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Monitoring of soil organic carbon over 10 years in a Mediterranean silvo-pastoral system: potential evaluation for differential management

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Abstract Soil organic carbon (SOC) plays a vital role in determining the susceptibility to land degradation. The recommended procedure for the recovery of the characteristic poor soils of the Southern region of Portugal is the installation of grazed permanent pastures and increase of soil fertility. The objectives of this study were: (i) to identify the spatial and temporal patterns of soil nutrients at four points in time over a 10-year period in a perennial pastureland; (ii) to test new tools for survey of the spatial variability of soil nutrients; (iii) to evaluate the potential for differential organic management. A 6 ha permanent bio-diverse pasture field, grazed by sheep and improved by annual application of super phosphate fertilizer, was installed on a shallow soil in Mediterranean conditions. Spatial variability and temporal stability of topsoil macronutrients (phosphorus, nitrogen and potassium), SOC and pH were measured. The results indicate that SOC and pH have great potential for implementing differential management. In the case of SOC, the management classes map shows that over 80 % of the area has temporal stability, while more than 50 % of the area has low levels of SOC (<10 g kg^{-1}), justifying the potential for differential application of C-rich organic soil amendments. The geospatial measurements of apparent soil electrical conductivity (EC_a) and NDVI index showed significant correlation between these parameters and soil properties, revealing the potential of these tools for producing detailed soil maps, decisive for understanding the changes in soil properties under sustainable management systems.

Keywords Soil organic carbon · Pastures · Spatial variability · Temporal stability · Grazing animal

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Introduction

Soil use management in Mediterranean region

Human activity has a long history in the Mediterranean basin with land cultivation having been continuously practiced for more than 5000 years (Romanya and Rovira 2011). More recently, agriculture has been intensified through the general use of machinery, fertilizers and other chemicals (Romanya and Rovira 2011).

In Southern region of Portugal, intensive land use with cereal monoculture, subject to soil tillage operations with heavy implements just after the first autumn rains has prevailed for decades. The characteristic undulating relief, in association with this form of land use management, has originated mechanisms of erosion and soil transport, leading to degraded, shallow and stony soils, with low organic matter content and a tendency to become acidic, all limiting factors for productivity (Yuan et al. 2007). Since low soil organic carbon (SOC) content may have negative impacts on soil physical properties and on nutrient cycling, efforts have been made to define soil degradation thresholds based on SOC content. It is estimated that 16 % of cultivated land in Europe is vulnerable to desertification, although this proportion may be even higher in areas with harsh climates such as in the Mediterranean, which experiences frequent summer droughts (Romanya and Rovira 2011).

The role of permanent pastures on soil fertility and SOC dynamics

Since the 1980s, soil conservation policies have been implemented, with preference for itineraries with reduced mobilization. In this framework, the standard procedure for the recovery of degraded and poor soils is the seeding of grazed permanent pastures and increase soil fertility through fertilizer applications (Efe Serrano 2006). Land cover management has been an effective strategy in managing land degradation through the reduction of water, soil and nutrient losses and increasing the soil fertility and quality (Yadav et al. 2014).

The existing knowledge about the influence of different soil management systems on the SOC dynamics in the Mediterranean agro-silvo-pastoral ecosystems is insufficient to develop conservative strategies (Seddaiu et al. 2013). SOC is a major component of the soil organic fraction and plays a vital role in determining many soil chemical, biological and physical properties and the susceptibility to land degradation (Mu et al. 2014). SOC in grasslands represents one of the largest reserves of carbon (C) on earth and is therefore an important part of the global C cycle (Rutledge et al. 2014), being one of the more important potential sinks of greenhouse gases in the effort to mitigate climate change (Mu et al. 2014; Ritchie 2014). Changes in the soil C storage occur when inputs of C (e.g. photosynthesis and organic matter imports) are not in balance with C outputs (e.g. ecosystem respiration, grazing, leaching and erosion) (Rutledge et al. 2014). Climate variability, anthropogenic land use and management practices can change these inputs and outputs and, consequently the soil C stocks (Whitmore et al. 2014). The C stock of soil under pasture represents the dynamic balance between the addition of dead plant material and the loss by decomposition or mineralization (Machado 2005). Numerous studies have reported the contribution of C mineralization to atmospheric CO_2 from intensively cropped land (Yan et al. 2012) and the consequent loss of SOC by conversion of natural vegetation to cultivated systems is well known (Rutledge et al. 2014). In contrast, little is known about the impact of permanent and grazed pasture ecosystems on SOC dynamics (Rutledge et al. 2014; Schipper et al. 2014).

New tools for monitoring soil properties

Precision agriculture strategy seeks to match resource application and agronomic practice with soil and crop requirements, since these vary in both space and time. Therefore, an understanding of both the temporal and spatial components of variability is essential before decisions can be made about the feasibility of site-specific management (Shi et al. 2002). Intensive grid-sampling is generally regarded as one of the most accurate means of evaluating the spatial variability. Taking into account the need for a large number of soil samples in order to achieve a good representation of any soil property, the traditional method of soil sampling, laboratory work and mapping is costly, labour-intensive and not feasible at the farm scale (King et al. 2005). Therefore, it is desirable to find more rapid and economical means of obtaining information for detailed soil mapping (King et al. 2005). The application of geospatial measurements of apparent soil electrical conductivity (EC_a) combined with the use of global navigation satellite systems (GNSS) and geographical information systems (GIS) is one of the most reliable techniques to characterize the spatial pattern of soil properties within fields (Moral et al. 2010). Precision agriculture tends to promote the use of efficient and inexpensive methods over larger areas in order to acquire and map soil and crop parameters, which is decisive for sustainable management. Several vegetation indexes obtained by means of remote and proximal sensing have been developed, tested and improved over the past 40 years by researchers in order to estimate and compare many leaf and canopy properties. Normalized difference vegetation index (NDVI) is normally correlated with vegetative vigour (Broge and Leblanc 2000; Gitelson 2004). This can be seen as another rapid means of obtaining information for detailed soil or pasture mapping.

Objectives of this study

Given the increasing demand for food production, a greater understanding of the evolution of soil properties under the diverse pasture management systems around the world is required (Schipper et al. 2014). Long-term studies are essential to evaluate the magnitude of temporal dynamics of SOC flux and pools in terrestrial ecosystems, to further the understanding of C cycling in productive soils, and to assess the responses of these systems to fertilizer management (Rutledge et al. 2014). Careful temporal measurements of soil C stocks in pasture-based agriculture are needed to quantify effects of different grazing management practices (Schipper et al. 2014). In this context, the objectives of this study were: (i) to identify the spatial and temporal patterns of soil nutrients at four points in time over a 10-year period in a perennial pastureland; (ii) to test new tools for survey of the spatial variability of soil nutrients; (iii) to evaluate the potential for differential organic management.

Materials and methods

Site characteristics and management history

The experimental field, with an area of 6 ha, is located at the Revilheira farm ($38°27'51.6''$N and $7°25'46.2''$W) in Southern Portugal. The predominant soil of this field is classified as a Leptic Luvisol (FAO 2006). The Leptic Luvisol profile is characterized by a pedogenetic differentiation of clay content with a lower content in the topsoil and a higher content in the subsoil. Luvisols on steep slopes are very prone to erosion in regions with distinct dry and wet seasons, such as the Mediterranean region, where the soils of the upper slopes are usually more shallow due to many years of deep cultivation for intensive cereal production. In this region these shallow soils are used mainly for extensive grazing or planted to tree crops (Serrano et al. 2014). Therefore, Alto Alentejo region in Southern Portugal has over 200 000 ha of grazing permanent pastures (Serrano et al. 2014), installed predominantly in areas with poor soils and with pronounced risks of erosion (Efe Serrano 2006).

The Mediterranean climate can be considered as a transition between temperate and dry subtropical climates. It is characterized by summer drought, variable rainfall, and mild or moderately cold winters (Romanya and Rovira 2011). The annual rainfall in the region is between 400 and 600 mm; rainfall occurs mainly between October and March and is practically non-existent during the summer. The monthly average temperature is between 8 and 26 °C; minimum temperatures are close to 0 °C between December and February.

A permanent pasture was established in this field in September 2000. Super phosphate fertilizer application is the basic factor for improving the biodiverse pastures (grasses and legumes) in this region (Efe Serrano 2006). During the 2000–2003 period, the field was used for grazing by sheep and maintained and improved by an annual homogeneous application of 300 kg ha^{-1} of super phosphate fertilizer 18 % (54 kg ha^{-1} of P_2O_5) in September/October.

In the following experimental period (10 years between 2004 and 2013) the field was subjected to two phases of intervention (Fig. 1): (i) field management 1 (2004–2007), during which the field was used for grazing by sheep in a flexible rotation system throughout the year and improved by an annual and variable-rate application of super phosphate 18 %; (ii) field management 2 (2007–2013), during which the field was left fallow without any animal grazing or fertilizer application.

Under the grazing system used in field management 1 (2004–2007), the area was divided into various parcels for grazing, and one of these was used as the experimental field. The parcels were fenced and the animals grazed each one during a variable length of time based on the state of the pasture, as determined by the farm manager. The aim was to ensure that the animals graze the pasture intensively, which is fundamental for full development of the botanic species. Following this intensive grazing, the land was left for a sufficiently long period without animals to allow the plant species to regenerate in the pasture. The annual and differential application of super phosphate 18 % during September and October, consisted of four differential application rates (80, 60, 30 and 0 kg P_2O_5

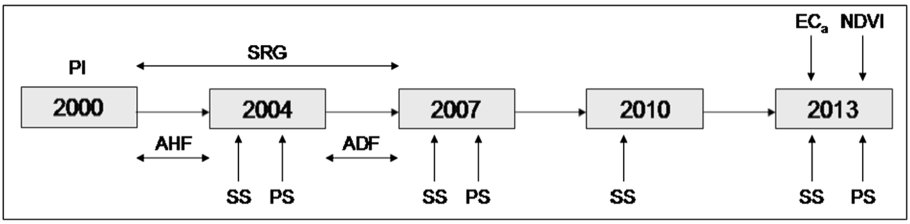

Fig. 1 Chronological diagram of the "Revilheira" pasture field management between 2000 and 2013. *PI* pasture installation, *SRG* sheep rotational grazing, *AHF* annual homogeneous fertilization, *ADF* annual differential fertilization, *SS* soil sampling, *PS* pasture sampling, *ECa* soil apparent electrical conductivity survey, *NDVI* vegetation multispectral survey

ha^{-1}) based on classes of existing soil P_2O_5 concentration at the end of the pasture growth cycle (May–June). The goal was to increase the concentration of P_2O_5 in the soil gradually to about 100 mg P_2O_5 kg^{-1}.

Digital elevation model

A topographic survey of the area was carried out using a real time kinematic (RTK) GPS instrument (Trimble RTK/PP—4700 GPS, manufactured by TRIMBLE Navigation Limited, USA). The altimetry data were sampled in the field with an all-terrain vehicle on paths approximately 10 m apart. The digital elevation model surface was created using the linear interpolation TIN tool from ArcGIS 9.3 (ESRI 2009) and converted to a grid surface with a 1 m grid resolution. The altimetry data were used to calculate the slope in the experimental field.

Soil and pasture sample collection and analysis

Seventy-six geo-referenced (with GPS) soil and pasture samples were taken from each 28 × 28 m square at four points in time over a 10-year period.

Soil samples were taken each year (2004, 2007, 2010 and 2013) at the end of spring (at the end of the crop growth period) using a gouge auger and a hammer, from the 0–0.30 m soil layer. Each composite sample comprised five sub-samples, one taken from the centre of the square and the other four taken near its corners. In 2004 and 2007 the texture (sand, silt and clay) was determined. The fine soil was characterized every sampling year in terms of pH, SOC, NO_3, P_2O_5 and K_2O. The soil samples were inserted in plastic bags, air-dried and analyzed for particle-size distribution using a sedimentographer (Sedigraph 5100, manufactured by Micromeritics), after passing the fine components through a 2 mm sieve. These fine components (<2 mm fraction) were analyzed using the following methods (Egner et al. 1960): (i) pH in 1:2.5 (soil: water) suspension, using the potentiometric method; (ii) SOC by dry combustion at 1300 °C in a Leco SC144DR elemental analyser (LECO Corporation, St. Joseph, Michigan, USA); NO_3 using the selective ion method; (iii) P_2O_5 using colorimetric method; (iv) K_2O using a flame photometer.

Samples from the pasture were taken manually in 2004, 2007 and 2013 from 1 m^2 areas in each square using shears. The pasture had been protected from grazing in the sampling areas using pre-installed exclusion cages at the southeast corner of each square in the grid. Sampling was carried out each year from March to May, depending on the vegetative growth stage of the pasture. The pasture samples were stored in marked plastic bags and weighed to determine the green matter production per hectare. The samples were placed in an oven at 65 °C for 48 h to determine moisture content, which was used to calculate dry matter yield.

Apparent soil electrical conductivity and vegetation multispectral surveys

Two devices were tested in February 2013 for the rapid mapping of the field:

i. Veris 2000 XA contact-type sensor (Veris Technologies, Salina, KS, USA), equipped with a global positioning system (GPS) antenna. This sensor was used to measure the

EC_a in the experimental field. It was programmed to take measurements every second, mapping the topsoil from the 0 to 0.30 m pseudo depths. This soil resistance sensor was pulled by a conventional tractor at an average speed of 5 km h^{-1}. Each 28 m by 28 m square was covered twice in opposite directions, with a spacing of about 14 m.

ii. OptRx active crop sensor, constructed by Ag Leader (2202 South River Side Drive Ames, IOWA 50010, USA) and used to generate multispectral databases. This sensor simultaneously measures three infrared bands: (i) RED—670 nm with a range of 20 nm; (ii) Red Edge—728 nm with a range of 16 nm; and (iii) NIR—775 nm with basically everything under 750 nm being filtered out. Based on these spectral bands, NDVI was calculated considering the following expression: [(NIR – RED)/(NIR + RED)]. Two OptRx crop sensors were mounted on a purpose built frame attached to an ATV (four-wheeler), at a height of 0.5 m above pasture vegetation. Multispectral information was collected at the same locations where soil and plant samples were collected. The OptRx crop sensor measurements were registered and point positioned by means of a Trimble GNSS GeoExplorer 6000 series, model 88951 with sub-meter precision (Trimble: GmbH, Am Prime Parc 11, 65479 Raunheim, Germany).

Classical statistics, spatial interpolation and regression analyses

Descriptive statistics, including mean, standard deviation (SD), coefficient of variation (CV), and range, were determined for each dataset.

After obtaining soil properties, the values were spatially represented in the form of maps generated in raster format. All surface maps of soil attributes were produced with the ArcMap/Spatial Analyst module of ArcGIS (ESRI 2009) using the raw data in a 28 m by 28 m grid.

The Welch's *t* test was used for mean separation between soil parameters and pasture dry matter yield obtained in sampling points of grid cells with and without trees ($p < 0.05$).

Linear regression analysis was used to study the relationships between soil variables and EC_a and NDVI data. Correlation coefficients "r" for the statistically significant ($p < 0.05$) regression relations were then presented.

Spatial variability analysis

The spatial variability of the soil parameters was calculated as the mean value ($\overline{y_i}$) at the *i*th sampling point over the years of evaluation (2004, 2007, 2010 and 2013) (Eq. 1) (Blackmore 2000; Shi et al. 2002; Xu et al. 2006):

$$\overline{y_i} = \frac{\sum_{t=1}^{n} y_{i_t}}{n} \tag{1}$$

where y_{i_t} is the soil parameter value at the sampling point *i* at time *t* and *n* is the number of sampling years.

Temporal stability analysis

The temporal stability of soil parameters was evaluated by the coefficient of variation at each sampling point over the years of evaluation (Eq. 2) (Blackmore 2000; Xu et al. 2006).

$$CV_i = \frac{\left(\frac{n\sum_{t=1}^{t=n} y_{i_t}^2 - \left(\sum_{t=1}^{t=n} y_{i_t}\right)^2}{n(n-1)}\right)^{0.5}}{\overline{y_i}} \times 100 \tag{2}$$

where CV_i is the coefficient of variation over time at sampling point i.

The average coefficient of variation ($\overline{CV}$) for each year for all sampling points was calculated as follows (Eq. 3) (Xu et al. 2006):

$$\overline{CV} = \frac{\sum_{i=1}^{m} CV_i}{m} \tag{3}$$

where m is the number of soil sampling points.

The annual $\overline{CV}$ for all sampling points was calculated to show the relative magnitudes of temporal variation for soil parameters; large values of $\overline{CV}$ indicate considerable temporal variation.

Maps of management classes

Although the two techniques described above quantify the spatial and temporal variation, they can be combined further into a single map of management classes, which can be used for future decision making. These maps distinguish between different areas of the field in relation to their spatial and temporal characteristics. The following five classes were established: 1- greater than field mean concentration and stable; 2- greater than field mean concentration and moderately stable; 3- smaller than field mean concentration and stable; 4- smaller than field mean concentration and moderately stable; and 5- unstable (Xu et al. 2006). Each sampling point was represented by a coded value. The sampling points were classified by applying combinational logic statements to the spatial variation and temporal stability data sets, considering the following conditions: condition 1 (relative value) identifies whether the point is above or below the average of all points for all the years; condition 2 (temporal stability) identifies the stability of soil parameters at a particular point by comparing the CV to an arbitrary threshold (15 and 25 %, stable and moderately stable respectively, as used by Xu et al. 2006). A point was considered to belong to a particular class if both conditions were true, and it was then assigned an arbitrary class code shown in brackets.

Results and discussion

Soil properties of the experimental field

The topographic map (Fig. 2a) shows the 76 points where soil and pasture were sampled (red circles identify sampling points in the 20 grid cells that include trees), altimetry, surface water flow lines and location of clusters of trees in the experimental field. The slope map (Fig. 2b) shows three clear types of relief in the landscape: a zone of reduced slope (<5 %) in the valley; a zone of maximum slope (>7.5 %), which provides the transition between the flow lines and the ridges; and a zone of intermediate slope (5–7.5 %) in the upper part of the experimental field, where a higher concentration of trees can be observed. The area with maximum slope (Fig. 2b) also corresponds to higher soil clay content (Fig. 3). These maps show that landscape topography is a cause of variability in

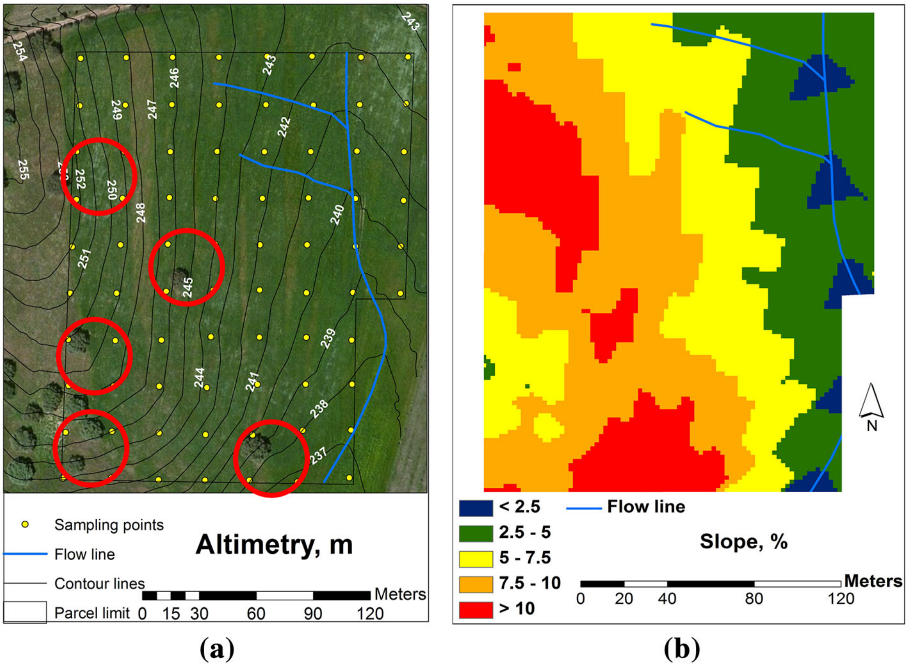

Fig. 2 Maps of altimetry (**a**) (*red circles* identify 20 sampling points in grid cells with trees) and slope (**b**) of the experimental field

many of the studied soil parameters, a phenomenon which was also observed by Kumhálová et al. (2011). The higher soil clay content in the upper areas of the field shows, in these shallow soils, that the B horizon is exposed or very near the soil surface in the eroded areas of the landscape, while in the valleys, this same clay horizon is located at a greater depth (Serrano et al. 2010).

Table 1 presents the mean, standard deviation and the range of soil and pasture parameters at the experimental field in sampling years. The general characteristics of the soil are: clay loam texture; low SOC concentration (predominantly between 8–12 g kg^{-1}, corresponding to soil organic matter concentration, SOM <2 %); slightly acid; relatively rich in potassium; poor in nitrogen and phosphorus. Corral-Fernández et al. (2013) emphasized that the climate and soil use are two factors that greatly influence SOC content in the Mediterranean climate, besides texture, slope and altitude.

Table 1 also shows that pasture productivity is low. The irregular rainfall distribution with a four month hot and dry season, combined with a shallow soil, leads to low and irregular annual production of pasture dry matter (Efe Serrano 2006). There is a very large increase in pasture dry matter yield and a reduction of spatial variability from 2004 (1659 ± 1045 kg ha^{-1}) to 2007 (3232 ± 941 kg ha^{-1}), as a result of the differential application of super phosphate 18 % fertilizer (between 2004 and 2007), coupled with a favourable rainfall distribution. According to Schipper et al. (2014), phosphorus fertilizer stimulates pasture production and, according to Serrano et al. (2013), soil moisture content is a determinant productivity factor in dry-land pastures. This results in a gain in average SOC (increased from 9.6 ± 1.6 g kg^{-1} in 2004 to 12.2 ± 2.9 g kg^{-1} in 2010), as

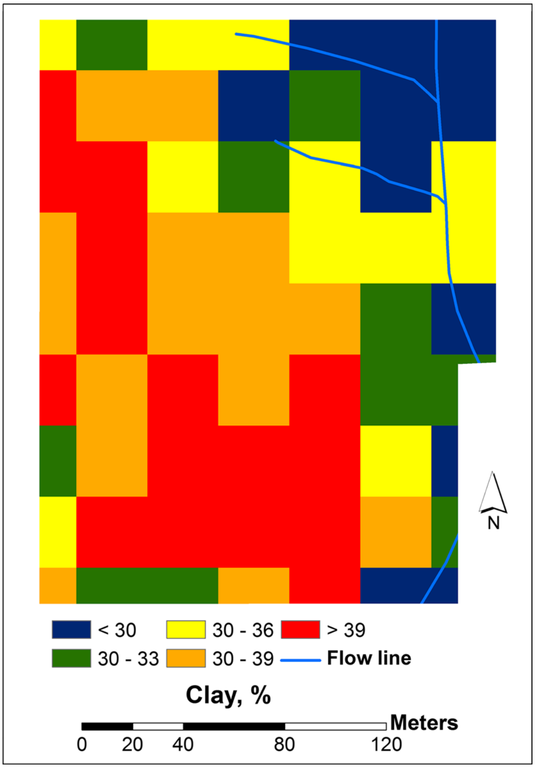

Fig. 3 Spatial pattern of soil clay content in the experimental field

suggested by Liu et al. (2014), due to improved use of the applied phosphorus fertilizer by the pasture. For a given soil and climate, it has been shown that fertilizer management can be used to increase C stocks under perennial pastures (Orgill et al. 2014). These perennial crops, with absence of soil disturbance, greater organic residue cycling levels, and addition of animal waste tend to increase SOC levels (Xavier et al. 2013; Whitmore et al. 2014).

In 2013, after six years without fertilizer application and without the presence of grazing animals, pasture productivity decreased to values lower than those obtained in 2004 (Table 1), accompanied by a decrease in the SOC (to 10.7 ± 2.9 g kg^{-1}). The SOC decrease may be attributed to three causes: (i) six years of no fertilizer application (2008–2013) and the consequent decrease of pasture productivity; (ii) the animal grazing suspension in the same period (Seddaiu et al. 2013); (iii) and the favourable conditions provided by Mediterranean climates for SOC decomposition (Romanya and Rovira 2011) by chemical and biological means and by the reduced rate of stabilization within aggregates and organo-mineral complexes (Whitmore et al. 2014).

Spatial variability and temporal stability of soil properties

Figures 4, 5, 6, 7 and 8 show the spatial variability and temporal stability of the soil properties (P_2O_5, K_2O, NO_3, pH and SOC) at four points in time, between 2004 and 2013. A pattern of accumulation of several nutrients (and pH increase) in the upper areas of the field (south-west corner) is evident, with this accumulation particularly significant in 2010.

Table 1 Mean, standard deviation (SD) and range of soil and pasture parameters at the experimental field in sampling years

Sampling year	2004		2007		2010		2013	
Parameter	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range
Soil								
Sand (%)	43.6 ± 7.3	[27.6–59.2]	43.5 ± 5.4	[30.5–55.5]	–	–	–	–
Silt (%)	22.6 ± 2.6	[14.8–27.5]	20.7 ± 4.1	[14.1–30.4]	–	–	–	–
Clay (%)	33.9 ± 6.2	[21.2–45.6]	35.8 ± 6.1	[23.0–49.2]	–	–	–	–
P_2O_5 (mg kg^{-1})	33.3 ± 12.2	[14.0–92.0]	52.5 ± 42.8	[20.0–394.0]	52.9 ± 21.1	[24.0–124.0]	61.3 ± 32.1	[36.0–184.0]
NO_3 (mg kg^{-1})	10.4 ± 7.1	[1.5–30.5]	4.2 ± 1.8	[0.5–9.5]	46.8 ± 16.4	[21.5–85.0]	9.1 ± 8.1	[3.0–39.5]
K_2O (mg kg^{-1})	94.1 ± 25.1	[56.0–244.0]	76.7 ± 36.7	[40.0–352.0]	111.7 ± 24.2	[80.0–166.0]	97.1 ± 21.3	[66.0–162.0]
SOC (g kg^{-1})	9.6 ± 1.6	[6.4–13.9]	8.9 ± 2.3	[4.6–22.0]	12.2 ± 2.9	[8.1–20.3]	10.7 ± 2.9	[3.5–18.6]
pH	6.2 ± 0.3	[5.7–7.4]	6.1 ± 0.4	[5.4–7.5]	6.0 ± 0.3	[5.4–6.9]	6.4 ± 0.2	[6.0–7.0]
EC_a (mS m^{-1})	–	–	–	–	–	–	4.0 ± 1.6	[1.5–8.3]
Pasture								
DM (kg ha^{-1})	1659 ± 1045	[301– 7167]	3232 ± 941	[1861– 6191]	–	–	1637 ± 924	[628–3867]
Soil and pasture								
NDVI	–	–	–	–	–	–	0.657 ± 0.039	[0.605–0.735]

DM-Pasture dry matter yield

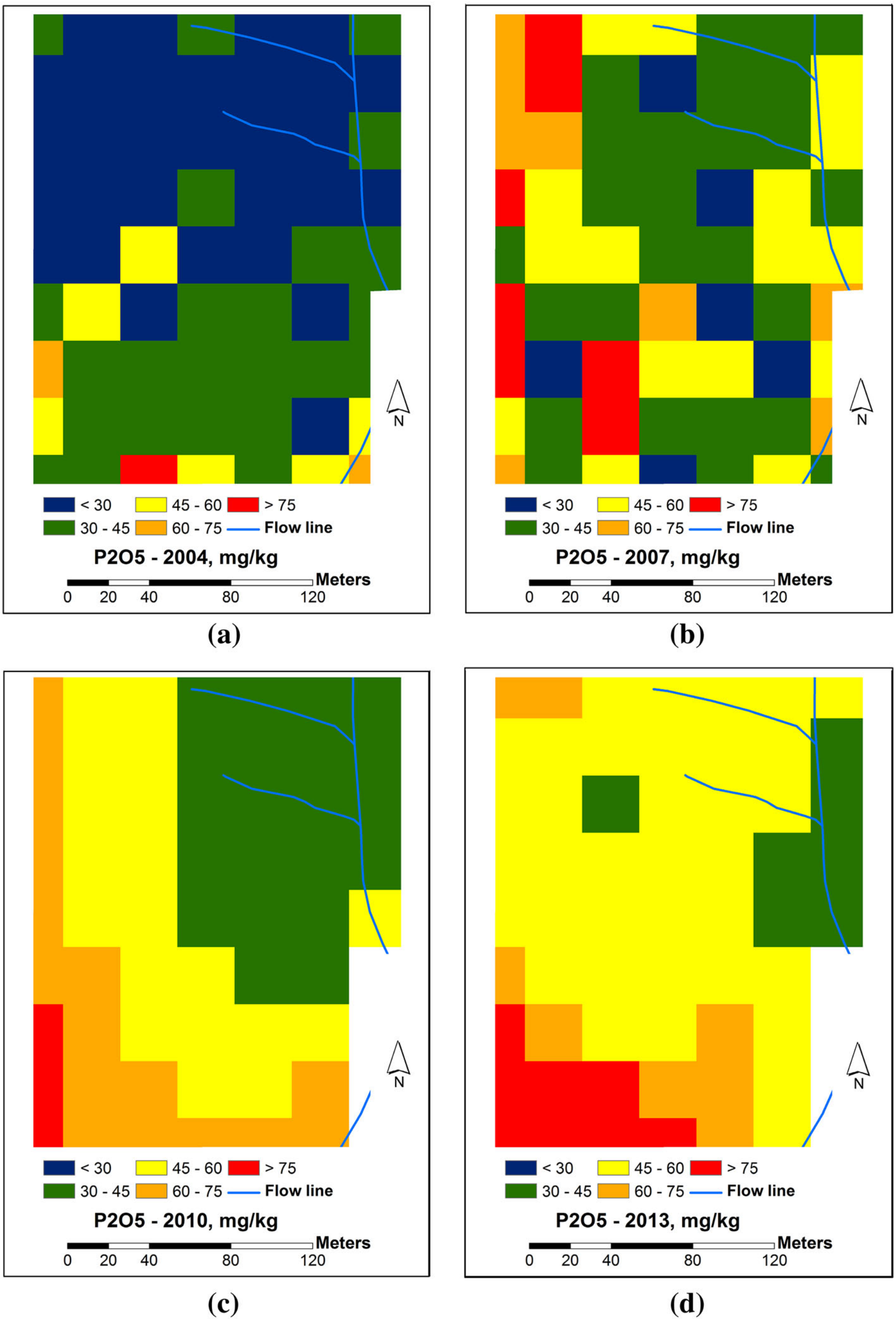

Fig. 4 Spatial patterns of P_2O_5 in the experimental field in sampling years (**a**, **b**, **c** and **d**, respectively 2004, 2007, 2010 and 2013)

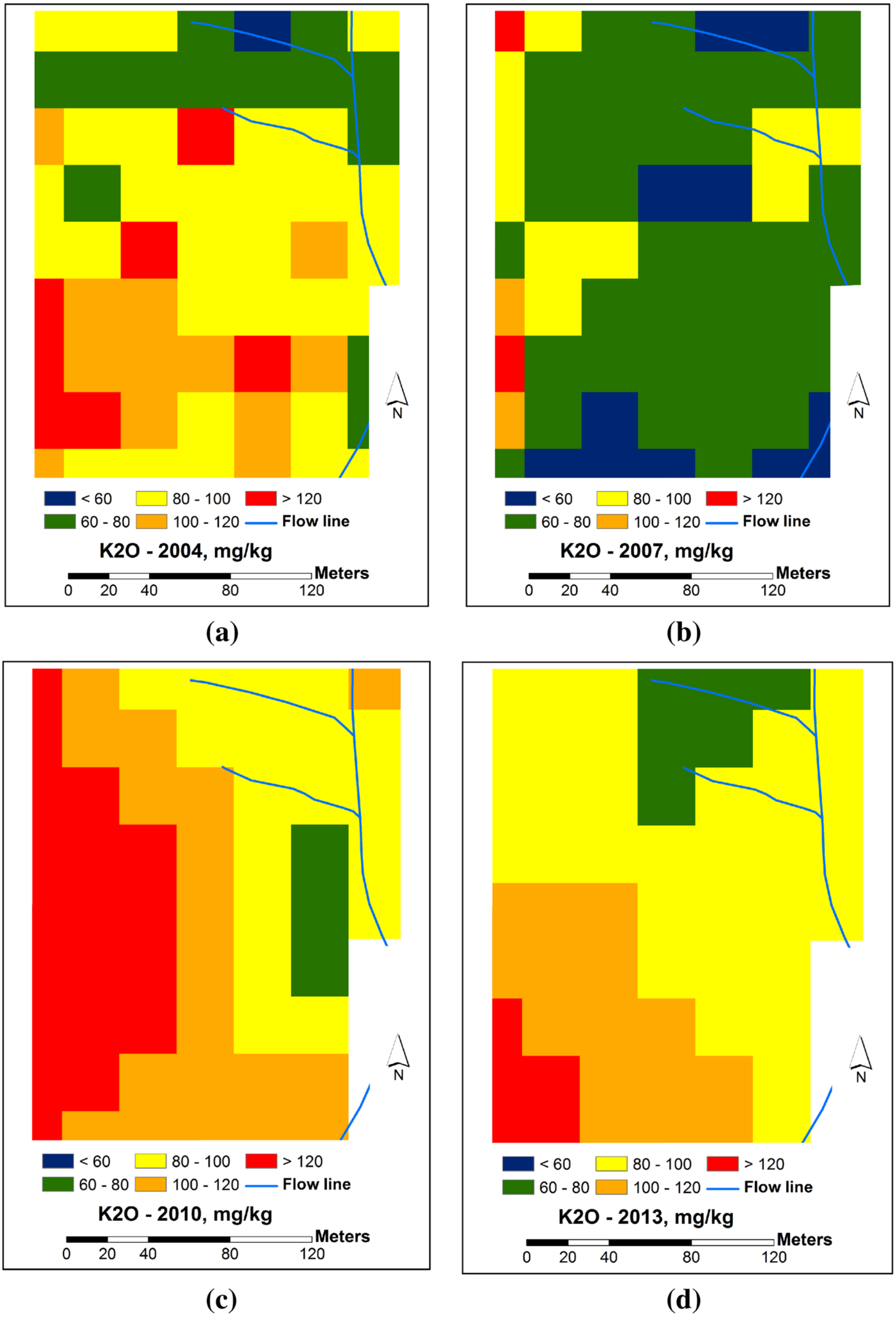

Fig. 5 Spatial patterns of K_2O in the experimental field in sampling years (**a**, **b**, **c** and **d**, respectively 2004, 2007, 2010 and 2013)

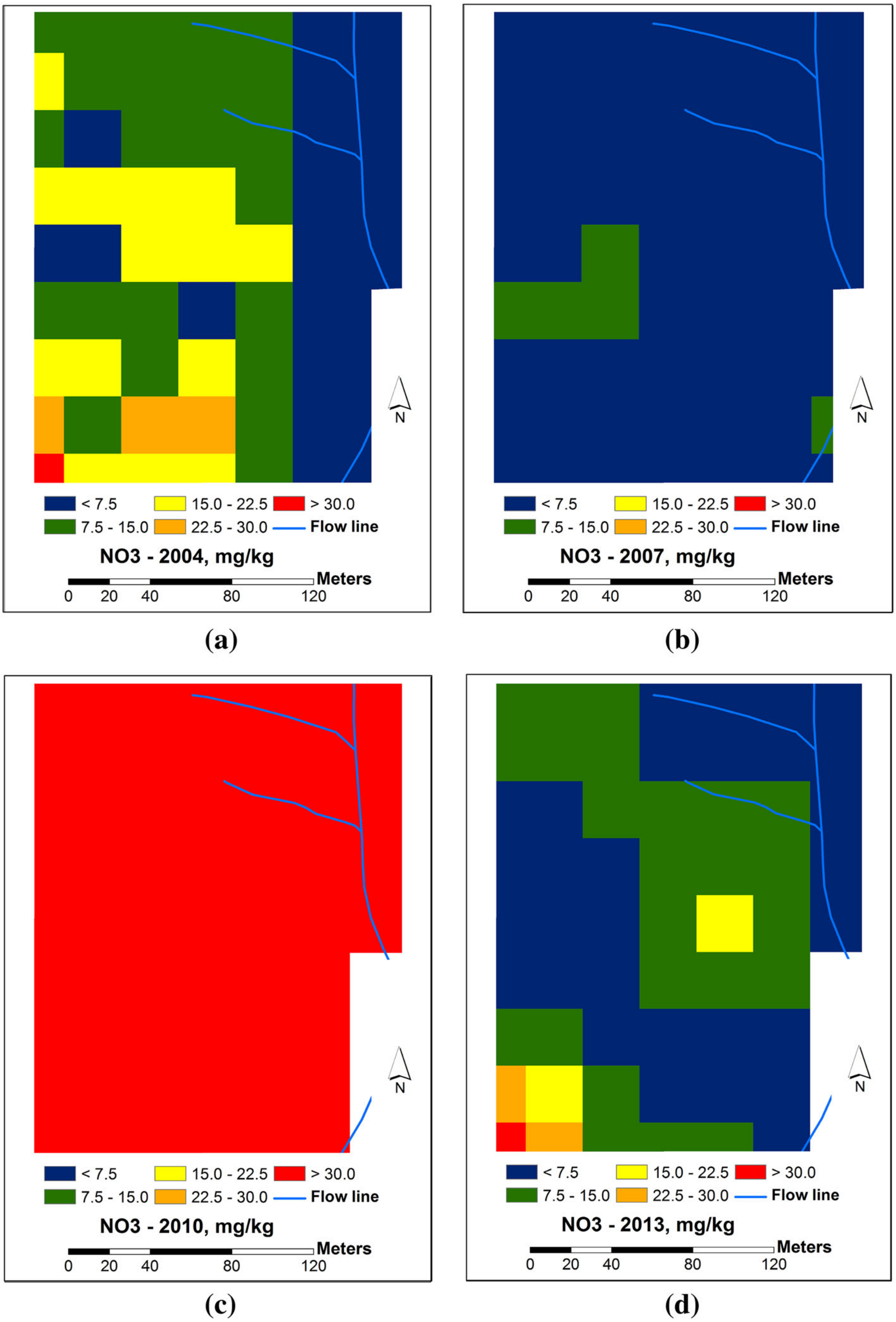

Fig. 6 Spatial patterns of NO_3 in the experimental field in sampling years (**a**, **b**, **c** and **d**, respectively 2004, 2007, 2010 and 2013)

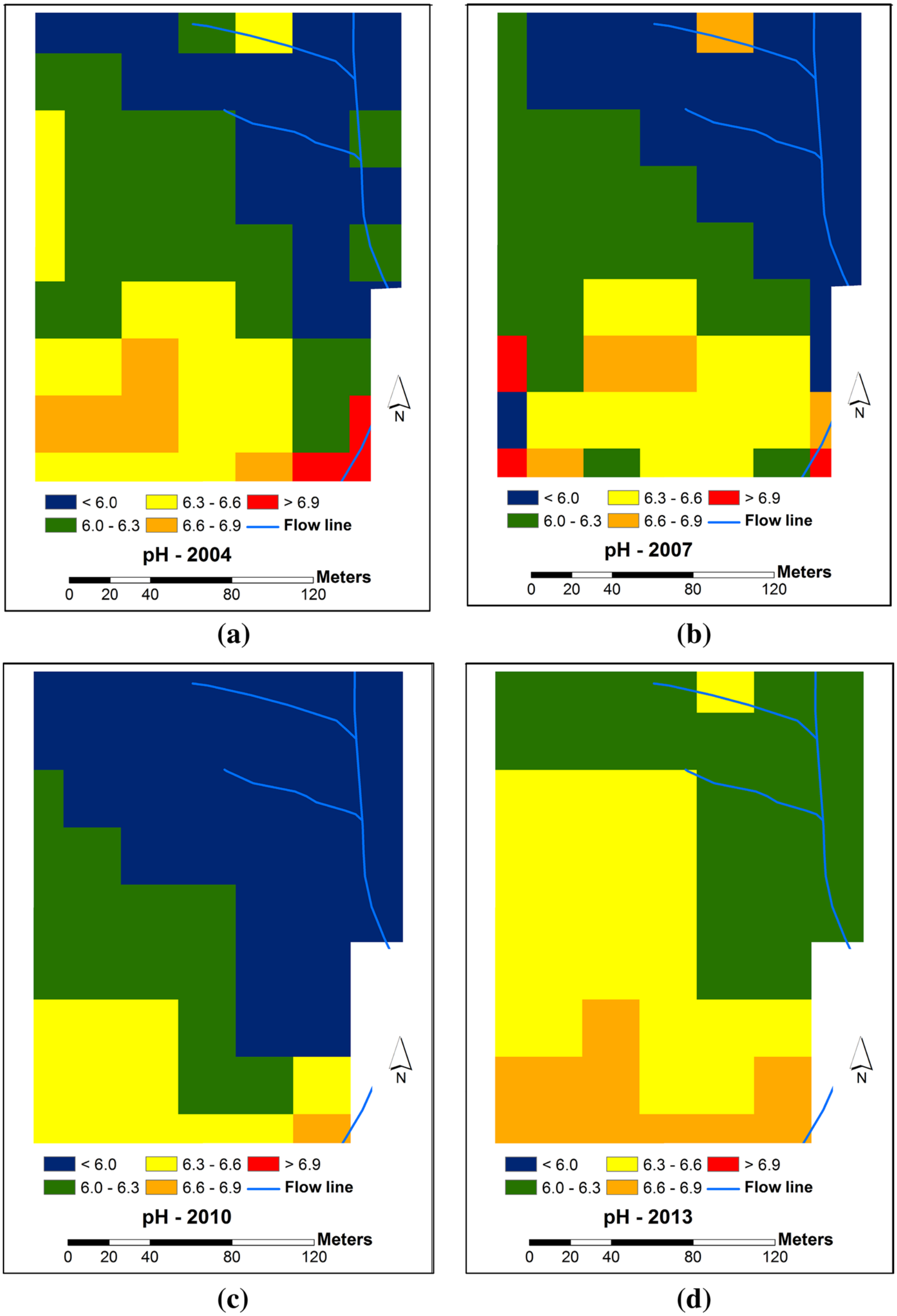

Fig. 7 Spatial patterns of pH in the experimental field in sampling years (**a**, **b**, **c** and **d**, respectively 2004, 2007, 2010 and 2013)

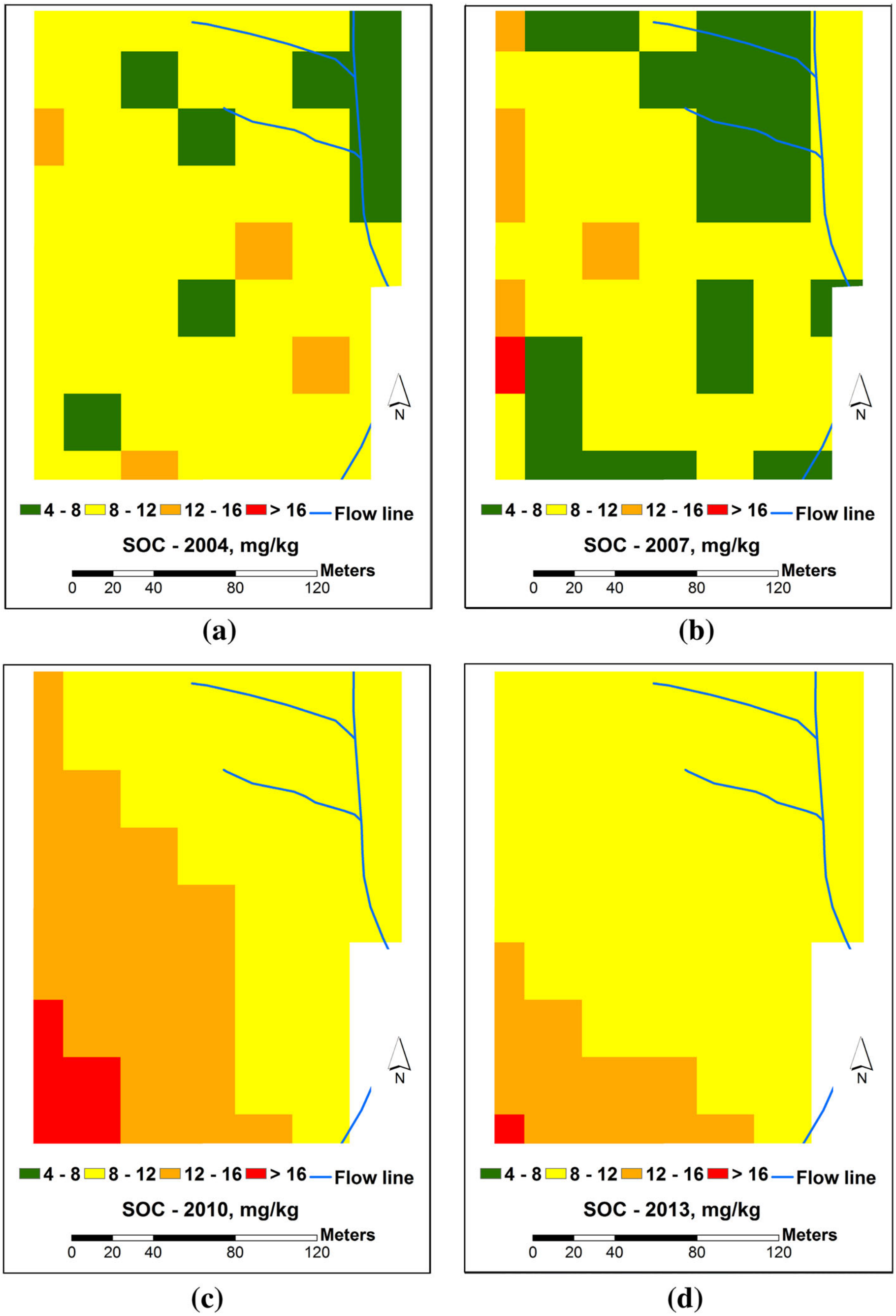

Fig. 8 Spatial patterns of SOC in the experimental field in sampling years (**a**, **b**, **c** and **d**, respectively 2004, 2007, 2010 and 2013)

This is justified, since the trees are located in these areas (Fig. 2a) and the animals have a tendency to spend more time in the shade of the trees, resulting in a concentration of dung deposition (Serrano et al. 2013).

Table 2 shows the mean ± standard deviation of soil parameters for all sampling points in grid cells with trees (20 sampling points, Fig. 2a), compared to the sampling points in grid cells without trees (56 sampling points, Fig. 2a). The analysis of variance shows that the effect of the presence of trees on the concentration of nutrients in the topsoil is significant, confirming the finding that the presence of trees, although with a low density, can positively affect soil properties (Seddaiu et al. 2013). Also Gómez-Rey et al. (2012) reported that soil C stock is influenced by the distance from trees. The potential for C sequestration in systems which combine pastures with trees increases because the secondary roots of the trees, which slowly accumulate great amounts of C in the soil, even in the underground, help to increase the SOC (Lozano-García and Parras-Alcántara 2013). This is particularly important since there were no significant differences in pasture productivity, although it shows a tendency to be higher in grid sampling cells with trees (Table 2).

On the other hand, it is widely accepted that clay particles can physically protect SOC against decomposition by stabilizing the organic components into micro- and meso-aggregates (Romanya and Rovira 2011). Greater values of SOC were also found in areas with a greater clay content, which is probably due to the fact that C attached to the fine fraction is more protected from microbial degradation processes than C stored in the coarse fractions (Römkens et al. 1999) (see Figs. 3, 8). According to Corral-Fernández et al. (2013) when soil clay content increases, there is an increase in the size and number of aggregates, leading to decreased SOC oxidation and N mineralization. The positive influence of greater clay content on SOC accumulation can be enhanced at sites with low precipitation, such as Mediterranean areas, where the decreased microbial activity associated with drier soils may reduce demand for C and amplify the stimulation of below-ground production and formation of soil aggregates (Seddaiu et al. 2013).

Soil apparent electrical conductivity and NDVI index: correlation with soil properties

Soil organic carbon concentration is a useful soil property to guide applications of chemical inputs (Ladoni et al. 2010). The usual analytical procedures for the quantification of SOC are laborious, and thus simple, accurate, rapid and inexpensive methods are needed to produce maps of surface SOC concentrations (Ladoni et al. 2010). There is a need to develop precise and portable methods to quantify in situ and real-time inventory of SOC (Machado 2005).

Remote sensing can provide a sampling strategy for large areas leading to improved representation of the spatial heterogeneity in SOC (Ladoni et al. 2010). To evaluate these new tools that facilitate the survey of soil variability, correlations were established between soil properties and EC_a and NDVI data (Table 3). Figure 9 shows the relationship between the EC_a and NDVI in the experimental field in February 2013. The significant correlation coefficients between EC_a and NDVI data, between EC_a data and soil parameters and between NDVI data and soil parameters, demonstrates the interest in using these technologies in mapping soil variability, the starting point for differential fertilizer management, including the application of organic correctives. The NDVI essentially measures the vegetative vigor (Broge and Leblanc 2000; Gitelson 2004), in this case the pasture growth, whereby the correlation with soil parameters may reflect the correlation between the

Table 2 Mean ± standard deviation of soil and pasture parameters at the experimental field in sampling years; comparison of grid cells with and without trees

Sampling year	Parameter	P_2O_5 (mg kg^{-1})	NO_3 (mg kg^{-1})	K_2O (mg kg^{-1})	SOC (g kg^{-1})	pH	DM (kg ha^{-1})
	With	36.3 ± 14.1	**15.4 ± 6.9**	**111.8 ± 37.0**	10.2 ± 1.4	**6.4 ± 0.3**	1749 ± 1090
2004	Without	32.3 ± 11.4	**8.7 ± 6.3**	**87.8 ± 15.2**	9.4 ± 1.6	**6.1 ± 0.3**	1585 ± 457
	p	0.210	**0.000**	**0.000**	0.058	**0.002**	0.540
	With	68.5 ± 78.8	**5.2 ± 2.0**	88.4 ± 63.8	**10.2 ± 3.4**	**6.4 ± 0.4**	3519 ± 1447
2007	Without	46.8 ± 14.8	**3.9 ± 1.5**	72.5 ± 19.1	**8.5 ± 1.5**	**6.0 ± 0.4**	3024 ± 804
	p	0.051	**0.002**	0.098	**0.003**	**0.001**	0.402
	With	**65.2 ± 20.3**	**53.3 ± 18.2**	**136.0 ± 19.0**	**15.4 ± 2.9**	**6.2 ± 0.2**	–
2010	Without	**48.6 ± 19.8**	**44.4 ± 15.3**	**103.1 ± 19.6**	**11.0 ± 1.8**	**5.9 ± 0.3**	–
	p	**0.002**	**0.037**	**0.000**	**0.000**	**0.000**	–
	With	**83.2 ± 52.3**	**13.0 ± 13.6**	**120.0 ± 23.9**	**13.3 ± 3.0**	**6.5 ± 0.1**	1707 ± 832
2013	Without	**53.4 ± 15.0**	**7.7 ± 4.2**	**88.9 ± 12.7**	**9.8 ± 2.3**	**6.3 ± 0.3**	1623 ± 634
	p	**0.000**	**0.011**	**0.000**	**0.000**	**0.000**	0.567

DM- Pasture dry matter yield, With- Grid cells with trees, Without- Grid cells without trees, are indicated in bold the significantly different means ($p < 0.05$)

Table 3 Significant correlation coefficients between the EC_a and the NDVI data and soil parameters

Parameters	EC_a (mS m^{-1})	NDVI
Soil		
Clay (%)	0.262*	0.350*
Silt (%)	0.315*	ns
Sand (%)	−0.479*	−0.294*
SOC (g kg^{-1})	0.617**	0.433*
pH	0.524**	0.512**
P_2O_5 (mg kg^{-1})	0.597**	0.548**
K_2O (mg kg^{-1})	0.460*	0.529**
NO_3 (mg kg^{-1})	0.555**	0.432*
EC_a (mS m^{-1})	1	0.546*
Soil and pasture		
NDVI	0.546*	1

** -Correlation is significant at the 0.01 level, * -Correlation is significant at the 0.05 level, ns-Correlation not significant

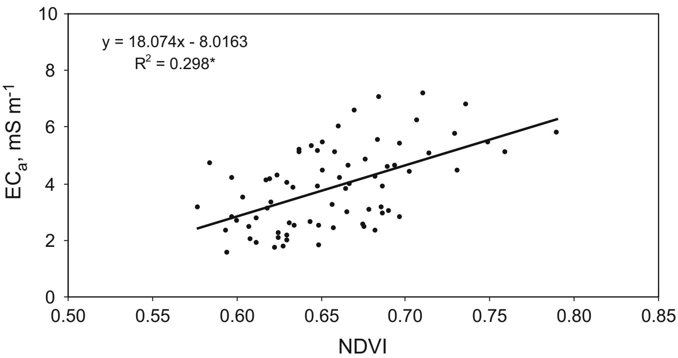

Fig. 9 Relationship between the EC_a and NDVI in the experimental field in February 2013

vegetation growth and soil characteristics. As the vegetation vigor integrates the influence of all environmental factors, NDVI can potentially be related to soil characteristics, such as EC_a. In particular, high EC_a values correspond to either high water, clay or nutrient contents, or a combination of these three. We therefore expect that a high EC_a would correspond to a high NDVI as these factors generally favor plant growth. These results justify more tests that allow calibrating the information gathered by the NDVI sensor and the productivity (pasture dry matter yield) and quality (composition) of pasture under different conditions.

Nutrient management classes

Table 4 presents the management classes and $\overline{CV}$ of soil parameters in the experimental field in sampling years. Temporal stability can be very important, because if the spatial patterns of soil parameters vary significantly from year to year, site-specific management may not be practicable (Xu et al. 2006).

Table 4 Management classes of soil parameters

Parameters	Management classes (%)					$\overline{CV}$ (%)
	1	2	3	4	5	
P_2O_5 (mg kg^{-1})	1.3	2.6	5.3	17.1	73.7	34.8 ± 16.2
NO_3 (mg kg^{-1})	0.0	0.0	0.0	0.0	100.0	114.8 ± 25.7
K_2O (mg kg^{-1})	1.3	21.1	18.4	23.7	35.5	22.1 ± 8.7
pH	47.4	0.0	52.6	0.0	0.0	3.5 ± 1.3
SOC (g kg^{-1})	11.8	17.1	26.3	25.0	19.7	19.1 ± 10.1

$\overline{CV}$-average coefficient of variation

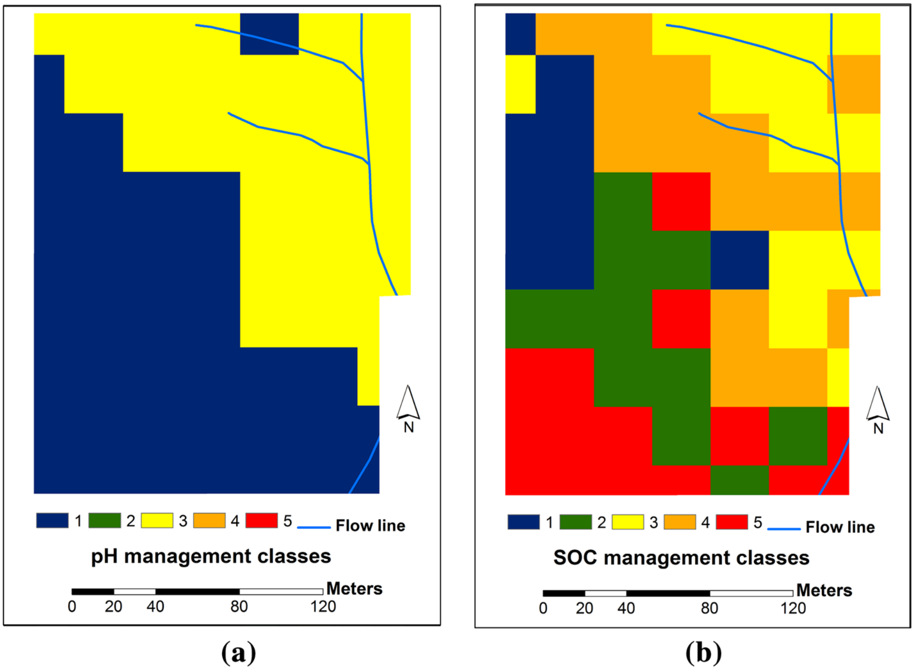

Fig. 10 Maps of pH (**a**) and SOC (**b**) management classes of the experimental field. *1* Greater than field mean concentration and stable, *2* Greater than field mean concentration and moderately stable, *3* Less than field mean concentration and stable, *4* Less than field mean concentration and moderately stable, *5* Unstable

The results show that SOC and pH (Fig. 10) are the parameters with greater potential for implementing differential management. In the case of SOC, over 80 % of the area has temporal stability and more than 50 % of the area has low levels of SOC (<10 g kg^{-1}), indicating the potential for differential application of C-rich organic soil amendments.

In a Mediterranean climate, with significant periods of water shortage, soils are inherently low in organic carbon, making it difficult to increase crop production (Liu et al. 2014). Soil C sequestration, through enhancing and maintaining SOC levels in agricultural soils are therefore important ways to reduce environmental degradation (Liu et al. 2014). Manure is the most widely applied soil amendment when organic farming takes place. This may be especially interesting in these regions, where the increase of SOM helps soils store C, improve their structure, increase fertility and control soil erosion (Lozano-García and

Parras-Alcántara 2013). Soil-management techniques that combine a restriction on tillage and the addition of organic residues are of potential interest for improving soil properties and diminishing atmospheric CO_2 concentrations by storing C in the form of organic matter (Nieto et al. 2010).

Conclusions

Long-term studies are essential to evaluate the magnitude of spatial and temporal dynamics of soil nutrient flux and pools in a terrestrial ecosystem, and to aid farmers and policy makers in making land use management decisions. The definition of soil degradation thresholds based on SOC content is considered essential to develop conservation strategies for soils at risk, as is the case of many soils in the Mediterranean region.

This study showed that SOC and the pH, both decisive factors in crop productivity, have great potential for implementing differential management strategies. In the case of SOC, the management classes map shows that over 80 % of the area has temporal stability and more than 50 % of the area has low levels of SOC (<10 g kg^{-1}), demonstrating the potential for differential application of C-rich organic amendments. Other strategies for the recovery of these soils, such as the application of fertilizers to increase the productivity of pastures in the poorest areas in SOC or a balanced distribution of trees, may also make a relevant contribution. The results demonstrated the effect of trees and their importance in the dynamics of soil nutrients in agro-silvo-pastoral systems and highlighted the importance of well-managed pasture and animal grazing for soil C sequestration as a potential measure for mitigating climate change.

The significant correlations between EC_a and NDVI index and soil properties obtained in this work demonstrate that these integrated processes can be effective tools for studying the spatial variability of SOC in extensive areas, reducing the amount of expensive measurements that are needed for environment characterization and decision making.

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References

Blackmore, S. (2000). The importance of trends from multiple yield maps. *Computers and Electronics in Agriculture, 26*, 37–51.

Broge, N. H., & Leblanc, E. (2000). Comparing prediction power and stability of broadband and hyperspectral vegetation indices for estimation of green leaf area index and canopy chlorophyll density. *Remote Sensing of Environment, 76*, 156–172.

Corral-Fernández, R., Parras-Alcantára, L., & Lozano-García, B. (2013). Stratification ratio of soil organic C, N and C:N in Mediterranean evergreen oak woodland with conventional and organic tillage. *Agriculture, Ecosystems & Environment, 164*, 252–259.

Efe Serrano, J. (2006). *Pastures in Alentejo: Technical basis for characterization, grazing and improvement*. Évora, Portugal (in Portuguese): Universidade de Évora ICAM.

Egner, H., Riehm, H., & Domingo, W. R. (1960). Utersuchungeniiber die chemische Bodenanalyse als Grudlagefiir die Beurteilung des Nahrstoff-zunstandes der Boden. *II. K. Lantbrhogsk. Annlr., 20*, 199–216. **(in German)**.

ESRI (Environmental Systems Research Institute) Inc. (2009). *ArcView 9.3 GIS Geostatistical Analyst*, Redlands:ESRI.

FAO (2006) World reference base for soil resources. Food and Agriculture Organization of the United Nations, World Soil Resources Reports N · 103, Rome, Italy.

Gitelson, A. A. (2004). Wide dynamic range vegetation index for remote quantification of biophysical characteristics of vegetation. *Journal of Plant Physiology, 161*(2), 165–173.

Gómez-Rey, M. X., Garcês, A., & Madeira, M. (2012). Soil organic-C accumulation and N availability under improved pastures established in Mediterranean oak woodlands. *Soil Use and Management, 28*, 497–507.

King, J., Dampney, P., Lark, R., Wheeler, H., Bradley, R., & Mayr, T. (2005). Mapping potential crop management zones within fields: Use of yield-map series and patterns of soil physical properties identified by electromagnetic induction sensing. *Precision Agriculture, 6*, 167–181.

Kumhálová, J., Kumhála, F., Kroulík, M., & Matejková, S. (2011). The impact of topography on soil properties and yield and the effects of weather conditions. *Precision Agriculture, 12*, 813–830.

Ladoni, M., Bahrami, H., Alavipanah, S., & Norouzi, A. (2010). Estimating soil organic carbon from soil reflectance: A review. *Precision Agriculture, 11*(1), 82–99.

Liu, D. L., Anwar, M. R., O'Leary, G., & Conyers, M. K. (2014). Managing wheat stubble as an effective approach to sequester soil carbon in a semi-arid environment: Spatial modelling. *Geoderma, 214–215*, 50–61.

Lozano-García, B., & Parras-Alcántara, L. (2013). Land use and management effects on carbon and nitrogen in Mediterranean Cambisols. *Agriculture, Ecosystems & Environment, 179*, 208–214.

Machado, P. (2005). Soil carbon and the mitigation of global climate change. *Química Nova, 28*(2), 329–334.

Moral, F., Terrón, J., & da Silva, J. M. (2010). Delineation of management zones using mobile measurements of soil apparent electrical conductivity and multivariate geostatistical techniques. *Soil and Tillage Research, 106*, 335–343.

Mu, L., Liang, Y., Xue, Q., Chen, C., & Lin, X. (2014). Using the DNDC model to compare soil organic carbon dynamics under different crop rotation and fertilizer strategies. *Spanish Journal of Agricultural Research, 12*(1), 265–276.

Nieto, O. M., Castro, J., Fernandez, E., & Smith, P. (2010). Simulation of soil organic carbon stocks in a Mediterranean olive grove under different soil-management systems using the RothC model. *Soil Use and Management, 26*, 118–125.

Orgill, S. E., Condon, J. R., Conyers, M. K., Greene, R. S. B., Morris, S. G., & Murphy, B. W. (2014). Sensitivity of soil carbon to management and environmental factors within Australian perennial pasture systems. *Geoderma, 214–215*, 70–79.

Ritchie, M. E. (2014). Plant compensation to grazing and soil carbon dynamics in a tropical grassland. *PeerJ, 2*, e233. doi:10.7717/peerj.233.

Romanya, J., & Rovira, P. (2011). An appraisal of soil organic C content in Mediterranean agricultural soils. *Soil Use and Management, 27*, 321–332.

Römkens, P., Plicht, J., & Hassink, J. (1999). Soil organic matter dynamics after the conversion of arable land to pasture. *Biology and Fertility of Soils, 28*, 277–284.

Rutledge, S., Mudge, P. L., Wallace, D. F., Campbell, D. I., Woodward, S. L., Walla, A. M., et al. (2014). CO_2 emissions following cultivation of a temperate permanent pastures. *Agriculture, Ecosystems & Environment, 184*, 21–33.

Schipper, L. A., Parfitt, R. L., Fraser, S., Littler, R. A., Baisden, W. T., & Ross, C. (2014). Soil order and grazing management effects on changes in soil C and N in New Zealand pastures. *Agriculture, Ecosystems & Environment, 184*, 67–75.

Seddaiu, G., Porcu, G., Ledda, L., Roggero, P. P., Agnelli, A., & Corti, G. (2013). Soil organic matter content and composition as influenced by soil management in a semi-arid Mediterranean agro-silvo-pastoral system. *Agriculture, Ecosystems & Environment, 167*, 1–11.

Serrano, J., Peça, J., Marques da Silva, J., & Shahidian, S. (2010). Mapping soil and pasture variability with an electromagnetic induction sensor. *Computers and Electronics in Agriculture, 73*, 7–16.

Serrano, J., Shahidian, S., & Marques da Silva, J. (2013). Small scale soil variation and its effect on pasture yield in Southern Portugal. *Geoderma, 195–196*, 173–183.

Serrano, J., Marques da Silva, J., & Shahidian, S. (2014). Spatial and temporal patterns of potassium on grazed permanent pastures—management challenges. *Agriculture, Ecosystems & Environment, 188*, 29–39.

Shi, Z., Wang, K., Bailey, J. S., Jordan, C., & Higgins, A. H. (2002). Temporal changes in the spatial distributions of some soil properties on a temperate grassland site. *Soil Use and Management, 18*, 353–362.

Whitmore, A. P., Kirk, G. J. D., & Rawlins, B. G. (2014). Technologies for increasing carbon storage in soil to mitigate climate change. *Soil Use and Manangement*. doi:10.1111/sum.12115

Xavier, F., Maia, S., Ribeiro, K., Mendonça, E., & Oliveira, T. (2013). Effect of cover plants on soil C and N dynamics in different soil management systems in dwarf cashew culture. *Agriculture, Ecosystems & Environment, 165*, 173–183.

Xu, H. W., Wang, K., Bailey, J., Jordan, C., & Withers, A. (2006). Temporal stability of sward dry matter and nitrogen yield patterns in a temperate grassland. *Pedosphere, 16*, 735–744.

Yadav, R. P., Sharma, P., Arya, S. L., & Panwar, P. (2014). *Acacia nilotica*-based silvipastoral systems for resource conservation and improved productivity from degraded lands of the Lower Himalayas. *Agroforestry Systems, 88*(5), 851–853.

Yan, Y., Tian, J., Fan, M., Zhang, F., Li, X., Christie, P., et al. (2012). Soil organic carbon and total nitrogen in intensively managed arable soils. *Agriculture, Ecosystems & Environment, 150*, 102–110.

Yuan, X., Chai, X., Gao, R., He, Y., Jin, H., & Huang, Y. (2007). Temporal and spatial variability of soil organic matter in a county scale agricultural ecosystem. *New Zealand Journal of Agricultural Research, 50*, 1157–1168.