% of total variance (**Figure 4**). Linear regressions on time of all variables grouped by treatment are in **Figure 5**. While variation along PCA Axis 1

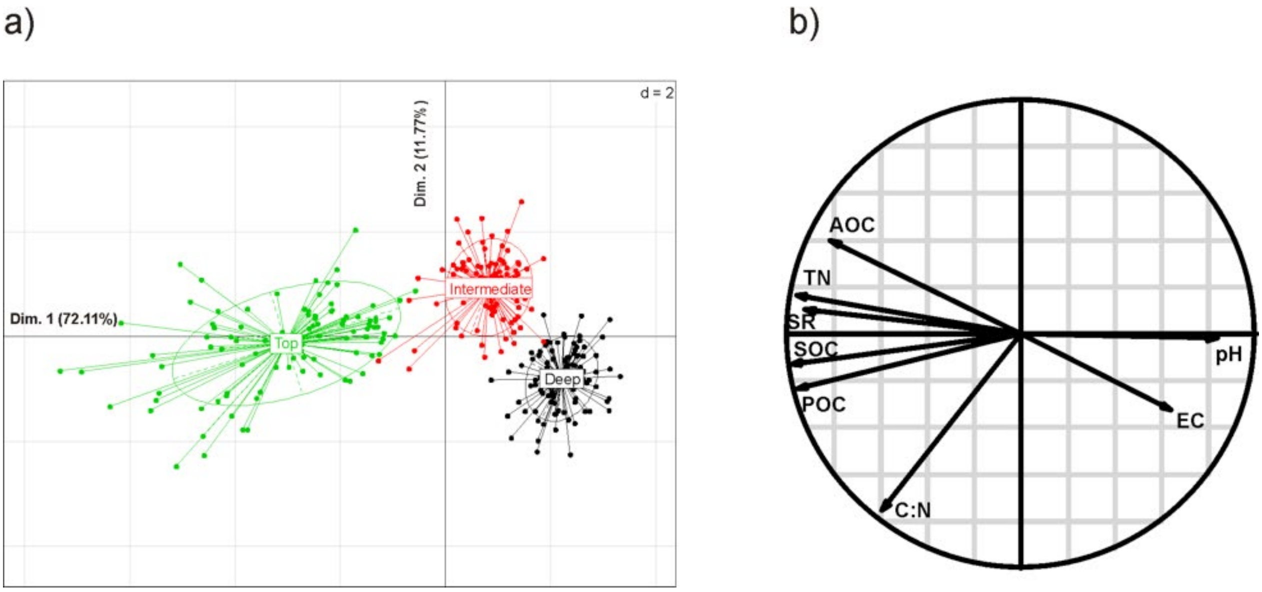

Figure 1. Principal component analysis (PCA) of the overall data set (samples taken at different times, experimental scenarios and soil depths). (a) Data points projected onto the bi-dimensional subspace derived from PCA. Confidence ellipses were drawn around points classified by soil depth; a clear segregation of groups can be observed. Dim. 1, 2: dimensions kept in the results. The scale of the graph is given by a grid, which size d is given in the upper right corner. (b) Correlation circle that shows how individual variables load on the components.

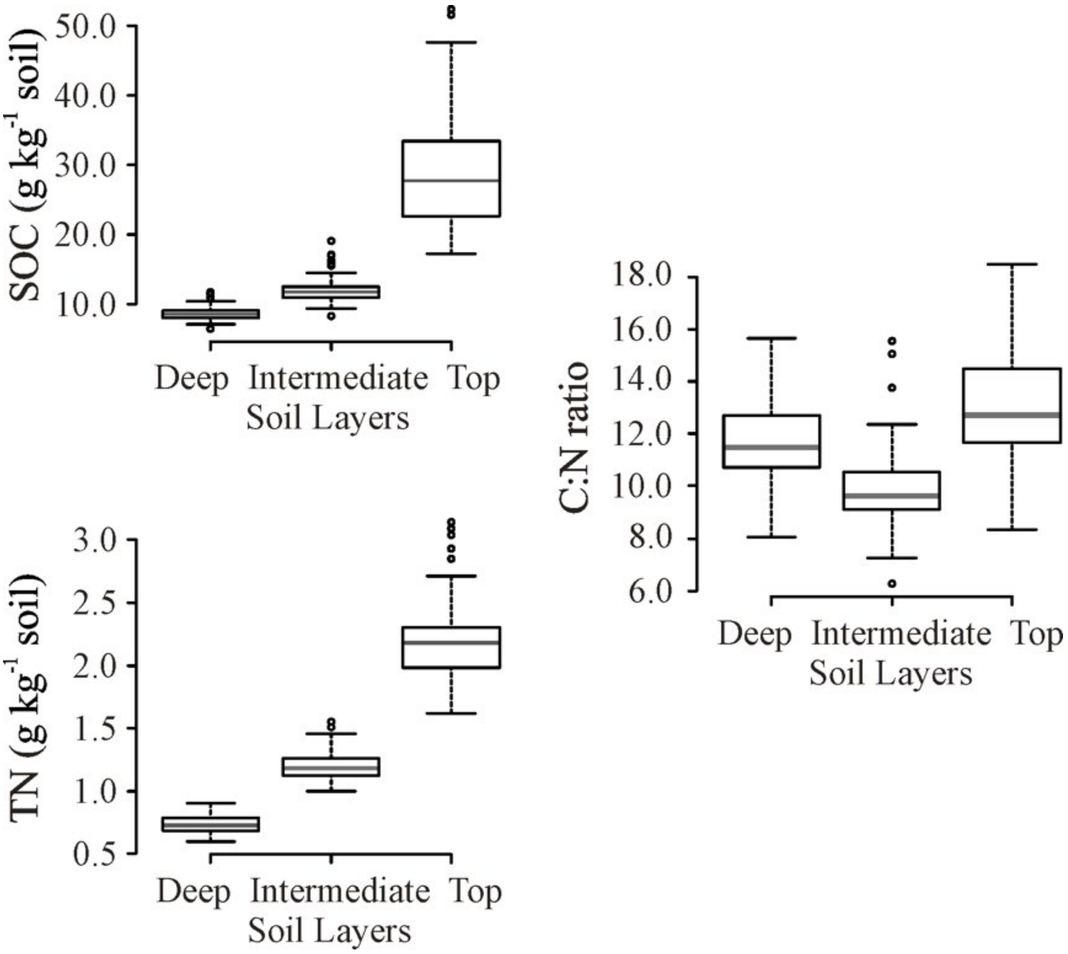

Figure 2. Statistical dispersion for soil organic carbon (SOC), total nitrogen (TN) and carbon:nitrogen (C:N) ratio for all data points across the different soil depth layers considered in this study. Both SOC and TN are given in percentages.

is positively related to nutrient availability and negatively related to EC, variation along PCA Axis 2 is mainly due to microbial activity in a positive way (**Figure 4c**). The ANCOVA for the scores (**Table 1**) derived from the leading or first component indicates treatment differences across time (heterogeneity of slopes). Thus, a contrasting behavior in slopes can be observed (**Figure 4a**). The direction of change for both ZT and GP is towards the positive domain of PCA Axis 1 (higher nutrient content and lower salinity), whereas the effect of CT orientates towards the negative side of such axis (soil impoverishment and salinization). The ANCOVA for the scores of the secondary PCA Axis reveals homogeneity of slopes (that is, no difference between treatments) and a generalized effect of time (**Table 1, Figure 4b**), suggesting the biological imprint (measured through soil respiration) of some regional factor acting on the study area during the field experiments.

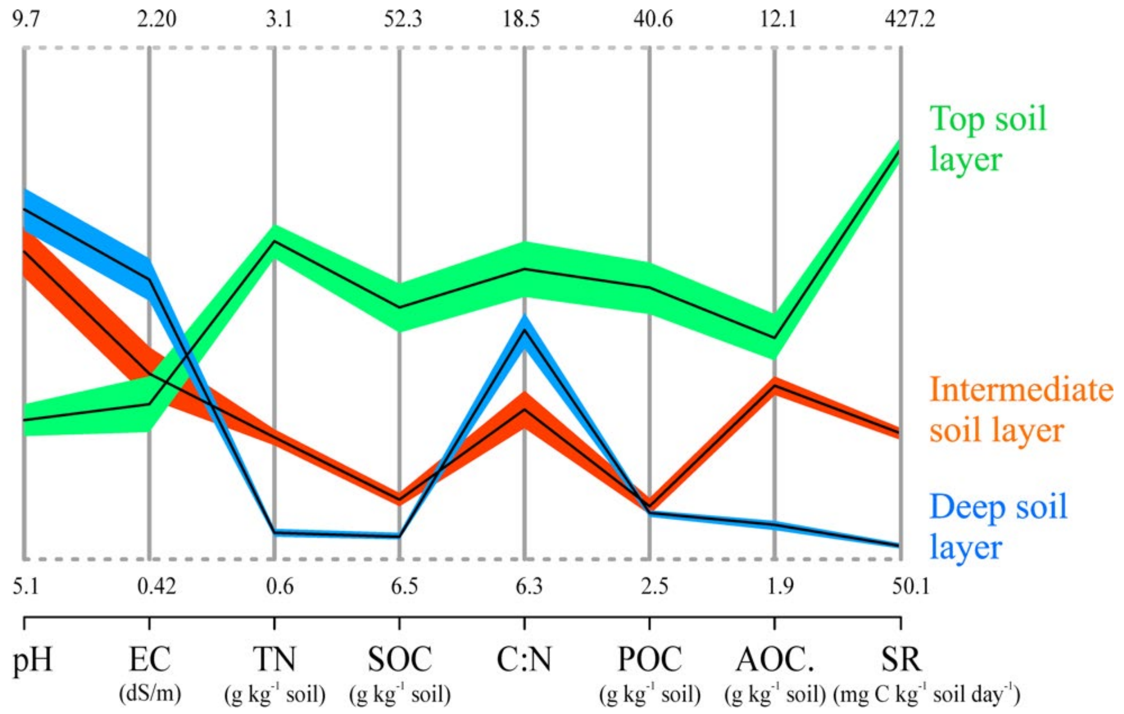

Figure 3. Parallel coordinates plot for the entire data set considered in this study. Data grouped by soil depth. Maximum and minimum values are indicated at the tips of axes representing the different variables. Means values and plus/minus three standard errors are connected through solid lines and polygon contours, respectively.

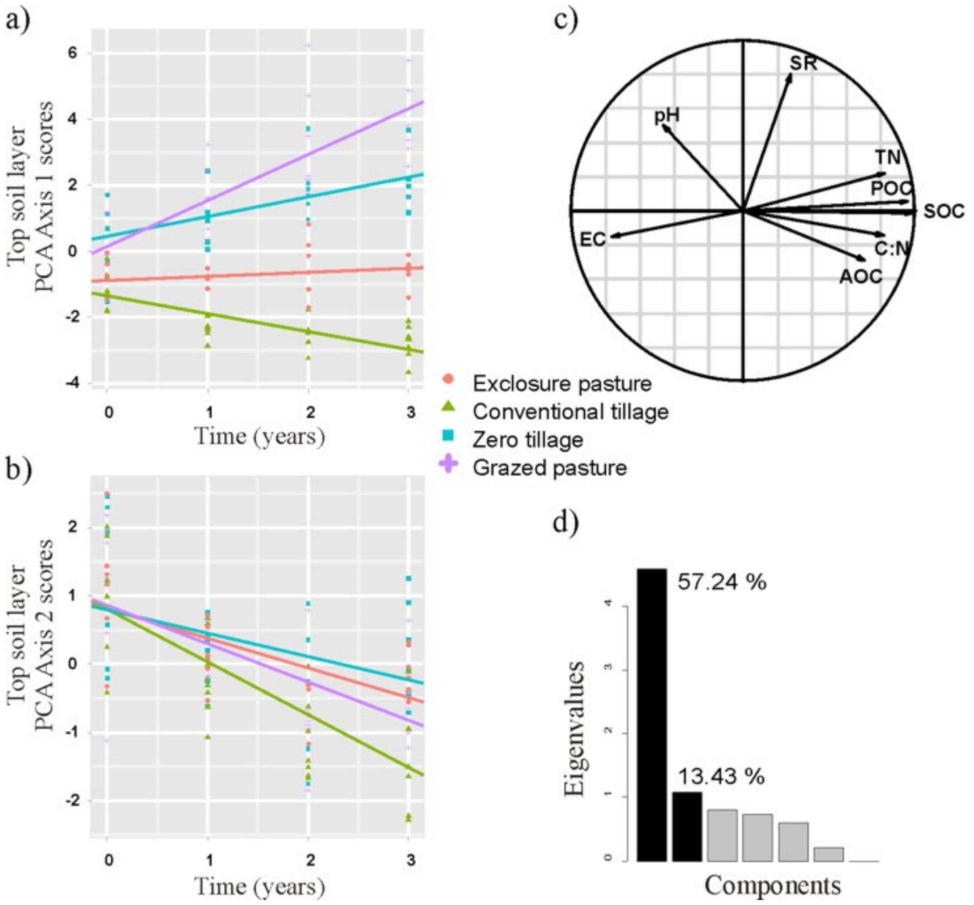

Figure 4. Principal component analysis (PCA) and associated linear regression of component scores applied to the top soil layer dataset. Regressions of PCA Axes 1 (a) and 2 (b) scores on time but separated by treatment. To the right, circle correlation (c) of variables with PCA axes and scree plot of eigenvalues (d) with bars of selected components in solid black.

Table 1. Output of linear regression models for PCA scores relating to the top soil layer

	Synthetic dependent variables (top soil layer)	
	PCA Axis 1 scores (1)	PCA Axis 2 scores (2)
Time (years)	0.123 (0.160)	-0.434*** (0.148)
Conventional tillage	-0.461 (0.395)	-0.007 (0.365)
Zero tillage	1.319*** (0.423)	-0.024 (0.391)
Grazed pasture	1.012** (0.423)	0.045 (0.391)
Time: Conventional tillage	-0.666*** (0.211)	-0.340* (0.195)
Time: Zero tillage	0.475** (0.226)	0.095 (0.209)
Time: Grazed pasture	1.269*** (0.226)	-0.125 (0.209)
Constant	-0.877*** (0.299)	0.815*** (0.276)
Observations	104	104
R^2	0.846	0.438
Adjusted R^2	0.834	0.397
Residual Std. Error (df = 96)	0.875	0.809
F Statistic (df = 7; 96)	75.184***	10.687***

Note: *p<0.1; **p<0.05; ***p<0.01

The PCA restricted to samples of the intermediate soil layer dataset yielded a different loading pattern of variables into the first two components (**Figure 6c**). They accounted for almost 60% of total variance (**Figure 6d**). Linear regressions of all separate variables grouped by treatment on time are graphically expressed in **Figures 6a-b**. Variables strongly associated with the first PCA Axis are SOC and POC. On the other hand, AOC, EC and TN load greatly on the second PCA Axis. Roughly speaking, ANCOVA applied to the scores of this subspace highlights treatment differences in the dynamics of carbon and nitrogen (**Table 2**). Detailed responses of variables can be observed in **Figure 7**. Unlike EP and CT, ZT and GP are directly related with scores of Axis 1 across years, and so with carbon content across years (**Table 2, Figures 6a, 7**). A different dynamic was detected for the second PCA Axis in which EP and GP increase, ZT remains unchanged and CT decreases through time (**Table 2, Figure 6c**).

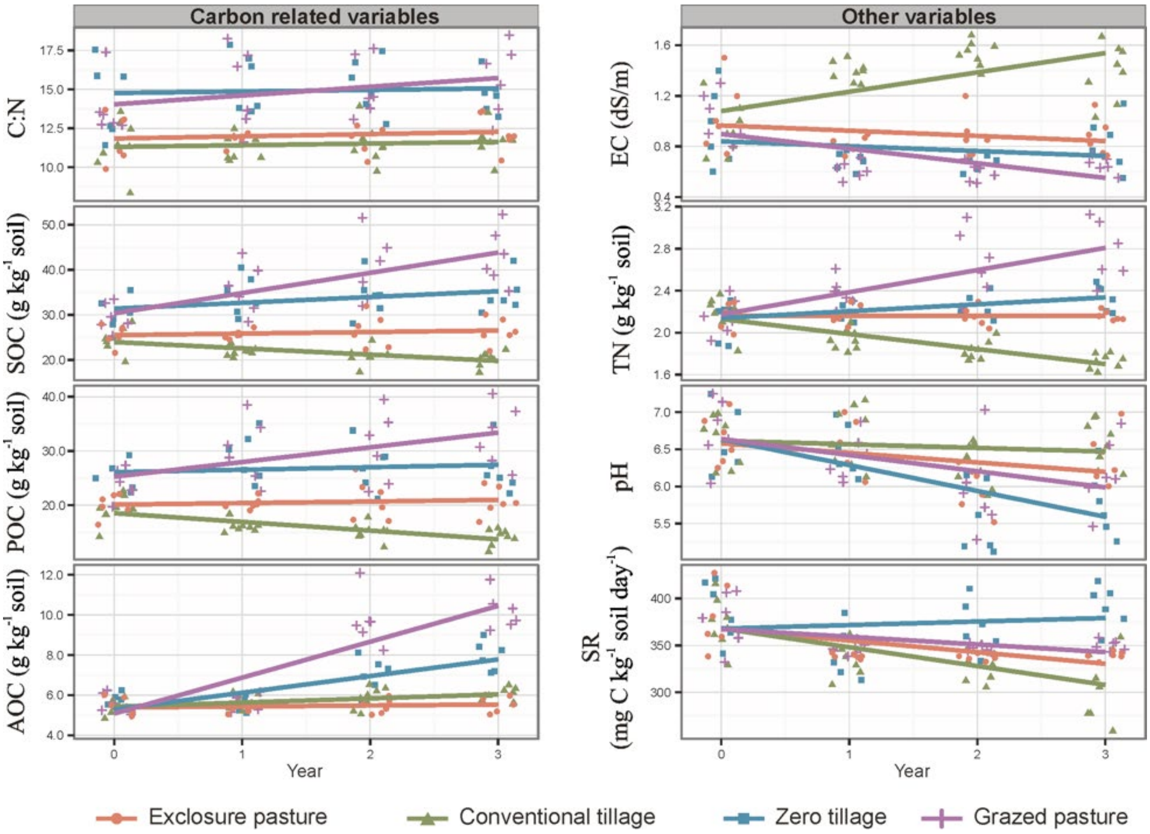

Figure 5. Response of variables over time in the top soil layer. Dots represent individual samples. For each treatment group, a linear regression to the mean for each time point is shown.

Table 2. Output of linear regression models for PCA scores relating to the intermediate soil layer

	Synthetic dependent variables (intermediate layer)	
	PCA Axis 1 scores (1)	PCA Axis 2 scores (2)
Time (years)	-0.095 (0.260)	0.605*** (0.149)
Conventional tillage	0.129 (0.644)	-0.714* (0.368)
Zero tillage	-0.705 (0.688)	-0.202 (0.394)
Grazed pasture	-0.483 (0.688)	-0.259 (0.394)
Time: Conventional tillage	-0.177 (0.344)	-0.849*** (0.197)
Time: Zero tillage	1.304*** (0.368)	-0.614*** (0.210)
Time: Grazed pasture	1.098*** (0.368)	0.152 (0.210)
Constant	-0.373 (0.487)	-0.029 (0.278)
Observations	104	104
R^2	0.382	0.627
Adjusted R^2	0.337	0.599
Residual Std. Error (df = 96)	1.425	0.815
F Statistic (df = 7; 96)	8.470***	23.006***

Note: *p<0.1; **p<0.05; ***p<0.01

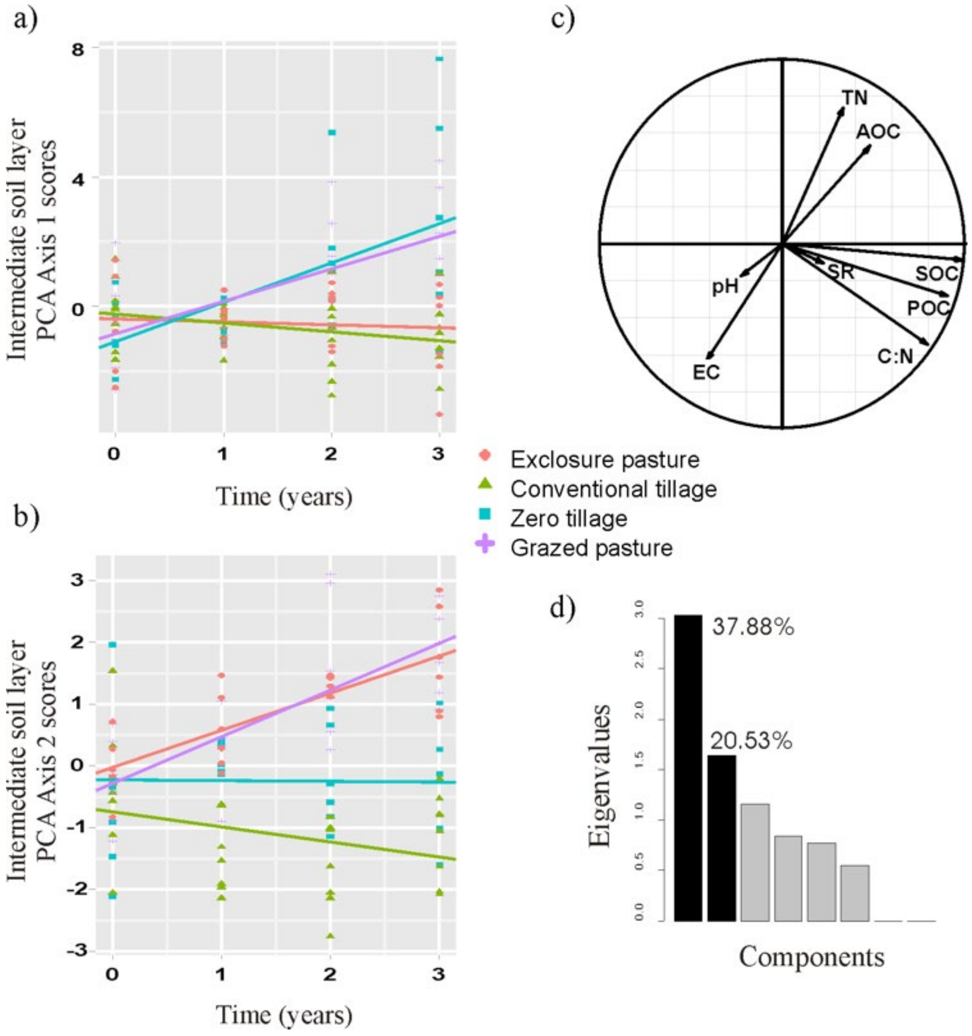

Figure 6. Principal component analysis (PCA) and associated linear regression of component scores applied to the intermediate soil layer dataset. Regressions of PCA Axes 1 (a) and 2 (b) scores on time but separated by treatment. To the right, circle correlation (c) of variables with PCA axes and scree plot of eigenvalues (d) with bars of selected components in solid black.

With regard to the deep layer, PCA yielded two major components accounting for 58.33% of total variance (**Figure 8d**). Linear regressions of all separate variables grouped by treatment on time are graphically expressed in **Figure 9**. Again, POC and SOC load greatly on the first component, whereas TN and EC contribute far more to the second one (**Figure 8c**). Zero tillage (significantly) and GP (borderline significant) increased the SOC content through time, but the other treatments did not affect in this aspect for the first component (**Table 3, Figure 8a**).

A generalized negative slope is recorded for scores of second component, suggesting a yearly nitrogen enrichment of the deep layer for all experimental conditions (**Table 3, Figure 8b**).

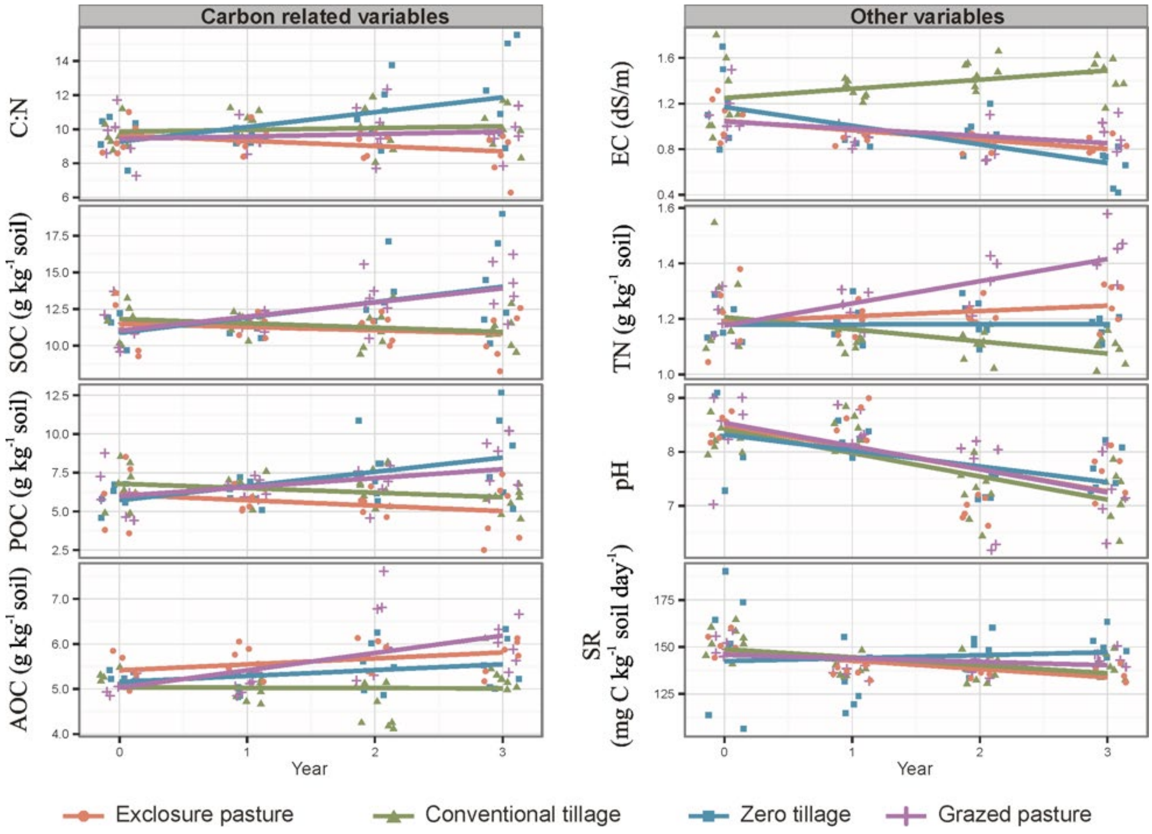

Figure 7. Response of variables over time in the intermediate soil layer. Dots represent individual samples. For each treatment group, a linear regression to the mean for each time point is shown.

Table 3. Output of linear regression models for PCA scores relating to the deep soil layer

	Synthetic dependent variables (intermediate layer)	
	PCA Axis 1 scores (1)	PCA Axis 2 scores (2)
Time (years)	0.362 (0.245)	-0.689*** (0.195)
Conventional tillage	-0.357 (0.607)	-0.950* (0.483)
Zero tillage	-0.034 (0.649)	-0.143 (0.516)
Grazed pasture	0.087 (0.649)	0.327 (0.516)
Time: Conventional tillage	0.279 (0.324)	0.454* (0.258)
Time: Zero tillage	0.984*** (0.347)	0.043 (0.276)
Time: Grazed pasture	0.669* (0.347)	-0.221 (0.276)
Constant	-1.146** (0.459)	1.135*** (0.365)
Observations	104	104
R^2	0.460	0.335
Adjusted R^2	0.420	0.286
Residual Std. Error (df = 96)	1.343	1.069
F Statistic (df = 7; 96)	11.670***	6.895***

Note: *p<0.1; **p<0.05; ***p<0.01

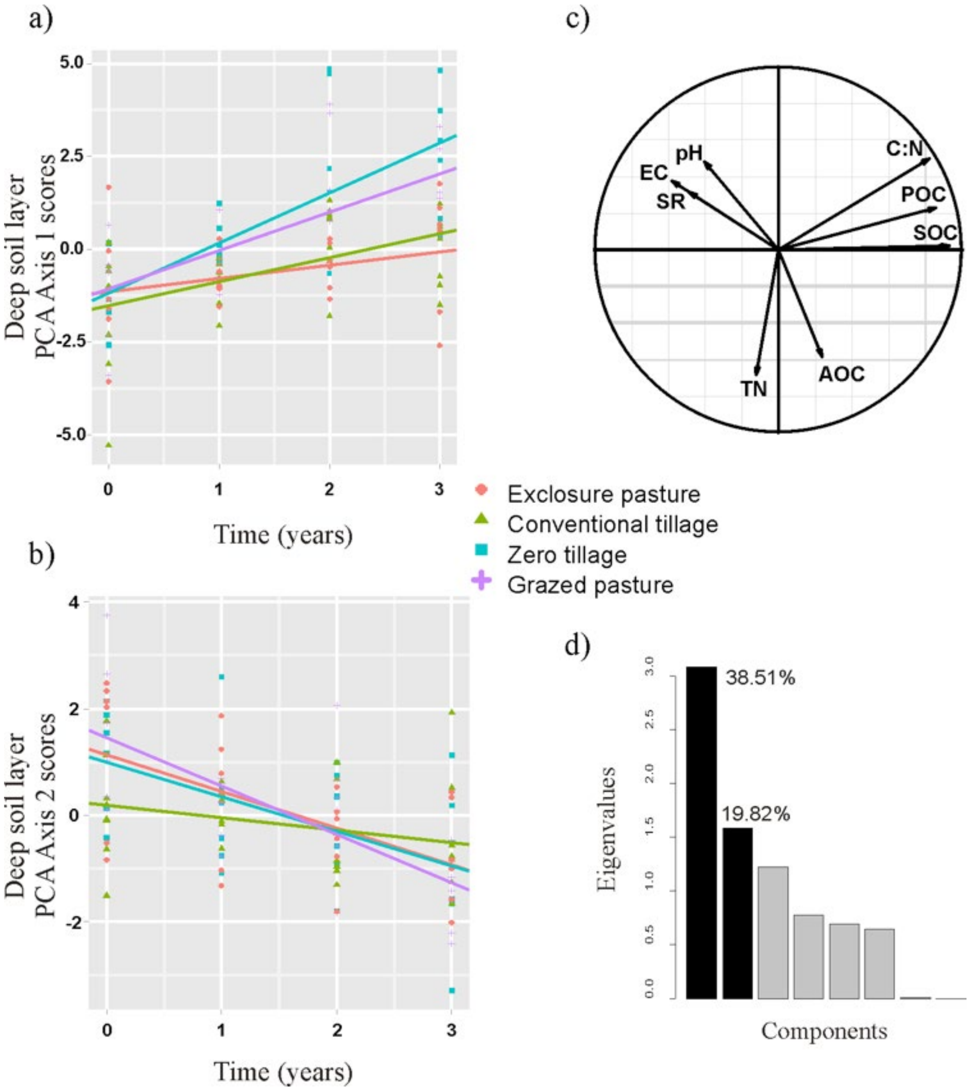

Figure 8. Principal component analysis (PCA) and associated linear regression of component scores applied to the deep soil layer dataset. Regressions of PCA Axes 1 (a) and 2 (b) scores on time but separated by treatment. To the right, circle correlation (c) of variables with PCA axes and scree plot of eigenvalues (d) with bars of selected components in solid black.

4. Discussion

4.1. Broad patterns

In this study, we analysed the dynamics of SQI under different contexts of land use and management practices such as ungrazed/grazed *C. gayana* Finecut and croplands subject to either zero or conventional tillage. Soil layers were different to each other through their profile of chemical and biochemical variables. Top soil was characterized by higher values of SOC, POC, AOC, C:N, TN and SR, but lower values of conductivity and pH. We observed that pH was lower in ZT and GP in the first 5 cm of depth. Nevertheless, there was a tendency to acidification over time for all treatments. Soil salinity (as inferred by electric conductivity) under conventional tillage show higher values compared to the other treatments, suggesting thus management less appropriate to this soil type and conditions given by saline and alkaline water table near surface (Zuccardi and Fadda 1985). With regard to the other layers a see-saw

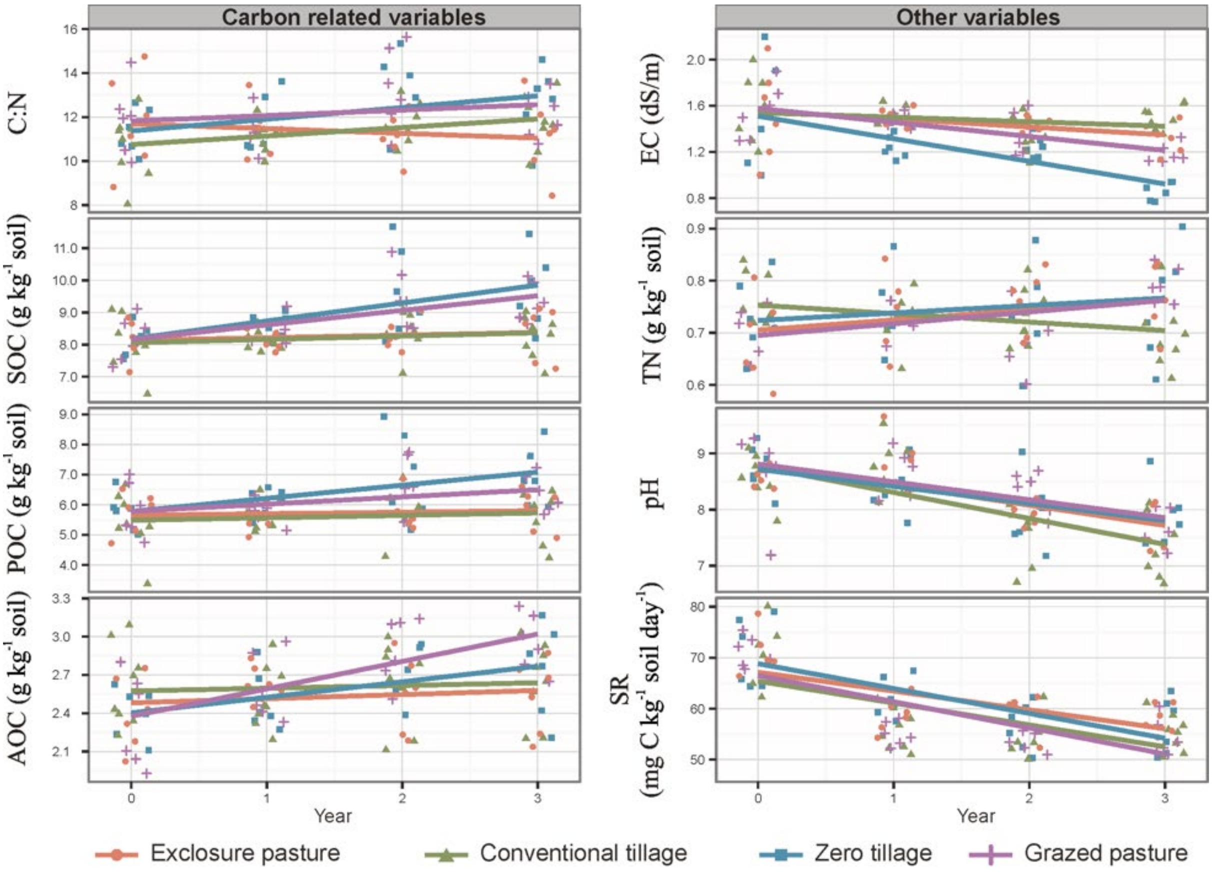

Figure 9. Response of variables over time in the deep soil layer. Dots represent individual samples. For each treatment group, a linear regression to the mean for each time point is shown.

effect was detected for C:N ratio, explained by higher amounts of nitrogen per unit of carbon at the intermediate layer. This phenomenon is probably tied to a decoupled dynamic between both variables. Since processes behind accumulation of SOC and TN can vary independently of each other such as different mechanisms of losses and gains involved, a partial decoupling could be expected in a given time, and thus, carbon and nitrogen stocks might change in opposite directions during this period (Asner et al. 1997; Piñeiro et al. 2010). Nitrogen in root tissues and locally circumscribed cycling within the root zone has been suggested as mechanisms that reduce nitrogen leaching and increase its conservation, potentially enhancing soil organic matter accumulation (Bird and Torn 2006). Nitrate leaching occurs when the soil's nitrogen immobilization and plant uptake capacity has been saturated. It has been hypothesized that N begins to be leached at C/N values below an upper threshold (Rowe et al. 2006). Nutrient leaching triggered by the low C:N ratio at the intermediate soil depth is probably behind the uprising values recorded for the C:N ratio at the deepest soil stratum.

Among other variables, SOC loaded greatly along the first PCA axis of the overall dataset (Figure 1). There is a clear distinction between top layers and the deeper ones marked alongside this first axis. Soil organic carbon could be considered as a single SQI since a large amount of data variability can be accounted for this variable. By virtue of its practical implementation and measurement (Doran and Parkin 1994; Franzluebbers 2002; Galantini and Rosell 2006; Campitelli et al. 2010), we reinforce the notion of SOC as the most appropriate SQI.

4.2. Top soil layer

The superficial stratum or top layer showed significant changes across time for the different variables as indicated by the ANCOVA analysis performed on the respective PCA axes 1 and 2. Soil organic carbon is representative for the behavior of scores along the first axis. Soil organic carbon increased significantly at a rate of 4.5 g C kg^{-1} soil y^{-1} across time for GP and decreased significantly at a rate of 1.4 g C kg^{-1} soil y^{-1} for CT. In the EP and ZT treatments, SOC values tended to remain stable over time. The higher SOC gain in GP than in the other treatments could be related to an intensification in livestock management/grazing systems in the last decades, increasing dry matter production of grazed pastures to support higher animal stocking rates. The greater aboveground dry matter production had a significant positive effect on SOC, especially in grazed pastures, since the residues are not removed and are thus able to contribute directly to soil organic matter formation (Poeplau et al. 2016). In general, Conant et al. (2001) demonstrated that soil C increased with improved grassland management practices, presumably by increasing C inputs from photosynthesis more than C losses from ecosystem respiration. Franzluebbers et al. (2000) also found greater contents of organic carbon and nitrogen under pasture than in zero tillage cropland at a depth of 0-5 cm, and they suggested that ruminant processing of forage and deposition of excreta may contribute to this difference. Increasing aboveground biomass as well as carbon and nitrogen in the soil are among the reported effects for grazing (Schuman et al. 1999; Ganjegunte et al. 2005). Increased carbon and nitrogen cycling in grazed rangelands has been attributed to physical breakdown, litter turnover and incorporation, and root exudation. Immobilization of carbon and nitrogen in litter may explain the lower carbon and nitrogen contents observed in exclosure soils (Schuman et al. 1999; Ganjegunte et al. 2005).

In the same way, grazing was responsible for the greatest gain (2.71 g C kg^{-1} soil y^{-1}) in the POC recorded at the top soil layer. The opposite behavior was reported for CT with a POC loss rate of 1.60 g C kg^{-1} soil y^{-1}. Interestingly, pattern of change across time for POC was not parallelized by the pattern associated with AOC. Although GP still achieves the largest gain rate (1.79 g C kg^{-1} soil y^{-1}); the relative AOC content did not change for CT (0.20 g C kg^{-1} soil y^{-1}, rate not significantly higher than zero). At the end of the study period, the percentage of POC ranged from 76% to 78% of the SOC content for all treatments except CT in which the percentage is lower (70%). At this depth, the labile fraction of organic carbon was mainly related to litter decomposition rate. Therefore, in the treatments with great contribution of residues that were deposited on soil surface and less contact with soil microorganisms (ZT, GP and EP treatments), POC contents were higher (Duval et al. 2013). On the contrary, in CT treatment residues are buried into the soil by plowing and oxidation increases concomitantly, thus accelerating the decomposition process and decreasing POC contents.

The SR is taken as representative for the behavior of scores along the second PCA axis in the top soil layer. Soil respiration decreased significantly across time for the reference level (i.e. the EP treatment) as well as for the GP and CT treatments. Although the SR was stable for ZT over time, the slope was significantly greater than the reference level. Consequently, the effect of ZT can be interpreted as a buffer effect for a more generalized phenomenon of diminished microbial activity throughout the region. We think this finding is remarkable and needs further in-depth analysis and contextualized with the general finding that no-till performed best under rainfed conditions in dry climates (Pittelkow et al. 2015).

4.3. Intermediate soil layer

The PCA performed at the intermediate soil layer revealed a large amount of data variance accounted for the first axis, again highly correlated with SOC. Importantly, both fractions of SOC (POC and AOC) were uncorrelated and loaded differentially on the two main PCA axes. Soil organic carbon increased significantly at a rate of 0.9 g C kg^{-1} soil y^{-1} and 1.0 g C kg^{-1} soil y^{-1} across time for GP and ZT, respectively. In these treatments, SOC and POC increments were positively associated, suggesting that SOC increases in this layer are mainly given by POC increments, possibly due to the important contribution of biomass and root system activity (root-derived inputs) (Franzluebbers et al. 2000). Total nitrogen has been selected as representative for the second PCA axis. Again, this reinforces the hypothesis about the decoupled dynamics between carbon and nitrogen. A difference relates to the imprint of the conventional tillage practice on the dynamics of TN, leading to a significant decrease with regards to the reference level. On the contrary, gains in TN were observed for GP.

4.4. Deep soil layer

As for the intermediate layer, SOC and TN loaded greatly on the first and second PCA axes associated with the deepest layer of soil. Zero tillage and GP led to a gain of SOC (0.47 and 0.37 g C kg^{-1} soil y^{-1}, respectively) at greater rates than the other treatments. Again, AOC and POC remained uncorrelated overall. The changes of TN across time for CT were degressive (i.e. -0.02 g C kg^{-1} soil y^{-1}) and opposite to the increasing changes verified for the rest of treatments.

4.5. General considerations for SOC and SR

Plots assigned to GP and ZT treatments ended up with higher values of POC and AOC than the other experimental units. The detrimental effect of CT on the light fraction of SOC was conspicuous and largely expressed at the topmost layer of soil. This finding shows the sensibility of this labile fraction of SOC when exposed to land use change. Franzluebbers and Stuedemann (2002) found that POC content was in relation to the aboveground biomass and its roots dynamics, as well as to the age of the prairie (stand age) at depths greater than 5 cm. At the deepest depth soil layer, significant SOC increases were recorded for ZT and GP with gain rates of 0.5 and 0.4 g C kg^{-1} soil y^{-1}, respectively. Exclosure pasture and CT did not show changes in SOC contents at this depth, suggesting that the effect of tillage was only present in the first 20 cm of the soil.

In regard to microbial activity, expressed through SR, significant differences were observed between depths. Regardless of land use and when comparing adjacent soil layers, SR was more than double in the upper layer. There are antecedents about the effect of management practices and types of vegetation on the SR rate and that could be attributed to differences in SOC contents (Frank et al. 2006). However, Eriksen and Jensen (2001) reported that management practices (i.e. conventional tillage versus zero tillage) increased CO_2 emission in the period within 2 h after conventional tillage, product of physical release from soil pores and solution rather than the result of an increased microbial activity. At the end of the study period, the higher values of SR corresponded to zero tillage and differences with the other practices are detected in the top and intermediate soil layers. At the deepest soil layer, a more general decreasing trend in SR is applicable to all the treatments. In concordance with our results, LeCain et al. (2002) showed little influence of grazing intensities (grazed and exclosure pastures) on SR rate, suggesting that cattle grazing does not alter SR components of the carbon cycle of the grass. According to this result, Fan et al. (2015) expressed that the annual cumulative respiration flux is not always consistent with organic C content because field management could change soil structure affecting soil microorganisms growth and SOC decomposition (Lai et al. 2013).

5. Conclusions

Behaviour of soil quality parameters in the Chacoan region from South America, devoted in the recent times to tropical productive activities, is a topic of outstanding importance. Here, we evaluate the imprint of different land uses (zero tillage, conventional tillage, exclosure and grazed pastures) on several physical-chemical indicators of soil quality, using for that purpose of long-term dataset spanning for 4 years. We think that our work allows a renewed look (through the help of multivariate statistics) at the study of soil quality parameters under different sources of variation acting across time. From the set of SQI used to assess the effect of different treatments, the largest amount of information is retrieved by SOC. By virtue of information content and facilities, measurement of total organic carbon at the very first 20 cm of soil is encouraged for monitoring land management systems in our study area.

Conventional tillage, which promotes soil removal and oxidation, decreased SOC, POC and TN content, while increased EC values, especially in the top layer (0-5 cm). Zero tillage and grazed pastures showed higher values for SOC, POC and TN gains rate, compared with the other treatments. The Chacoan region represents a hotspot of productive transformation, since cattle ranching and soybean cultivation advance over forests, and the latter activity replaces grasslands. The effects of these changes on the broad spectrum of soil quality remain largely unknown. This work aims to fill this gap of information, highlighting for instance the beneficial effects of ZT and grazed systems in preventing soil profile salinization, and promoting SOC, POC and TN gains. Land use change is not just a matter of differentiated activities, but also management practices. So, agricultural or cattle systems should be analysed recognizing heterogeneity on farming practices and identifying their impacts on a specific site.

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