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ORIGINAL ARTICLE

Influence of topography on sediment dynamics and soil chemical properties in a Mediterranean forest historically affected by wildfires: NE Iberian Peninsula

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Abstract
Wildfires are a major concern in Mediterranean areas and play an important role in the pedogenic process, as they usually increase soil credibility due to the destruction of vegetation cover and soil structure. On top of these factors, slope and aspect also determine the degree of retention and availability of water and nutrients in soils after fire, which in turn influence the recovery of vegetation and its protective effect against erosion. This work aims to describe the effects of slope and aspect on soil development in an area historically affected by wildfires. The study area is located in Ódena (NE Iberian Peninsula) in a Mediterranean forest. Four representative soil profiles were sampled from a south-facing steep slope, north-facing steep slope, south-facing gentle slope and north-facing gentle slope. In each profile 11 samples were sampled. The amount of soil organic matter (SOM), inorganic C (IC) and total N (TN) as well as cation availability, pH, and electrical conductivity (EC) were determined for all the horizons of each profile. Results showed that IC, TN, *C/N* ratio, pH, EC and K were mainly affected by aspect, whereas organic matter, *C/N* ratio, pH, EC, Ca and Mg were especially influenced by slope. Slope determined the amount and availability of SOM and nutrients, which highlights the need to prioritise the management of areas susceptible to erosion in order to ensure soil and ecosystem functionality.

Keywords Soil chemical nutrients · Soil degradation · Soil formation · Fire recurrence · Sediment dynamics

Introduction

Soil is a natural and non-renewable resource (Jenny 2012) and constitutes one of the most vulnerable and valuable systems on Earth (Certini et al. 2005; Santín and Doerr 2016). According to the popular equation published by Jenny (1941), soil development and properties are function of climate (c), relief (r), organisms and humans (o), parent material (p) and time (t) (Jenny 2012). This proposal has set the basis for numerous studies that have attempted to increase the accuracy of the function by quantitatively considering the influence of r, o, p and t (McBratney et al. 2003). However, further scientific knowledge is necessary to better understand soil formation and properties in the different regions across the globe, and particularly in those areas where soil forming factors exhibit high heterogeneity and complex interactions among them. This can be the case of the Western Mediterranean, which is considered as target to study soil processes because of the high erosion and degradation risk in this region (van der Knijff and Montaranella 2000). In relation to the main soil determining factors in Western Mediterranean, climate (c) is characterized by long-lasting summer droughts and the occurrence of intense rainstorms, which contribute to intense soil erosion-sedimentation processes (García-Ruiz et al. 2013; Sánchez-García et al. 2019). The relief (r) is heterogeneous, often mountainous with presence of steep slopes and different aspects, which also can influence soil processes and properties (Porta

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et al. 2010; Przepióra et al. 2017). Additionally, the flammability of Mediterranean-type vegetation and human activity (o), as well as land-use changes experienced during last decades have increased the propensity of these regions to wildfires (Alcañiz et al. 2018; Fernández-García et al. 2019a, 2020a, b), which have also been considered as a major soil forming factor (Certini 2014).

Focusing on the geomorphology, flat areas usually develop deeper and more fertile soils than steep areas (Lavee et al. 1995; Smith and Dragovich 2008). This difference is attributed to erosion and sedimentation processes, as soils in steep slopes are, in general, less protected by vegetation (Koulouri and Giourga 2007), more eroded by runoff (Armstrong et al. 2011), exposed to higher wind speeds, and more susceptible to gravitational movements than soils in flat areas (McNab 1993). Moreover, although sediment dynamics are not strictly related to nutrient fluxes (Armstrong et al. 2011), it has been demonstrated that slope influences soil nutrient content. In general, soil nutrient concentrations and organic matter (OM) are higher in flat areas than in zones with steep slopes (Jenny 1994; Sariyildiz et al. 2005; Porder and Hilley 2011; Osborne et al. 2017). Slope aspect may also influence soil erosion rates and soil physicochemical properties (Losche et al. 1970; Boerner et al. 1984). In Mediterranean Europe, north-facing soils usually present a denser vegetation cover than in south-facing slopes, as a consequence of differences in water availability (Bellin et al. 2011). Thus, south-facing soils are more vulnerable to erosion and may require longer to develop than northerly exposed soils. Likewise, several studies in Mediterranean ecosystems have found that north-facing slopes are richer in soil nutrients and soil organic matter (SOM) than south-facing slopes (Kutiel 1992; Jendoubi et al. 2019).

Apart from relief, forest fires play a major role in Mediterranean ecosystems, causing profound impacts on soil processes and properties (Certini 2005; Shakesby 2011; Keeley et al. 2012; Fernández-García et al. 2019b). High severity fires might intensify erosion-sedimentation processes due to the removal of vegetation and deterioration of soil structure (Santín and Doerr 2016; Francos and Úbeda 2021). The effects of fire can be particularly intense in steep slopes prone to erosion, as well as in south-facing slopes where fires used to be more severe. Additionally, wildfires modify soil chemical properties not only by heating and ash deposition (Francos et al. 2019; Fernández-García et al. 2019a, b), but also through changes in soil sediments and erodibility, thus interacting with topographic factors such as slope and aspect (Keeley 2012). Fire–soil interactions are complex, to the point that fires can be considered a soil-forming factor (Certini 2014), but they are also a cause of soil loss. Erosion rates can increase rapidly after severe fires which eliminate the protective cover and may destroy soil structure, consequently increasing soil erodibility (Santín and Doerr 2016; Fernández-García et al. 2019a). This impact can be particularly relevant in Mediterranean ecosystems where torrential rainfalls are frequent and lead to extreme erosion events (Fonseca et al., 2017). Fire also has immediate effects on soil chemical properties such as pH, electrical conductivity (EC) and nutrient content (Fernández-García et al. 2019a), that can last several years and even decades depending on fire severity (Francos et al. 2018a). The study of fire impacts on soils is usually focused on the uppermost soil layers, as in most cases, direct fire-induced changes can only be detected in the first 5 cm of soil (Girona-García et al. 2019; Fernández-García et al. 2020a). However, the effect of forest fires on soil throughout history can also be analysed in deeper layers of the soil profile because the uppermost layers can be detached from a specific site and then, transported and buried in another.

Although many studies have investigated the effects of wildfires in sediment dynamics and soil properties (Francos et al. 2018a; Fernández-García et al. 2019a), very few have provided insights into soil dynamics and properties in relation to relief in fire-affected areas (Przepióra et al. 2017). Moreover, further understanding on the legacy of frequent wildfires on complete soil profiles is necessary, as most research has focused on the uppermost layers, rarely exceeding 20 cm (Pellegrini et al. 2017, 2018) or 50 cm depth (Walker et al. 2019). This study aims to describe the sediment dynamics and chemical properties of entire soil profiles developed under different conditions of slope and aspect in an area historically affected by wildfires. Thus, this study contributes to make advances in the soil and fire science disciplines as it is pioneer in the analysis of entire soil profiles in contrasting topographic conditions and after frequent fires. Our hypothesis is that sediment dynamics and soil chemical properties will vary depending on slope steepness and, to a lesser extent aspect. In addition, these differences in soil erosion-sedimentation processes and soil properties related to topographic features will be aggravated by the occurrence of wildfires.

Materials and methods

Study area and experimental design

The study area is located in Ódena (NE Iberian Peninsula) (Fig. 1). Vegetation is mainly composed by *Pinus halepensis* Miller, *Pinus nigra* Arnold and *Quercus ilex* L. with an understorey layer composed of *Genista scorpius* L. and *Pistacia lentiscus* L. (Francos et al. 2020a). Geological substrate is composed mainly of sediments originating from Palaeocene shale (Panareda-Clopés and Nuet-Badia 1993). Soil is classified as Fluventic Haploxerept (Soil Survey Staff 2014). The mean annual temperature of

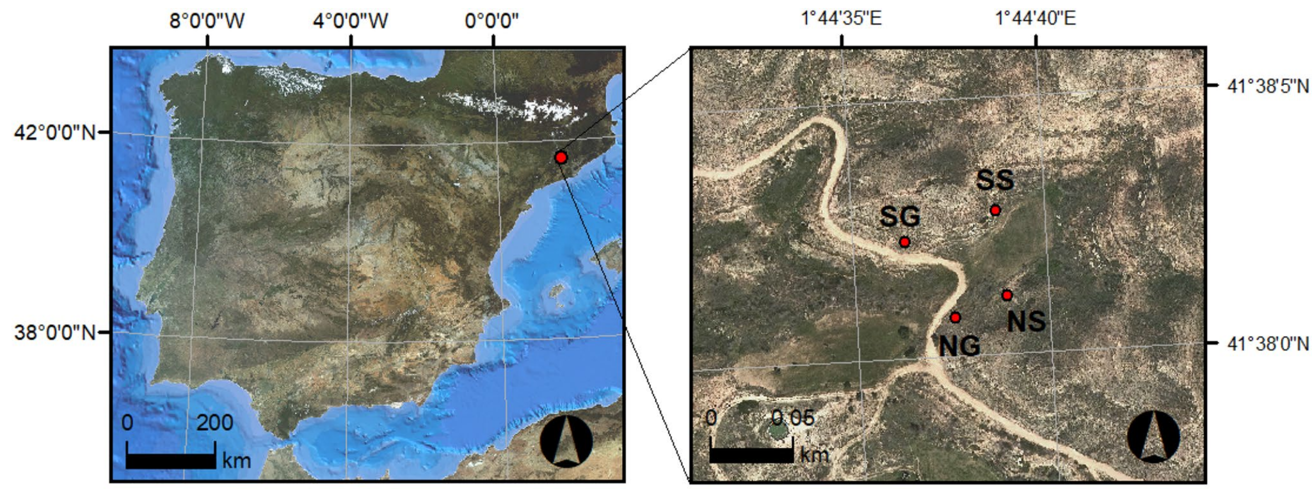

Fig. 1 Location of study area and soil profiles sampled

Table 1 Soil profiles selected

Profile	Aspect	Slope
SS	South	Steep (> 10°)
NS	North	Steep (> 10°)
NG	North	Gentle (< 10°)
SG	South	Gentle (< 10°)

SS southerly-steep slope, *NS* northerly steep slope, *NG* northerly gentle slope, *SG* southerly gentle slope

the study site is 14.2ºC and mean annual rainfall ranges between 500 and 600 mm according to the El Bruc meteorological gauging station (41°34′44″ N–14°60′57″ E) classified as *Csa* by Köppen (1900). In this study area, two wildfires have been registered in the last four decades, in 1986 and in 2015, as described Francos et al. (2020b). The selected study areas comprise the following: (1) an area with steep slope and southerly aspect (SS), (2) an area with steep slope and northerly aspect (NS), (3) an area with gentle slope and northerly aspect (NG), and (4) an area with gentle slope and southerly aspect (SG) (Table 1). Soil and slope were classified according to Sikdar et al. (2004).

In this regard, the study area is defined by four soil profile types. Each of the profiles represent different properties considering aspect and slope as crucial issues in the soil formation. Generally, aspect is characterised by NW- and SE-facing slopes. Furthermore, the slope steepness decreases, on average, from 30 to 0.5% from top to bottom positions. Evidence of runoff processes can be observed in the steeper areas located in the areas without vegetation. However, land degradation processes are not severe enough to accelerate the process to become a badland.

Soil samples were collected at different depths along each profile, based on the delimitation of genetic soil horizons and proportionally to their thickness (Úbeda and Sala 1995). The wildfire recurrence in the area is evidenced by the presence of pyrogenic carbon materials within the soil, which appear at the same depth for all studied soil profiles. These charred vegetal remains were also considered when sampling, collecting soil from 1–2 cm above and beneath their position, which are considered to be a good and representative approximation for studying the recurrence of paleo-fires and soil characteristics (Conedera et al. 2009). A similar methodology was used by Blake et al. (2006), who collected samples in an area affected by recurrent fires using stratigraphy and at different depths in each profile to study fire severity. Other studies have collected a sample in each of the different layers instead of sampling homogeneously along the profile. This is the case of the study carried out by Yulianto et al. (2004), in which they collected 12 samples in each profile at 150 cm, showing the validity of this method despite the low number of samples collected in each layer. Other authors have used only one sample from each layer in order to determine changes in sediment dynamics and soil properties, and this is a valid and widely used method as in the case of Armas-Herrera et al. (2019).

Laboratory and statistical analyses

Soil samples were air-dried for 7 days at room temperature (23 °C) and then sieved through a 2-mm mesh to analyse the fine earth (< 2 mm). The soil organic matter (SOM) and inorganic carbon (IC) were determined using the loss-on-ignition method (Heiri et al. 2001). For each sample, 1 g of air-dried soil was pulverised and oven-dried at 105 °C for 24 h in a muffle furnace. To determine SOM, oven-dried samples were subjected to a temperature of 550 °C in a muffle furnace for 4 h and to calculate IC, the samples were further exposed to a temperature of 950 °C for 2 h. Organic Carbon (OC) was calculated using the values of soil organic matter (SOM), as follows: OC = SOM/1.724 (Al-Gburi et al. 2017). The total nitrogen (TN) was analysed using a Flash 112 Series (Thermo-Fisher, Milan) and data calculations were carried out with Eafer 300 software. The soil *C*/*N* ratio was calculated as the proportion of OC to TN. Soil pH [1:2.5] and electrical conductivity (EC, expressed in µS/cm) [1:2.5] were determined in an extraction of deionised water. Extractable major cations (Ca^{+2}, Mg^{+2}, Na^{+} and K^{+}) were determined in an extraction [1:20] of ammonium acetate (Knudsen et al. 1982) by inductively coupled plasma mass spectrometry (ICP-MS), using a PerkinElmer Elan-6000 Spectrometer and a PerkinElmer Optima-3200 RL Spectrometer. A redundancy analysis (RDA) was carried out to identify the relations between the variables, using CANOCO 4.5.

Results and discussion

Soil erosion and sediment dynamics

The four selected profiles were classified according to the geographical and topographic characteristics by which they are defined. On the one hand, the profiles were divided according to the steepness of the slope in which they are located (gentle or steep). On the other hand, the aspect of the hillslope was also considered (north or south). The aggradation in areas with similar characteristics to those studied is clearly dependent on the slope and the rainfall events, that in most of the cases, move finer materials from the upper parts of the slope to the lower parts, while thicker materials are rather transported during extreme events, depositing them in the lowest areas, from where the samples of the present study were collected. Erosion processes in certain areas are closely related to the high recurrence of wildfires (Shakesby 2011). This area is not an exception and is, therefore, of interest for the study of the relationship between soil and forest wildfires in the long term (Francos et al. 2018a).

The analysed soils showed deeper profiles in the south-facing slopes, as can be observed in Fig. 2. This result is somehow unexpected, because burnt south-facing slopes are commonly linked, especially in Mediterranean areas, to higher erosion rates than their north-facing counterparts, as a consequence of several interrelated factors such as the increased evapotranspiration, slow recovery of the vegetation, and lower SOM content (Shakesby 2011). The bedrock was observed to be closer to the surface in the NS and NG profiles, suggesting that this finding might be linked to variability in the depth of rock weathering (Weil and Brady 2017) rather than aspect-related processes. However, topography is not definitive when it comes to characterising the studied soils since in all cases slopes do not exceed 20°. On the other hand, it is possible to observe a certain correlation between the slope and soil chemical properties and horizon formation by differentiating both slope and aspect, as explained below.

At the level of granulometry, the profiles located in the steep slopes are formed by angular gravels distributed throughout the profile and present a loam texture in the first centimetre of the uppermost horizon, this trait being related to the erosive dynamics of the steep slope (Sidari et al. 2008). Likewise, the soils located in the area of gentle slopes present a high gravel content in certain horizons, probably related to hillside erosion during extreme torrent events (Coppus and Imeson 2002). As represented in Fig. 2, the uppermost horizon is thicker in the less steep profiles, because the soil was sampled closer to the lower part of the slope, where more material is deposited. In this way, comparing the four profiles, thicker elements such as gravel were detected in horizons located in the middle of the slope, while in the profiles located in the lower part of the slope, they were more concentrated in specific layers. This characteristic is explained by the dynamics of the slope, because in the middle part of a slope, the movement of material is more chaotic than in the bottom part, where the depositional processes are more intense. Therefore, these layers can show us specific erosion events that could be related to forest fires and subsequent rains, when soil erosion is higher (Shakesby and Doerr 2006).

Soil chemical properties

Soil organic matter, inorganic carbon, total nitrogen and C/N ratio.

In general, soil organic matter (SOM) content increased with depth (Fig. 3) and was similar for the studied soil profiles at the surficial and medium-depth horizons (A and B) (Fig. 3). Focusing on topographic factors (slope and aspect), we found that in the deepest horizons of each profile SOM was higher in gentle (SG and NG) than in steep-slope profiles (NS and SS). However, we have not found common patterns in relation to aspect in the studied soil profiles. Although SOM is usually concentrated in the uppermost 30 cm of soil (Hiederer 2009; Wang et al. 2010; Ismail-Meyer et al. 2018), large variations in the vertical distribution of SOM can be found, related to climate and land use (Hiederer 2009; Wang et al. 2010). For this reason, in some ecosystems such as Mediterranean shrublands, increases in organic C with increasing depth are common (Hiederer 2009). In general, the content of SOM in a soil profile is controlled by several factors such as water saturation, oxygen concentration, soil nutrients, vegetation and soil organisms (Ismail-Meyer

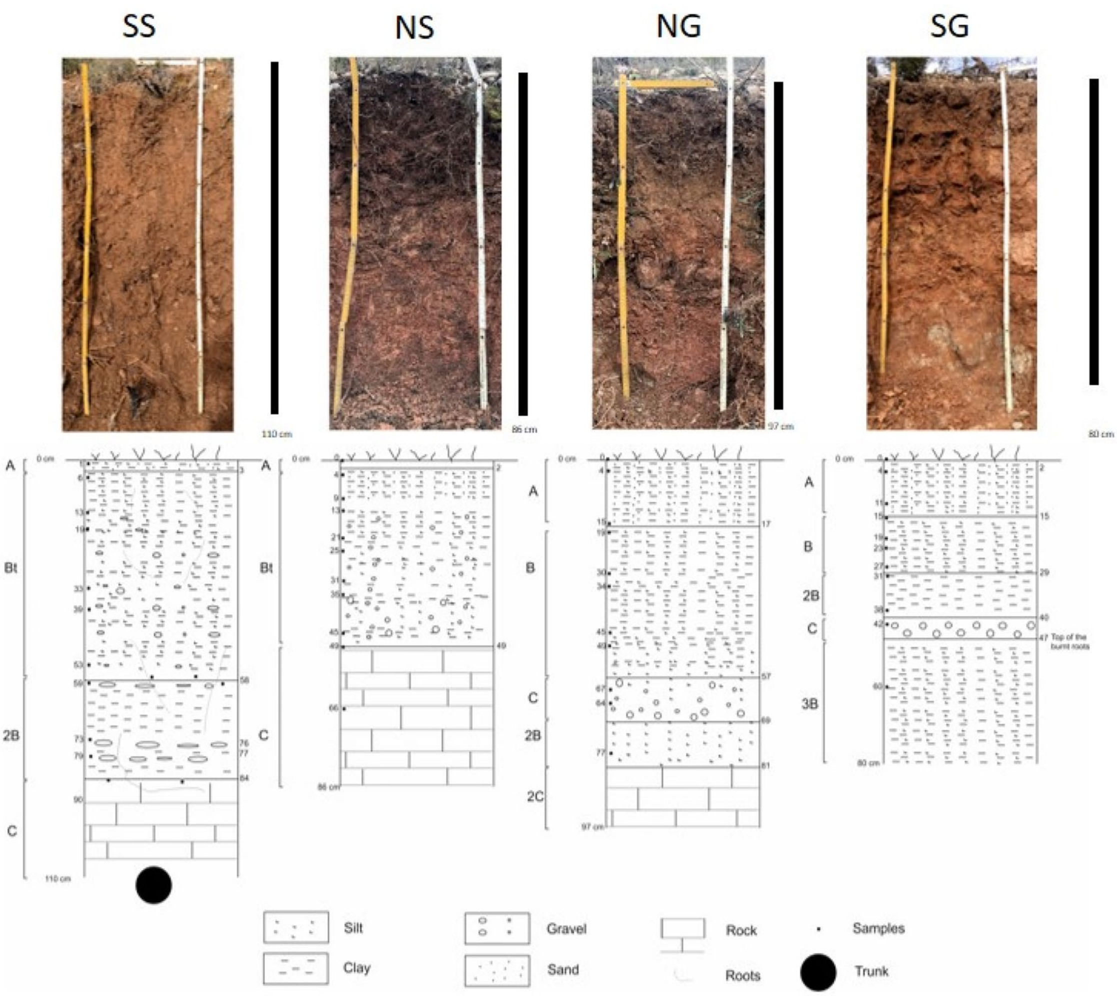

Fig. 2 Top: Photographs of the four profiles analysed (by Marcos Francos); bottom: lithostratigraphic description of the profiles with the sampled points. Profiles: SS (southerly steep slope), NS (northerly steep slope), NG (northerly gentle slope) and SG (southerly gentle slope)

et al. 2018). Thus, the increases in depth found in the present study can be attributed to variations in these factors, but also to inputs from the leaching of dissolved surficial organic matter into the soil profile and to contributions from root biomass (Wang et al. 2010; Kramer et al. 2017; Ismail-Meyer et al. 2018). Topography is one of the factors that influence organic carbon concentration and consequently SOM (Wang et al. 2021). Likewise, our results indicating that SOM content is higher in gentle than in steep slopes can be explained by (1) lower water saturation in steep soils, facilitating oxidation processes; (2) lower nutrient availability in steep soils; and (3) higher erosion rates in steep soils, thus facilitating the loss of SOM (Jia et al. 2009). Sidari et al. (2008), in their study in southern Italy, observed lower values of organic carbon in north-facing slopes. This is mainly caused by the decomposition of litter and weight loss (Nicolardot et al. 2001) produced by the quicker mineralisation processes occurring in that aspect than in south-facing slopes (Stevenson 1994). In the present study, there are no differences between the two aspects. Notwithstanding, any such differences would be very slight, given the preceding explanation. Another possible reason for the SOM increase in deeper horizons of the gentle slope profiles could be past periods of intense erosion of SOM-enriched horizons at the top positions in the slope, which were subsequently deposited and buried downslope, where they eventually were stabilised (Billings et al. 2019).

Generally, soil inorganic carbon (IC) decreased with depth, from the B horizon to the deepest ones, with the exception of the SS profile (Fig. 4). In relation to slope, we did not find consistent patterns among soil profiles. On the contrary, results showed that IC tended to be higher in the southerly exposed profiles, particularly in the C horizon. The decreases in IC with depth in the soil profiles studied are consistent with those reported by Wang et al. (2010) in different landscapes, including forests and shrublands. These

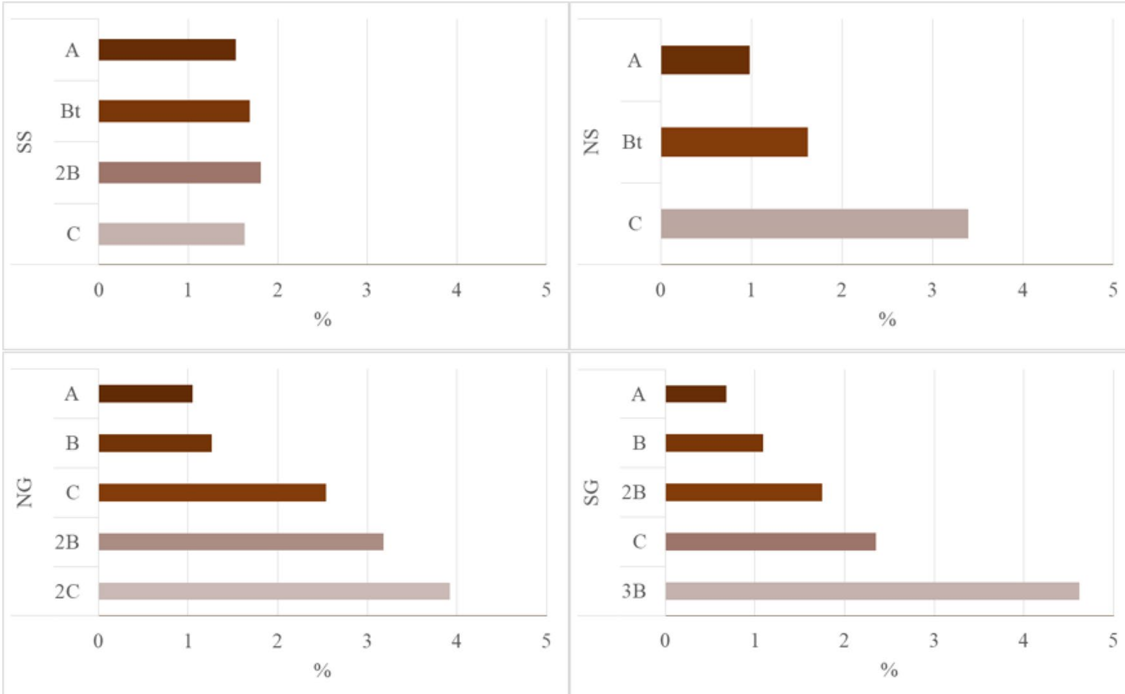

Fig. 3 Soil organic matter (SOM) in the four soil profiles. SS (southerly-steep slope), NS (northerly-steep slope), NG (northerly gentle slope) and SG (southerly gentle slope)

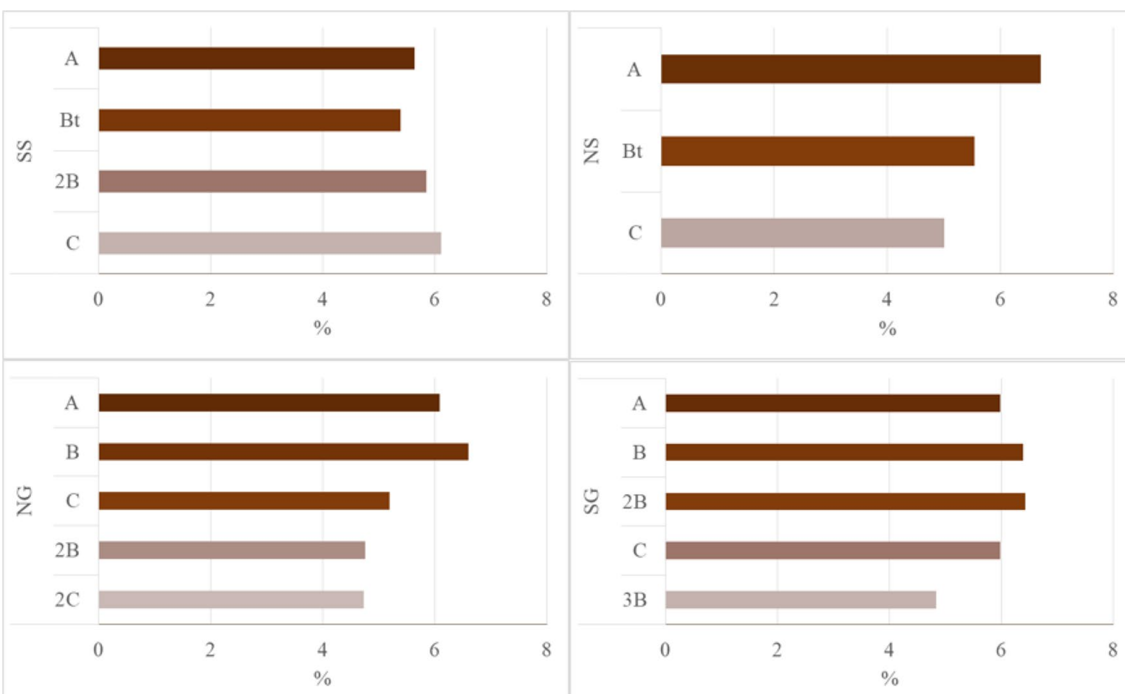

Fig. 4 Inorganic carbon (IC) in the four soil profiles. SS (southerly steep slope), NS (northerly steep slope), NG (northerly gentle slope) and SG (southerly gentle slope)

authors inversely related the IC content to humidity, the most arid soils having high IC content. This factor may explain the higher IC in our southerly-exposed soils.

Total nitrogen (TN) increased with depth in all four soil profiles (Fig. 5). In relation to topographic factors, results indicate that increases in TN with soil depth were more pronounced in gentle than in steep slopes, and slightly more pronounced in northerly- than in southerly exposed soils. TN content in soil profiles depends on the parent material, biota, climate and topography (Zhong et al. 2019) and is strongly correlated with SOM, as most of the N in soil is in organic form (Zhong et al. 2019; Ren et al. 2020). Topographic effects on TN can be related to SOM, but also to differences in vegetation (Lozano-García et al. 2016; Zhong et al. 2019). Authors such as Fan et al. (2015) reported that despite the topographical differences, soil N increases with soil depth, as occurs in the present study. This broadly explains the vertical distribution of TN in the studied profiles. Moreover, topography can affect TN, which decreases in southerly exposed soils (Lozano-García et al. 2016).

The *C*/*N* ratio presented similar values across the profiles studied, decreasing slightly with soil depth (Fig. 6). We have not found clear effects of topographic factors on the *C*/*N* ratio, relating to either slope or aspect. Our results in relation to *C*/*N* agree with those reported by Batjes (1996). This author found slight declines in the *C*/*N* ratio with depth in most soil types worldwide, reflecting a higher degree of breakdown and greater age of the humus stored in the deepest layers. Results from Kramer et al. (2017) suggest that organo-mineral associations can drive *C*/*N* trends relating to soil depth.

Soil pH, electrical conductivity and major elements

Soil pH decreased with depth, except in the SS profile (Fig. 7). We have not found a consistent influence of topographic factors (slope and aspect) on soil pH among the studied soil profiles. The pH decrease in deeper horizons can be related to concomitant increases in SOM as it is well known that SOM has an acidic character, comprising many acidic substances such as humic and fulvic acids (Hempfling and Schulten 1990). Moreover, the breakdown of SOM can increase the concentration of H^{+}, due to the liberation of organic, carbonic and sulphuric acids, among others. In relation to topographic factors, several authors have suggested that both slope and aspect have an influence on soil pH (Zhang et al. 2019), but we have not found clear effects of these variables, probably due to the dominant influence of other factors such as SOM.

Soil electrical conductivity (EC) decreased with depth in SS and increased with depth in NS and SG. We have not identified a consistent influence of topographic factors on soil electrical conductivity among the soil profiles studied (Fig. 8). Soil chemical properties in hillside areas depend on

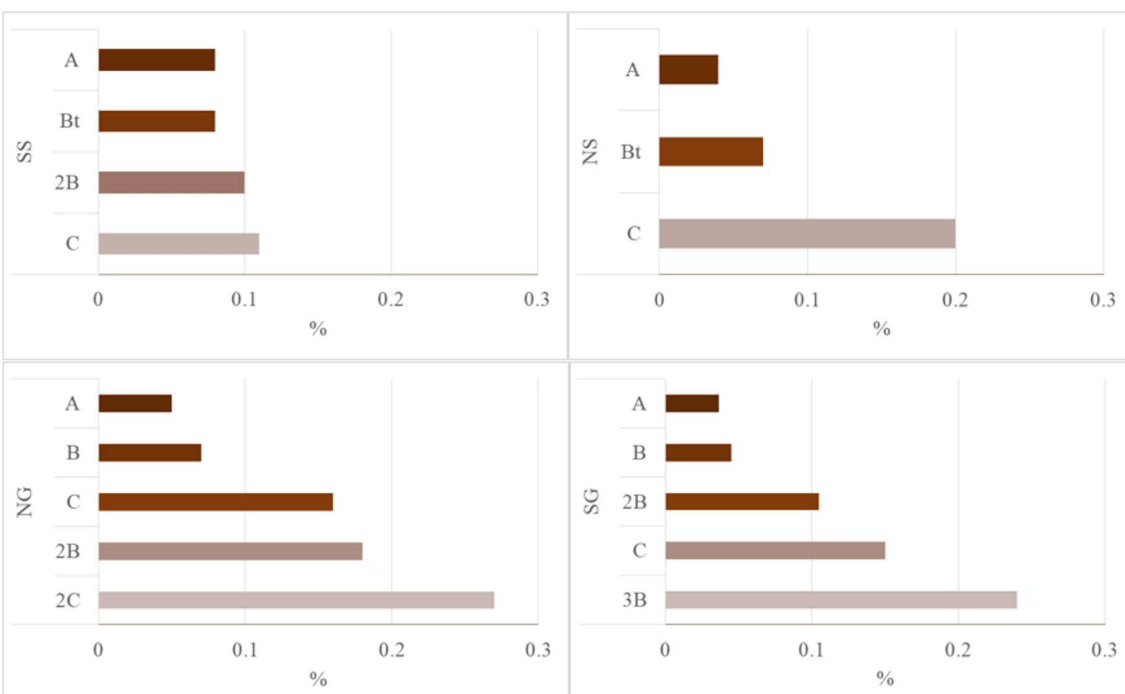

Fig. 5 Total nitrogen (TN) in the four soil profiles. SS (southerly steep slope), NS (northerly steep slope), NG (northerly gentle slope) and SG (southerly gentle slope)

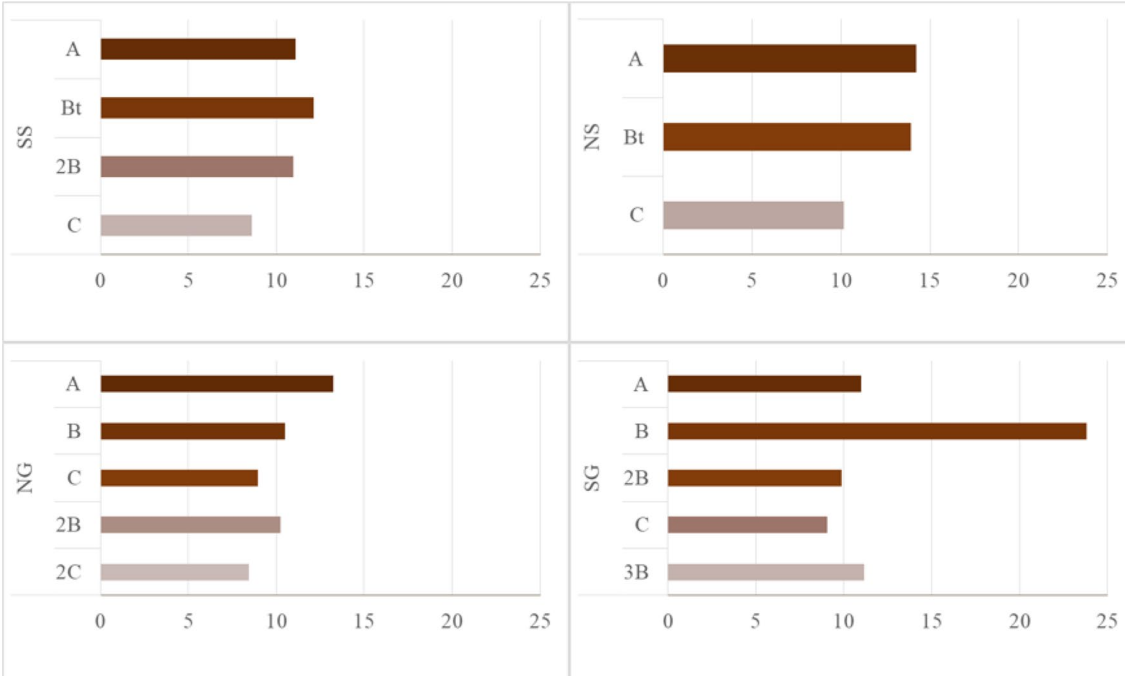

Fig. 6 *C*/*N* ratio in the four soil profiles. SS (southerly steep slope), NS (northerly steep slope), NG (northerly gentle slope) and SG (southerly gentle slope)

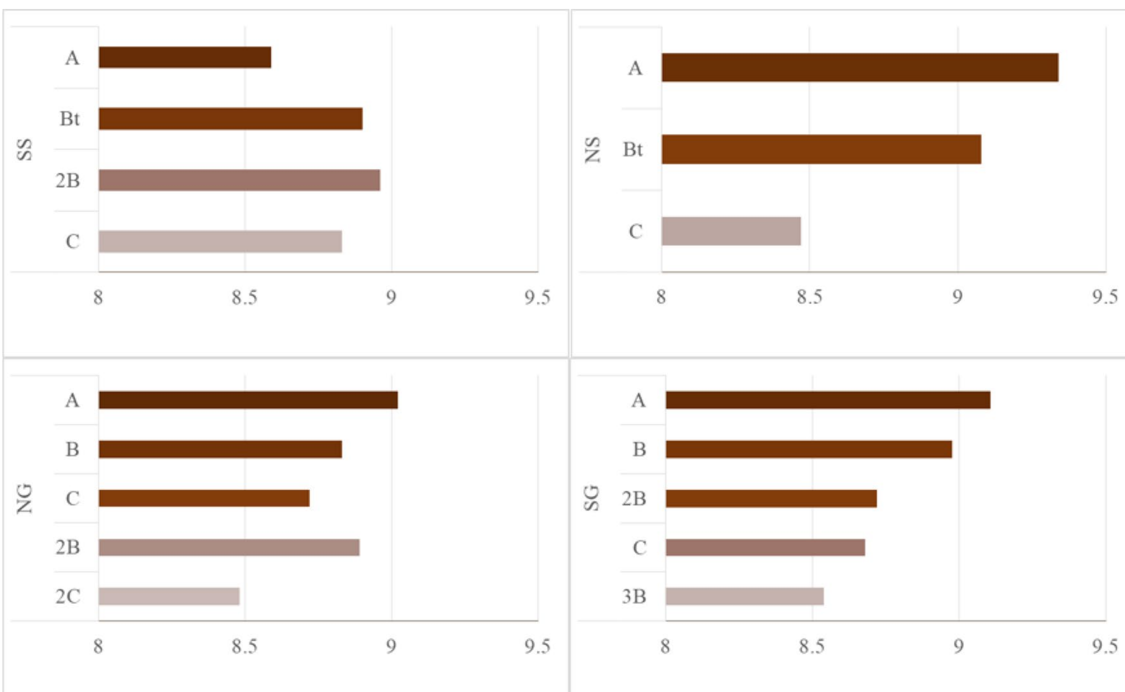

Fig. 7 Soil pH in the four soil profiles. SS (southerly steep slope), NS (northerly steep slope), NG (northerly gentle slope) and SG (southerly gentle slope)

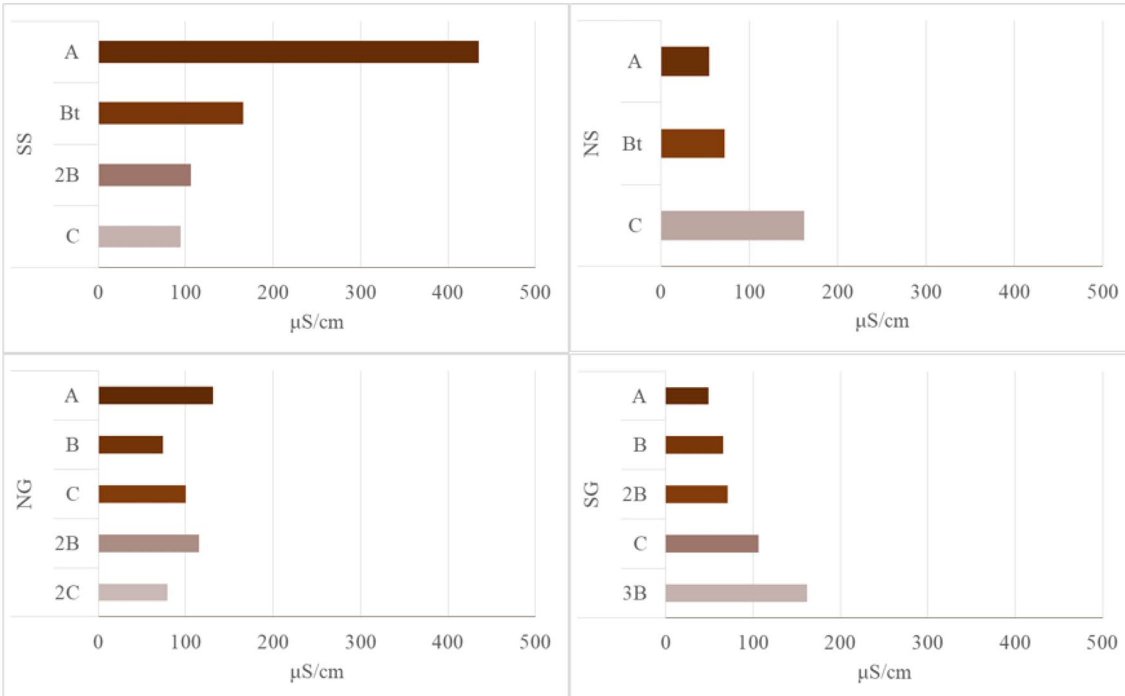

Fig. 8 Electrical conductivity (EC) in the four soil profiles. SS (southerly steep slope), NS (northerly steep slope), NG (northerly gentle slope) and SG (southerly gentle slope)

topography (slope and aspect), due to the different erosive processes influencing soil nutrient concentration (Vitousek et al. 2003; Hilton et al. 2013; Weintraub et al. 2015). We have not been able to isolate clear effects of slope and aspect on EC, probably because of the dominant influence of other factors such as organic matter.

Soil extractable Ca decreased with depth in all four soil profiles, showing similar values among them for all horizons. Focusing on topographic factors (slope and aspect), we found that in the horizons of each profile, extractable Ca was higher in gentle (SG and NG) than in steep profiles (NS and SS). We have not detected common patterns in relation to aspect in the studied soil profile (Fig. 9). As previously observed, the gentle slopes had greater amounts of SOM and TN and also higher extractable Ca than steep slopes. Such results were also obtained by Jia et al. (2009), who conclude that the higher amounts of nutrients and extractable Ca were produced by the higher SOM content. The results showed that these greater amounts were more prevalent in north-facing slopes where the accumulation of nutrients is higher than in a southerly aspect, producing a higher content of extractable Ca, as previously noted by Zhang et al. (2011).

Soil extractable Mg decreased with depth in SS and increased with depth in SG and NG. Focusing on topographic factors (slope and aspect), we found that in the horizons of each profile extractable Mg was higher in gentle (SG and NG) than in steep profiles (NS and SS). We have not found common patterns in relation to aspect in the studied soil profiles (Fig. 10). Results for extractable Mg (as for extractable Ca) show the greatest amounts in north-facing gentle slopes, due to the higher SOM content and water availability (Jia et al. 2009; Zhang et al. 2011).

Soil extractable Na decreased with depth in SS and NS. In relation to slope, we found that in the horizons of each profile, extractable Na was higher in the SS profile than in SG. We have found differences in relation to aspect, being the quantity of extractable Na higher in SS than in NS. On the other hand, the dynamic is very similar in SG and NG (Fig. 11). Slope can produce changes in the vertical distribution of extractable Na. In our study, gentle slope areas showed similar values along the soil profile, whereas in the case of steep slope areas, there is a decrease of extractable Na with increasing depth. The increment in slope steepness can increase runoff speed, promoting erosion and thus, a decrease in some soil nutrients (Hook and Burke 2000) that could include extractable Na. We have not identified clear effects of aspect, probably because of the dominant influence of other factors such as organic matter, water-holding capacity and temperature (Zhang et al. 2011).

Soil extractable K increased with depth in NS, SG and NG. In relation to slope, there are no differences between NS and NG, but the dynamic and amount of extractable K differs between SS and SG. Regarding aspect, SS and NS showed different trends, despite the dynamic being

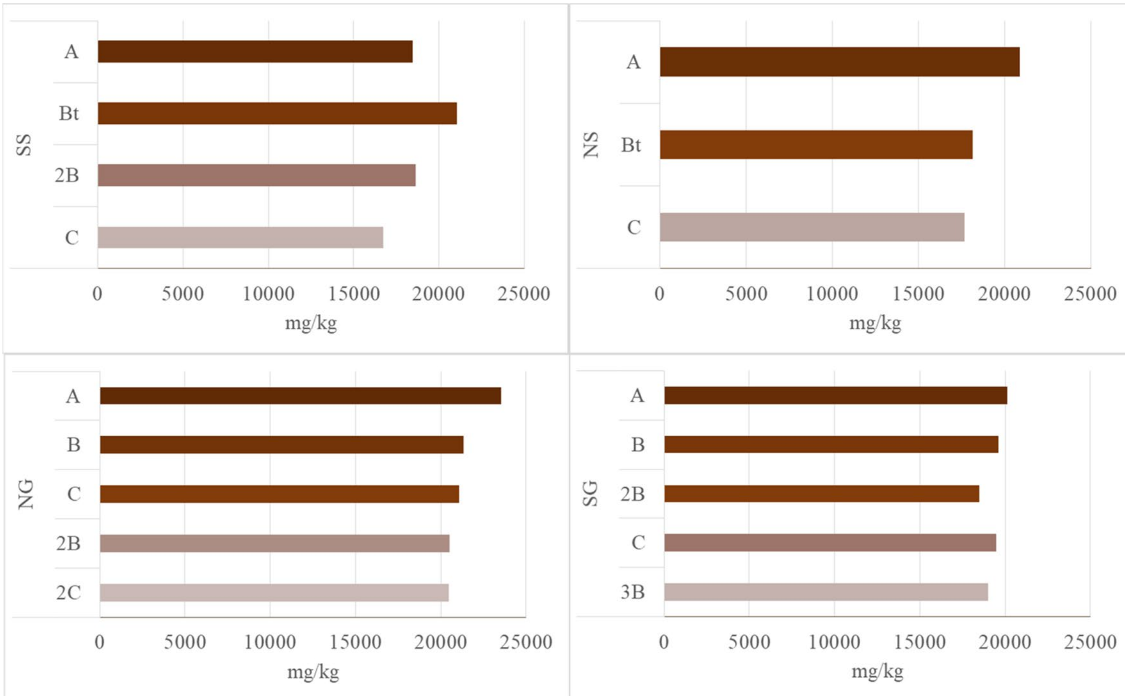

Fig. 9 Extractable Ca (Ca) in the four soil profiles. SS (southerly steep slope), NS (northerly steep slope), NG (northerly gentle slope) and SG (southerly gentle slope)

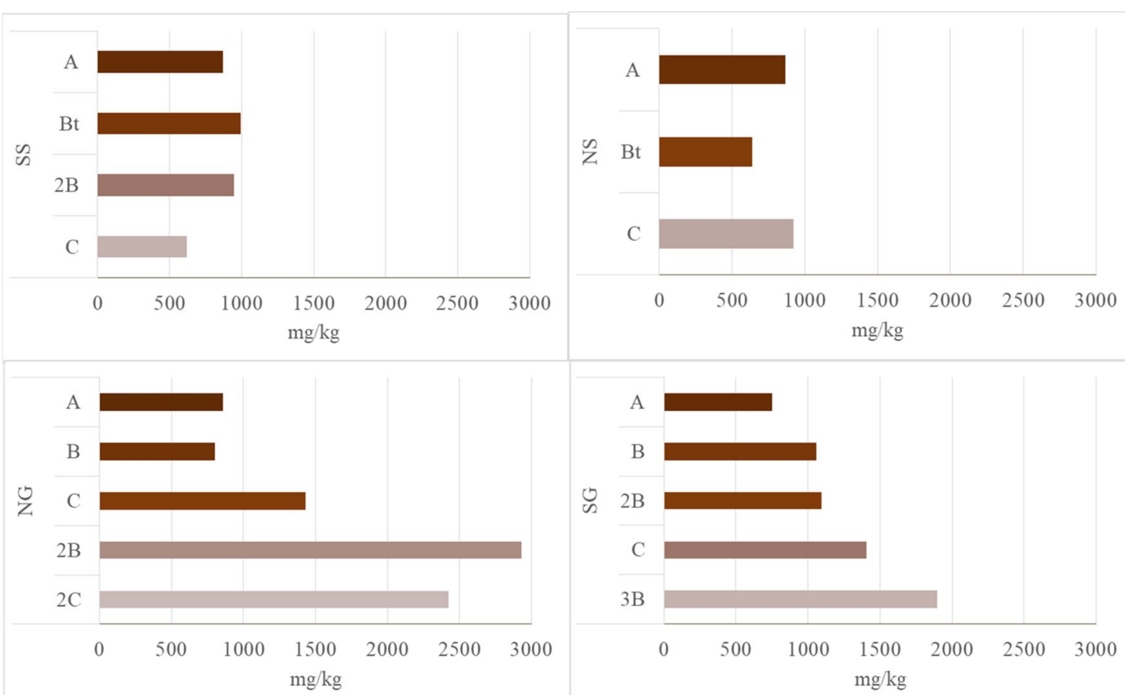

Fig. 10 Extractable Mg (Mg) in the four soil profiles. SS (southerly-steep slope), NS (northerly steep slope), NG (northerly gentle slope) and SG (southerly gentle slope)

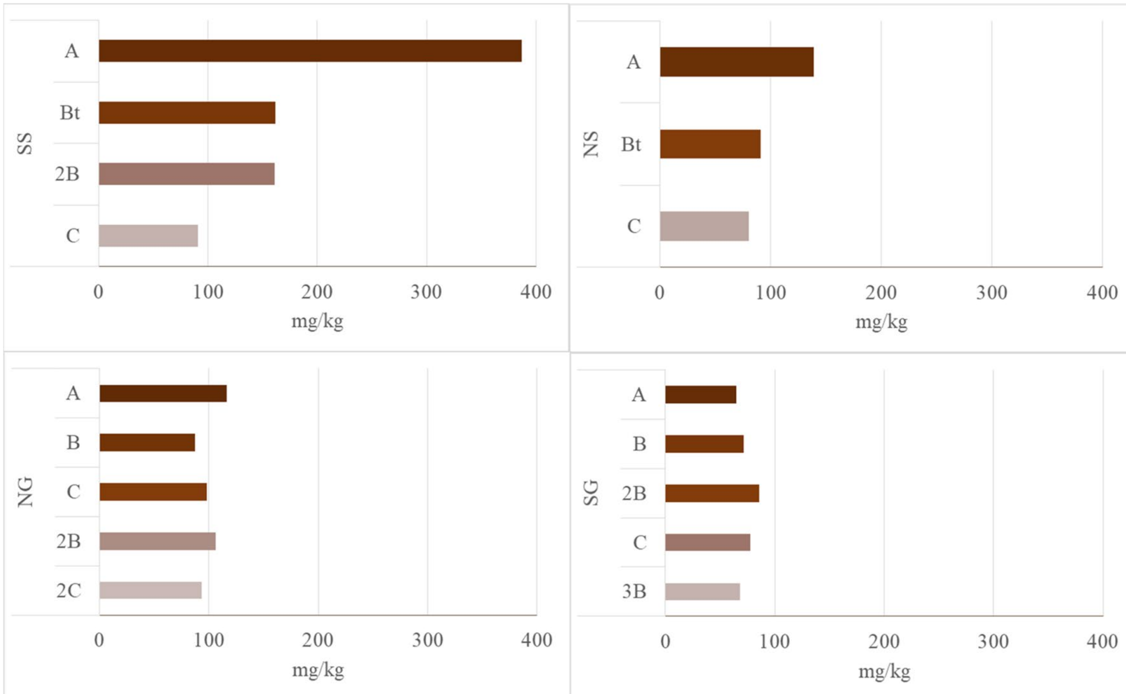

Fig. 11 Extractable Na (Na) in the four soil profiles. SS (southerly steep slope), NS (northerly steep slope), NG (northerly gentle slope) and SG (southerly gentle slope)

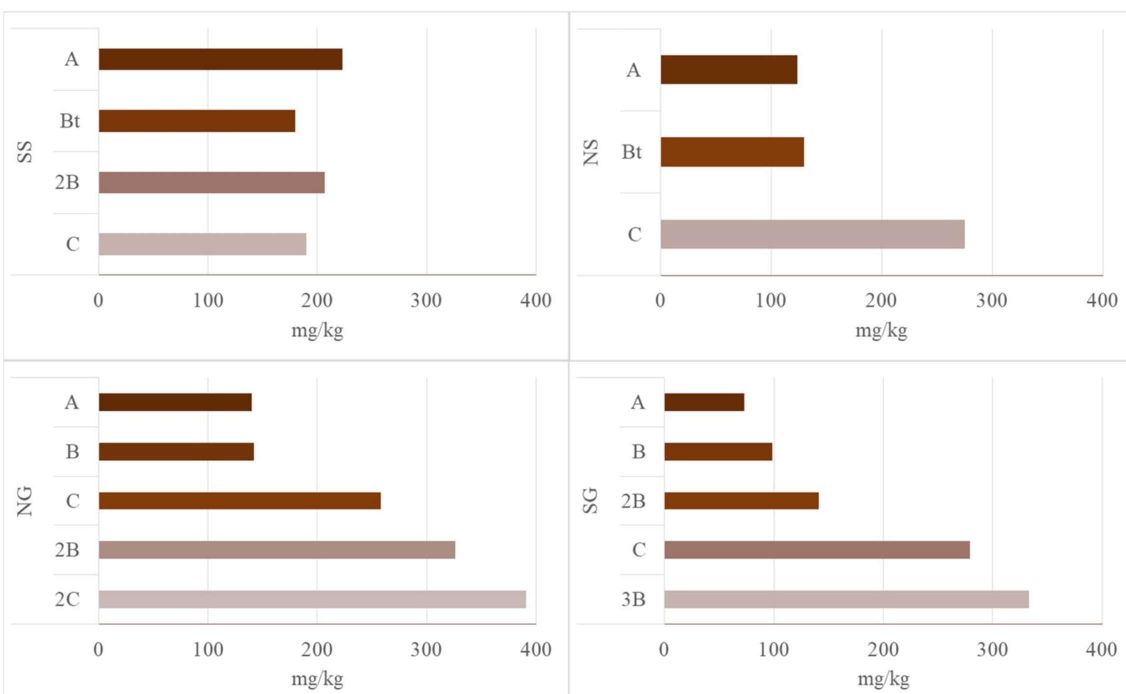

Fig. 12 Extractable K (K) in the four soil profiles. SS (southerly steep slope), NS (northerly steep slope), NG (northerly gentle slope) and SG (southerlygentle slope)

similar, and the amount of extractable K was higher in NG than in SG (Fig. 12). Soil extractable K was highest in the north-facing gentle slope, which authors such as Maren et al. (2015) and Liu et al. (2018) pointed out that could be a consequence of lower solar radiation received on north-facing slopes, producing lower soil temperatures than on south-facing slopes. Solar radiation and temperature could influence SOM content and, consequently, the nutrient concentrations in soil (Wang et al. 2006; Brandt et al. 2010), which would explain the differences observed between the two aspects, particularly in gentle slope areas. Soil extractable K mainly depends on climate conditions but also on topography (Li et al. 2021). Steep areas generally show lower nutrient content than gentle slope areas, due to lower soil moisture and the faster decomposition of organic matter (Hook and Burke 2000), as we can see in the different dynamic exhibited by both N and extractable K, according to slope. In the case of steep slopes, there is no clear trend, probably due to higher erosion and degradation processes. Li et al. (2021) observed differences in extractable K according to the inputs that can affect to soil forming, which could also be detected in the present study when comparing the two southern-aspect slopes, as K values were lower in the steep one.

Multivariate analysis and implications for land management

The Redundancy Analysis (RDA) allowed us to determine just how different the soil is, in each profile, following exposure to different topographical conditions. Factor 1 in the RDA explains 23.7% of the variance and Factor 2 explains 12.4%, with 36.1% of the total variance thus being explained. The variables with greatest explanatory capacity are Na, EC, Ca and Mg, while the properties with least explanatory capacity are OM, TN and *C/N* ratio (Fig. 13). In the RDA, it is difficult to identify different groups of more than two soil chemical elements. We can identify one group composed of Na and EC and another composed of OM and TN. There is clearly a degree of similarity between the SG and NG profiles where the slope was gentle. This may be indicative of the similarity in their chemical properties, as shown in the RDA, suggesting a stronger influence of slope than of aspect. This is also reflected in the contrast between

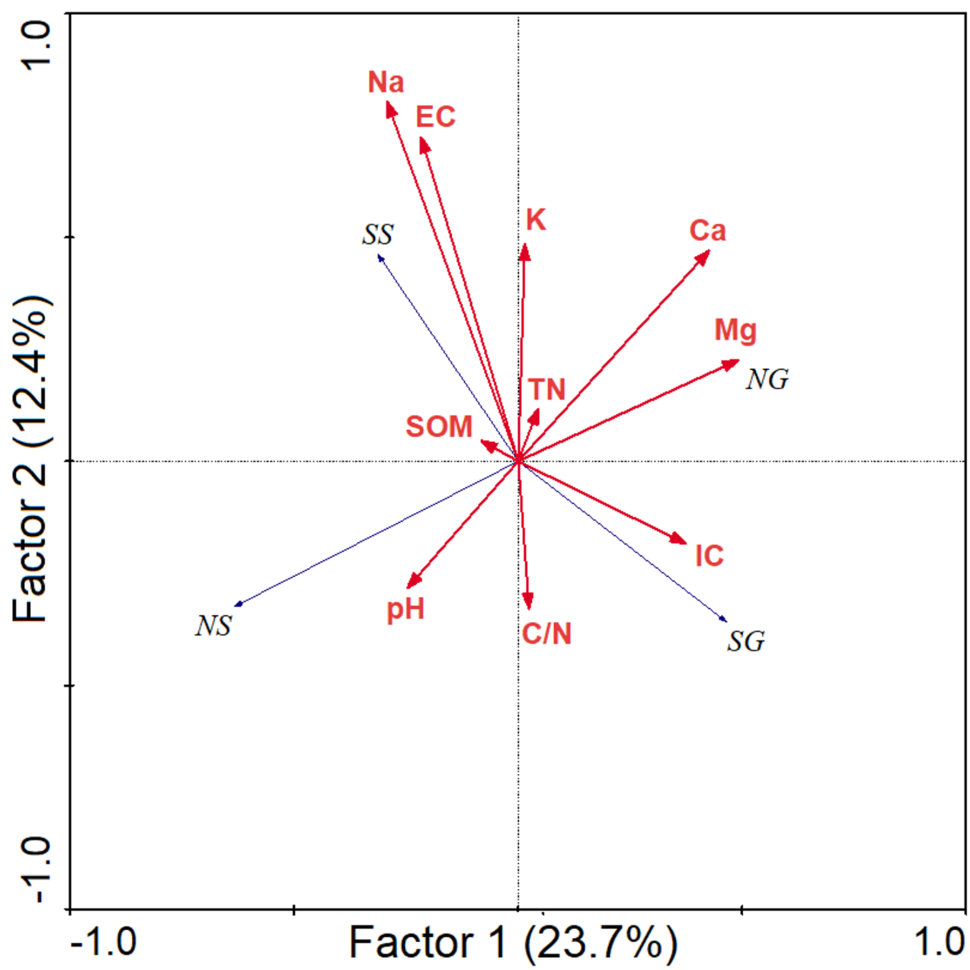

Fig. 13 RDA showing Factor 1 and Factor 2 loadings. Organic matter (OM) content, inorganic carbon (IC), total nitrogen (TN), carbon/nitrogen ratio (*C/N*), pH, electrical conductivity (EC), extractable calcium (Ca), extractable magnesium (Mg), extractable sodium (Na) and extractable potassium (K)

the plots of steep and gentle slopes, for both aspects. Thus, slope is the determining factor in the dynamics of the chemical properties of the soils (Fig. 13). These results manifest the need for the application of erosion mitigation measures in order to ensure the retention of SOM and nutrients in the soil.

Our results confirm that erosive processes can be highly relevant in fire-prone ecosystems. In general, we found evidences of different sedimentary processes (erosion in steep slopes and deposition in gentle slopes) and variability in the nutrient content of soil profiles, according to slope (higher SOM, total N, extractable K and Mg in gentle than in steep slopes). Authors as Komolafe et al. (2021) demonstrated the correlation between soil nutrient and soil topography. Accordingly, we warn of the risk of soil loss and soil degradation in fire-prone Mediterranean areas. Moreover, we recommend focusing post-fire restoration actions aimed at conserving soils in those burnt areas with steep slopes, especially after very severe fires (Pereira et al. 2018). Topographical differences can affect the recovery of vegetation (Lin et al. 2021; Liu et al. 2021) and thus, post-fire management should be prioritized in critical areas to avoid soil degradation using low-impact or alternative treatments that limit the degradation of these areas (Francos et al. 2018b). Protection against erosion and preservation of soil quality after fire in these vulnerable areas may be achieved through the provision of a protective ground cover, shortening the distance of uninterrupted flow paths, promoting substrate stabilisation and enhancing vegetation recovery (i.e., application of mulch, erosion barriers, chemical improvers and seeding, respectively) (Girona-García et al. 2021).

Conclusions

This study provides valuable data of soil properties and sediment dynamics in a study site affected by recurrent fires over 40 years. After studying four entire soil profiles developed in slopes of different steepness and aspect, we found that sediment dynamics and soil properties are influenced by wildfire recurrence and topographical factors. Soils in south aspect burned areas are deeper than those in north-facing slopes; on the other hand, A horizons were thicker in gentle than in steep slopes, explained by the lower magnitude of the erosive processes and the higher sedimentation in the former. Soils in gentle slopes present higher values of OM, Ca and Mg, and lower of Na than those in steep areas. In relation to aspect, IC and Na are higher in the south-facing profiles while TN and K are higher in north-facing soils. However, despite the differences observed across the studied profiles, soil IC, TN, *C*/*N*, pH, EC and K do not vary with slope, and OM, *C*/*N*, pH, EC, Ca and Mg are not influenced by aspect. Moreover, results show an influence of slope on SOM content and the availability of major cations, being lower in steeper areas, which indicates the need for mitigating erosion processes after wildfires in these slopes in order to protect the ecosystem services provided by soils.

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