Variation of soil organic carbon, stable isotopes and soil quality indicators across an eroding-deposition catena in an historical Spanish olive orchard

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Abstract. This study compares the distribution of bulk soil organic carbon (SOC also reported as C_{org}), its fractions (unprotected, physical, chemical and biochemically protected), available P (P_{avail}), organic nitrogen (N_{org}) and stable isotopes ($\delta^{15}N$ and $\delta^{13}C$) signatures at four soil depths (0–10, 10–20, 20–30, 30–40 cm) between a nearby forested reference area and an historical olive orchard (established in 1856) located in Southern Spain. In addition, these soil properties, as well as water stable aggregates (W_{sagg}) were contrasted at eroding and deposition areas within the olive orchard, previously determined using ^{137}Cs. Results highlight a significant depletion of SOC stock in the olive orchard as compared to the forested area, approximately 120 vs. 55 t C ha^{-1} at the top 40 cm of soil respectively, being severe in the case of unprotected carbon fraction. Erosion and deposition within the old olive orchard created large differences in soil properties along a catena, resulting in higher C_{org}, P_{avail} and N_{org} contents and $\delta^{15}N$ at the deposition area and therefore defining two areas with a different soil quality status (degraded vs. non-degraded). Differences in $\delta^{15}N$ at such different catena locations suggest that this isotopic signature has the potential for being used as an indicator of soil degradation magnitude, although additional studies would be required to confirm this finding. These overall results indicate that proper understanding of C_{org} content and soil quality in olive orchards require the consideration of the spatial variability induced by erosion/deposition processes for a convenient appraisal at farm scale.

1 Introduction

Research on soil organic carbon (SOC) and its dynamics has increased after the declaration of 4 per thousand program (Lal, 2015), which seeks to increase global soil organic matter stocks by 0.4 percent per year as a compensation for the global emissions of greenhouse gases by anthropogenic sources. Under this program special emphasis is given to combat soil

degradation, as it is a process which has a strong impact on the global carbon cycle because of the depletion of the SOC stock. For instance, in European agricultural soils, Lugato et al. (2016) reported that erosion-induced SOC fluxes were in the same order as the current gains from improved management and must be reduced to maintain soil health and productivity.

35 Lal (2003) estimated the global erosion-induced displacement of SOC at 5.7 Pg C yr^{-1} , and of that amount approximately 70 % is redistributed and redeposited over the landscape and the remaining 30% is transported by rivers into aquatic ecosystems. SOC is the most important indicator of soil quality (Rajan et al., 2010) and erosion-induced loss of SOC affects soil fertility on-site and the environment quality off-site (Lal, 2019). However, the effects of soil erosion and the fate of the specific SOC fraction transported by erosion remains poorly understood. Because of the agro-environmental impact of SOC

40 dynamics and SOC variability, more site and crop specific investigations are needed.

Olives are one of the most important crops in the Mediterranean region, where they cover approximately 9.7 Mha (FAOSTAT, 2019). Within the olive growing area there are regions where it becomes a dominant crop with a huge social and environmental significance, shaping the landscape of a great proportion of the territory. One of these regions is Andalusia. Located in Southern part of Spain, this is a region where olives cover approximately 17 % (Gómez et al., 2014)

45 and about 36 % of the agrarian utile territory. Olive cultivation has been linked to severe environmental issues including the acceleration of erosion and soil degradation (e.g. Beaufoy, 2001, Scheidel and Krausmann, 2011). In fact, soil degradation is common in olive orchards as they have been traditionally cultivated under rainfed conditions on sloping land, at relatively low tree density, limited canopy size by pruning and bare soil management to optimize water use by the tree under the semiarid conditions which characterize the Mediterranean climate (Gómez, 2014). Indeed, there are many studies which

50 have measured high erosion rates in olive orchards on sloping areas (e.g. Gómez et al., 2014), although these high erosion rates are not necessarily a consequence of current management. Vanwalleghem et al. (2011) in a study of historical erosion rates in several ancient olive orchards of Montefrío (Southern Spain) reported unsustainable erosion rates in the range of 23 to 68 Mg ha^{-1} y^{-1} during the XIX and early XX centuries when these orchards were managed with bare soil, albeit based on animal ploughing. Vanwalleghem et al. (2011) also reported a further increase of these erosion rates when bare soil

55 management in these orchards started to be implemented in the late XX century using mechanization and herbicides. In the last five decades (Ruíz de Castroviejo, 1969), there has been an attempt to control soil degradation, while maintaining a favourable soil water balance for the tree through the gradual development of temporary cover crops (grown during the rainy season) (Gómez et al., 2014). These high erosion rates have also been linked to the degradation of soil properties observed in olive orchards. Gómez et al. (2009b) measured the differences in soil properties in a 5-year long experiment on runoff plots

60 reporting a decrease in SOC, aggregate stability and infiltration rates in bare soil management as compared to cover crops. Such scientific evidence which links changes of soil properties to different erosion rates in olive orchards under controlled conditions are rarely reported in the literature. Indeed, most of the studies connecting soil properties with different soil managements in olives come from surveys of soil properties in orchards on similar soil types but with differences in soil management. An example of these studies are those of Álvarez et al. (2010) or Soriano et al. (2014) who found an

65 improvement in soil properties, particularly aggregate stability, SOC and biological activity, in organic olive orchards with

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cover crops, when compared to bare soil ones. In recent years, these studies have started to deepen our understanding in investigating key properties such as SOC. For instance, Vicente-Vicente et al. (2017) evaluated the impact of cover crops in the distribution of unprotected and protected SOC in the top 15 cm of the soil. These field studies take samples in a representative area of the slope, which is a common assumption in many soil quality studies (e.g. Andrews and Carroll,

70 2001). Although there are a limited number of experiments on the spatial variability of soil properties in olive orchards, they suggest a significant in-field variability (see Gargouri et al., 2013; Huang et al. 2017). Moreover, Gómez et al. (2012) suggested that part of this in-site variability of soil properties, regarding of organic carbon, might be related to erosion/deposition processes.

In-field variability associated with erosion/deposition processes is relatively well documented for organic carbon content in

75 field crops (e.g., De Gryze et al. 2008, Mabit and Bernard, 1998, 2010; Van Oost et al., 2005).While the human-induced acceleration of soil erosion has depleted the SOC stock of agroecosystems, the fate of SOC transported over the landscape and that deposited in depressional sites is not fully understood, despite the fact that it might explain a high proportion of the in-site variability of soil properties.

Most of the erosion rates recorded or established in olive orchards come from runoff plots or small catchment experiments

80 (e.g. Gómez et al., 2014). The use of the ^{137}Cs approach has also demonstrated its potential in establishing long-term soil erosion rates in this specific land use. An example of these studies is that of Mabit et al. (2012) in which erosion as well as deposition rates since the 1950´s were determined in one ancient olive orchard in the municipality of Montefrío, showing an average annual rate in the eroding part of the slope of 12.3 t ha^{-1} yr^{-1}, and an average deposition rate in the lower section of the hillslope, much shorter than the eroding section, of 13.1 t ha^{-1} yr^{-1}. This study involved a reference area for establishing

85 precisely the initial ^{137}Cs inventory, a natural undisturbed area located at 200 m from the orchard. To complement and/or to circumvent some limitation associated with the use of this anthropogenic radioisotope (see Mabit et al., 2008) and to maintain the capacity to determinate erosion and deposition rates without the need to use direct measurements, other natural radioisotopes such as [210]Pb (e.g. Mabit et al., 2014; Matisoff et al., 2014) or stable isotopes such as δ ^{15}N or δ [13]C (e.g. Meusburger et al., 2013) have been proposed.

90 In this study, we hypothesized that the contribution of the long-term erosion-deposition processes on the in-field variability of soil properties in olive orchards (or other woody crops) under medium-high slope is relevant and should be taken into account when analysing the effects of specific strategies on SOC sequestration or on soil properties. In addition, we exploited the advantage provided by the unique location of an ancient olive orchard near an undisturbed reference area and the previous information on this site from studies on historical erosion rates, to fulfil the following objectives:

95 1- To quantify the long-term variability in soil total organic carbon and in their different fractions, and soil quality indicators in relation to erosion and deposition areas in an historical olive orchard;

2- To evaluate these differences in relation to the reference values found in an undisturbed natural area;

3- To evaluate differences in stable isotopes (δ ^{13}C and δ ^{15}N) and explore their potential for identifying degraded areas within the olive orchard.

2 Materials and Methods

2.1 Description of the area

The study area is located in the municipality of Montefrío, southwestern Spain (Figure 1). The municipality extension is around 220 km², of which 81 % is cultivated, mostly with olive trees. The climate in the region is continental Mediterranean with a long-term (1960–2018) average annual precipitation of 630 mm, a mean annual evapotranspiration of 750 mm, and a yearly average temperature of 15.2 ℃. It is a mountainous area, with elevation ranging between 800–1600 m a.s.l at the highest point (Sierra de Parapanda). Soil sampling took place in two areas around the archaeological site "Peña de los Gitanos", where the soils are classified as Calcic Cambisol according to the FAO classification. The reference undisturbed area was inside an archaeological site (Figure 1). This undisturbed area is covered by open Mediterranean forest interspersed with shrubs and annual grasses on limestone material (calcarenites). The status of this protected site guarantees that no anthropogenic activities have impacted it for a long period of time, approximately since the end of XVI century. Combined with its flat topography, this area has the potential to allow the establishment of reference values for undisturbed soil in the area. The area studied was an olive orchard located close to the reference area (Figure 1) which had been established in 1856. Both areas were described in detail in previous studies on historical erosion rates in the region (Vanwalleghem et al., 2011, Mabit et al., 2012). This olive orchard is rainfed, and soil management in the decades before the sampling was based on bare soil with pruning residues (trees pruned every 2 years) being chopped and left on the soil surface. Olives are fertilized annually with 5 kg of 15 N-P-K per tree, spread below the tree canopy area.

2.2 Soil sampling

The reference site was sampled in two perpendicular transects, spaced at an average distance of 6 m. Using the excavation method, a total of 13 micropits in this reference site were collected per 5 cm increments until bedrock was reached (i.e. 0–5, 5–10, 10–15, 15–20 and when possible, 20–25, 25–30, 30–35, 35–40, 40–45, 45–50, 50–55 and 55–60 cm). In the olive orchard a mechanical soil core of 8 cm diameter was used to sample 8 points in a 452 m long catena. At each sampling point soil was taken at different depths (0–10, 10–20, 20–30 and 30–40 cm). In a previous investigation, soil erosion and deposition rates were determined at each sampling point, comparing the ^{137}Cs inventory among these points and that of the undisturbed reference area (Mabit et al., 2012). The positions of all sampling points were recorded by RTK-GPS at submeter resolution (Table 1).

2.3 Physicochemical analysis

Soil samples were passed through a 2 mm sieve and homogenized, and stoniness determined as % in mass. Soil organic carbon concentration (C_{org}) was determined according to Walkley and Black (1947). Separation of the various soil C_{org} pools was performed by a combination of physical and chemical fractionation techniques through a three-step process developed by Six et al. (2002) and modified by Stewart et al. (2009), summarized here. First a partial dispersion and physical

fractionation of the soil is performed to obtain three size fractions: >250 mm (coarse non-protected particulate organic matter, POM), 53–250 mm (microaggregate fraction), and <53 mm (easily dispersed silt and clay). This physical fractionation is done on air-dried 2-mm soil sieved over a 250-mm sieve. Material greater than 250 mm remained on the sieve. Microaggregates were collected on a 53-mm sieve that was subsequently wet-sieved to separate the easily dispersed

135 silt- and clay-sized fractions from the water-stable microaggregates. The suspension was centrifuged at 127 x g for 7 min to separate the silt-sized fraction. This supernatant was subsequently separated, flocculated and centrifuged at 1730 x g for 15 min to separate the clay-sized fraction. All fractions were dried in a 60 ºC oven and weighed. Afterwards there is a second step involving a further fractionation of the microaggregate fraction isolated in the first step. A density flotation with 1sodium polytungstate was used to isolate fine non-protected POM (LF): After removing the fine non-protected POM, the

140 heavy fraction was dispersed overnight by shaking and passed through a 53 mm sieve to separate the microaggregate-protected POM (>53 mm in size, iPOM) from the microaggregate-derived silt and clay-sized fraction. The resulting suspension was centrifuged to separate the microaggregate-derived silt- versus clay-sized fraction as described above. A final third step involved the acid hydrolysis of each of the isolated silt- and clay-sized fractions. The silt- and clay-sized fractions from both the density flotation and the initial dispersion and physical fractionation were subjected to

145 acid hydrolysis. The concentration of organic carbon in each of the isolated fraction was determined by wet oxidation using sulfuric acid and potassium dichromate following the methodology of Anderson and Ingram (1993).

Inorganic carbon was removed prior to stable isotope analysis by acid fumigation following the method of Harris et al. (2001). Moistened subsamples were exposed to the exhalation of HCl in a desiccator overnight. Afterwards, the samples were dried at 40º C before measuring the stable isotope ratio. The N measurements were done with unacidified samples and

150 the stable N isotope ratios and the C and N concentrations were measured by isotope ratio mass spectrometry (Isoprime 100 coupled with an Elementar Vario Isotope Select elemental analyser; both instruments supplied by Elementar, Langenselbold, Germany). The instrumental standard deviation for δ ^{15}N is 0.16% and 0.11% for δ [13]C. Stable isotopes are reported as delta values ($°/_{oo}$) which are the relative differences between the isotope ratios of the samples and the isotope ratio of a reference standard.

155 In addition, available phosphorus (P_{avail}) was determined by the Olsen method (Olsen and Summers 1982) and organic nitrogen (N_{org}) was determined by the Kjeldahl method (Stevenson, 1982). Water stable aggregates (W_{sagg}) were measured using the method of Barthes and Roose (2002). Soil particle size distribution was determined using the hydrometer method (Bouyoucos, 1962) for the topsoil (0–10 cm) of the reference area and the olive orchard. As proposed by Hassink and Whitmore (1997), theoretical values of carbon saturation were established from the soil particle analysis. Finally, the soil

160 degradation index developed by Gómez et al. (2009a) was calculated from the C_{org}, P_{avail} and W_{sagg}.

2.4 Statistical analysis

The overall effect of depth and area (reference site vs. olive orchard or eroded vs. deposition area within the olive orchard) were evaluated using a two factor ANOVA ($p < 0.05$). Additionally, for some comparison at similar soil depth, values of soil

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properties between two different areas were assessed using a one-way ANOVA test ($p<0.05$). In both situations, data were

165 log-transformed when necessary to fulfil ANOVA requirements. The Pearson correlation coefficient was calculated among variables. The statistical software package Stata SE14.1 was used for these analyses.

3 Results

Table 2 shows the significance of the differences of bulk soil C_{org} and the various C_{org} fractions between reference and olive orchard plots, between soil depth and due to the interaction between both (Table 2A) and the effects of erosion/deposition

170 ratio (Table 2B). Bulk soil C_{org} are always significantly higher in the reference area as compared to the olive orchard (Table 2A and Figure 2A), and this is independent of the soil sampling depth. C_{org} values in the reference site are 2 to 5 times higher than that of the olive orchard for a given depth, with the greater differences in the top 10 cm of the soil. Soil depth has a significant effect on bulk C_{org} and C_{org} fractions, with values decreasing with depth in both areas. Unprotected, physically, chemically and biochemically protected factions are higher in the reference site as compared to the olive orchard (Table 2A

175 and Figure 3). C_{org} values are 2 to 6 times higher for the unprotected and chemically protected fractions, and between 2 to 3.5 times higher for the physically and biochemically protected fractions, with differences tending to decrease with the soil depth.

Within the olive orchard, the overall analysis using a two-way ANOVA also highlights statistically significant differences between the erosion and deposition areas (Table 2B). Higher C_{org} values (1.1 to 0.6%) were observed in the deposition area

180 located downslope, whereas lower values (0.85 to 0.55 %) were measured in the areas with net erosion in the upper and mid sections of the catena. It is worth noting that these differences between erosion and deposition areas are detected for the overall analysis using a two-way ANOVA (Tables 2A and B), although an individual analysis at each depth (Figure 2B) does not detect statistically significant differences, probably due to the moderate number of replications. Significant differences between the deposition and eroding area are also found for the unprotected and the physically and chemically protected

185 fractions (Table 2B, Figure 4). However, differences for the biochemically protected (Table 2B, Figure 4) are not.

The percentage distribution of SOC fractions is also significantly different between both areas (reference vs. olive orchard), except for the biochemically protected fraction (Table 3A, Figure 5). The reference area stores most of the C_{org} in the unprotected fraction (between 50 and 65% approximately) with no significant trend with depth (Table 3A, Figure 5), followed in relative importance by the chemically and physically protected fractions which contain between 18–30 % and

190 10–20 % of the bulk soil C_{org}, respectively. The biochemically protected fraction represents a very low percentage (between 4 to 6 %). In the olive orchard, C_{org} is stored predominantly in the physically and chemically protected fractions which accounted for about 38 to 27 and 34 to 28 % respectively, followed by the pool of unprotected fraction (between the 22 to 32%) (Figure 5).

The biochemically protected fraction represents from 11 to 4% of the organic carbon stored in the olive orchard,
195   approximately. There are no clear differences in the organic carbon distribution among the different fractions between the
        erosion and deposition areas in the olive orchard (Table 3B and Figure 6).

        Figure 7 shows the mean SOC stock for the top 40 cm of the soil. SOC stock in the reference site is as large as 120 t ha^{-1} and
        is significantly higher than the olive orchard which stores between 41 and 54 t ha^{-1} in the eroded and deposition areas
        respectively, without significant differences between these two.

200   Texture distribution of the topsoil (0–10 cm) along the catena in the olive orchard presents an average clay, silt and sand
        content of 41, 37 and 22% and low variability, respectively (average coefficient of variation of 17%) without significant
        changes between the erosion and deposition areas. In the reference area, the soil has an average clay, silt and sand content of
        30, 31 and 39% respectively, also with a homogeneous distribution across the sampling area (coefficient of variation of
        10%). According to the Hassink and Whitmore (1997) model, the percentages of organic carbon of maximum soil stable C_{org}
205   are of 1.94 and 1.15 % in the reference site and olive orchard, respectively. So, protected C_{org} in the reference and olive
        orchard areas account for 87 % and 64 % of the maximum soil stable C_{org}, respectively at the topsoil

        Figure 8 and Table 4A compare stable isotope delta values between the reference site and the overall olive orchard by depth.
        There are statistically significant differences in δ ^{15}N, δ ^{13}C, and δ ^{13}C:δ ^{15}N ratio between the two areas, although in the case
        of δ ^{15}N at the top 20 cm, soil depth had a significant effect. When comparing differences between the erosion and deposition
210   areas within the olive orchard, we detected statistically significant differences only in δ ^{15}N and δ ^{13}C:δ ^{15}N ratio, especially
        in the 10–20 cm of the soil (Figure 9, Table 4B).

        Figure 10 depicts the comparison between the P_{avail}, N_{org}, W_{sagg} as well as the soil degradation index (SDI, Gómez et al.
        2009a) at the top 10 cm of the soil between the erosion and deposition area of the olive orchard. Table 5 presents a similar
        comparison for N_{org}, P_{avail} and bulk density at the different soil depths. P_{avail} in the deposition area is much higher than that of
215   the erosion area, with a similar trend, while not statistically significant, for N_{org} and W_{sagg}. SDI, which is an aggregated
        indicator of these three soil variables, in the eroded area is about 3 times higher than that in the deposition area.

4 Discussion

        After approximately 175 years of contrasted land use between the undisturbed reference site and the olive orchard, bulk soil
        organic carbon concentration and its fractions have been dramatically reduced in the olive orchard. Current levels of C_{org}
220   concentration in the soil profile are approximately 20–25% of the reference area covered by the natural vegetation in the area
        adjacent to the orchard. This ratio is similar, albeit in the lower range, of the comparison of C_{org} in topsoil among olive
        orchards with different managements and natural areas reported for the region (Millgroom et al., 2007). The increased soil
        disturbance, the lower annual rate of biomass returned to the soil and the higher erosion rate in the olive orchard explain this
        difference. In both areas, the C_{org} is clearly stratified, indicating that despite the different mechanisms involved there is a
225   periodic input of biomass from the olive trees (e.g. fall down of senescence leaves and tree pruning residues) plus the annual

ground vegetation. Vicente-Vicente et al. (2017) estimated this biomass contribution in the range of 1.48 to 0.56 t ha^{-1} yr^{-1}. It is worth noticing that the decrease in C_{org} as compared to the natural area is much higher than the reported rates of increase in C_{org} in olive orchards using conservation agriculture (CA) techniques, such as cover crops and incorporation of organic residues from different sources. In a meta-analysis Vicente-Vicente et al. (2016) found a response ratio (the ratio of C_{org}

230   under CA management as compared to bare soil managed orchard) from 1.1 to 1.9 suggesting that under a CA management, which combines cover crops and organic residues, C_{org} doubled as a maximum.

Combining all C_{org} data of the olive orchard, the variability was about 35% which is similar to what has been reported so far in the few studies on soil C_{org} variability in olive orchards. For instance, Gargouri et al. (2013) indicated a 24% coefficient of variation (CV) in a 34 ha olive orchard in Tunisia, while Huang et al. (2017) reported an average CV of 41% in a 6.2 ha

235   olive orchard in Southern Spain. Neither of these two studies reported clear trends on the distribution of C_{org} with topography. Huang et al. (2017) pointed out the additional difficulties in the determination of $C_{org.}$ due to the topography heterogeneity, although this was compounded by the fact that within the orchards there were two areas with different planting dates for the trees. Gómez et al. (2012) reported a CV of 49% with higher C_{org} in areas where there was a change in slope gradient from the hillslope to a draining central channel into the catchment, although they could not find a simple

240   relationship between the increase in content and the topographic indexes. Despite the fact that a lot of work has been done on the correlation between erosion-deposition and the redistribution of soil Corg, (e.g. Van Oost et al. (2005)), our study is, to our knowledge, the first attempt to quantify this in detail under olive orchard agro-environmental condition. The variability induced by the combined effects of water and tillage erosion in this olive orchard was similar to that described in other agroecosystems. For instance, Van Oost et al. (2005) measured on two field crop sites under temperate climate, a clear

245   correlation between the erosion-deposition rates and the topsoil C_{org} concentration, which ranged between 0.8 % of the erosion to 1.4% of the deposition sites in the top 25 cm of the soil. Besides this, Bameri et al. (2015) in a field crop site with a semi-arid environment, measured also a higher C_{org} in lower part of the field where deposition of the eroded soil from the upper zones took place with a mean C_{org} value of 0.95% in the top 20 cm of the soil and a CV of 53%. Overall, under such landscapes cultivated for a long time, the cumulative effect of tillage and water erosion on the redistribution of soil across

250   the slope has been observed (Dlugoß et al., 2012). These processes also produce a vertical redistribution of C_{org} resulting in a relatively homogeneous profile in the tilled layer (top 15–20 cm) and a gradual decline below this depth, as noted in this study.

This horizontal distribution due to tillage and water erosion also simultaneously affected other soil properties and has been described previously in other field crops areas. For instance, De Gryze et al. (2008) described, in a field crop area under

255   conventional tillage in Belgium, how P_{avail} almost doubled (22.9 vs. 12.2 mg kg^{-1}) in the depositional area as compared to the eroding upper part. They also reported that in half of the field under conservation tillage these differences in P_{avail} between the upper and lower areas of the field disappeared. We have also observed in our sampled orchard a pronounced increase in topsoil P_{avail} in the deposition area of around 400% as compared to the eroding part of the orchard. The cumulative effects of the differences in C_{org}, P_{avail}, and the trend towards higher, although non-significant, W_{sagg} in the deposition area, allow us to

260   delimit two distinctive areas within the orchard with marked differences in soil quality: the eroded part which is within the range considered as degraded in the region (Gómez et al., (2009a) and the depositional area which is within the range of non-degraded according to the same index, and represents the 20% of the orchard transect length (Table 1). This again raises the need for a careful delineation of sub-areas when analysing soil quality indicators and/or SOC carbon stock within the same field unit. Topography and sediment redistribution by erosive processes introduce a gradient of spatial variability that

265   questions the concept of representative area when it comes to describing a whole field. In fact, several studies (e.g. Dell and Sharpley, 2006), have suggested that the verification of compliance of environmental programs such as those related to C_{org} sequestration should be based preferentially, at least partially, on modelling approaches.

The differences between the reference site and the olive orchard are similar to those described previously when comparing cropland and forested areas, with the latter presenting a higher concentration of C_{org} (and most of it in the unprotected

270   fraction) while the cropland presented a higher fraction of the carbon in the physically and chemically protected fractions (e.g. Poeplau and Don, 2013). This is likely due to the fact that under soil degradation and low annual organic carbon inputs, as is the case under olive orchard land use, most of the unprotected C_{org} decomposes relatively quickly and a great proportion of the remained low SOC is protected. In addition, the mobilisation of the unprotected C_{org} is expected to be reduced in the protected forested area because of the canopy and the existing vegetation on the ground that protects the soil against runoff

275   and splash erosion processes. In fact, the protected C_{org} concentration in the topsoil of the olive orchard in the eroded area is about the 60 % of the upper limit of protected C_{org} (1.19 %) according to the model of Hassink and Whitmore (1997). Therefore, the low unprotected SOC concentration found in the olive orchard is an issue in the increase of SOC stocks. Furthermore, the percentage of organic carbon of maximum soil stable C_{org} in the olive orchard was 59 % of that of the reference site, and therefore the soil degradation in the olive orchard does not only decrease the level of C_{org} but also the

280   capacity for C_{org} stabilization. This is because protected fractions are fuelled from recently derived, partially decomposed plant residues together with microbial and micro, meso and macrofaunal debris (unprotected organic carbon) throughout processes like SOC aggregation into macro- and/or microaggregates (physically protected SOC) and complex SOC associations with clay and silt particles (chemically protected SOC) which are disrupted in the cropland area as in comparison with the reference area. The distribution among soil C_{org} fractions in the orchard of this study was similar to the

285   result obtained by Vicente-Vicente et al. (2017) who measured C_{org} fractions distribution in olive oil orchards with temporary cover crops, with the exception of the unprotected SOC, which was much higher in soils under cover crops than that of our study under bare soils. The study of Vicente-Vicente et al. (2017) showed a large variability among orchards attributed, among other reasons, to the large variability in biomass production by the cover crops in the orchards. In our study, the erosion/deposition processes also induced significant differences in C_{org} concentration and contributed to

290   increasing the variability in the distribution of organic carbon among the different areas of the olive orchard. The greatest differences between eroded and deposited area were observed for the unprotected SOC, especially for the top 10 cm of soils. This is likely due to the transport of the low density, and prone to water floating, of the partially decomposed plant and microbial and animal residues from the eroded part to the deposited part of the orchard. Differences in physically and

chemically protected SOC between eroded and deposited areas also indicate selective deposition of soil aggregates, although
295   this is not reflected in the change in topsoil texture, which could be explained by the homogenizing effect of other processes
of soil redistribution across the slope (e.g. tillage erosion, creeping, …) and the relatively high silt and clay content of the
soil.

The relatively high variability of C_{org} and other soil quality indicators due to erosion/deposition process indicates that this
variability needs to be addressed for a proper appraisal of the distribution of organic carbon among the different fractions in
300   a given orchard. Differences in vegetation types induced differences in $\delta\ ^{13}C$ between the olive orchard and the reference
area but, as expected, no differences in $\delta\ ^{13}C$ were detected between the erosion and deposition areas in the olive orchard
given the same origin of vegetation derived organic matter, C3-plants. Interestingly, within the olive orchard, significant
differences in $\delta\ ^{15}N$ were detected between the erosion and deposition areas, especially for the top 20 cm of soils (Figure 9).
This suggests the possibility of using $\delta\ ^{15}N$ as a variable for identifying degraded area in olive growing fields, as has been
305   proposed for other eroding regions in the world (e.g. Meusburger et al. 2013), which might provide an alternative when other
conventional or isotopic techniques are not available. The source of N in soil is multifarious and subject to a wide range of
transformations that affect $\delta\ ^{15}N$ signature and therefore we can only speculate on the reasons for this difference in $\delta\ ^{15}N$ in a
relatively homogeneous area. Bulk soil $\delta\ ^{15}N$ tended to be more positive (e.g. more enriched in $\delta\ ^{15}N$) as N cycling rate
increases soil microbial processes (e.g. N mineralization, nitrification and denitrification) resulting in products (e.g. nitrate,
310   N_2O, N_2, NH_3) depleted in ^{15}N while the substrate from which they were formed becomes slightly enriched (Robison, 2001).
The higher $\delta\ ^{15}N$ signature of the soil at deposition location suggests that rates of processes involved in the N cycling are
higher than in the erosion area and that is in accordance with the higher bulk C_{org} and P_{avail} contents and lower SDI of the
deposition site. The relatively lower soil $\delta\ ^{15}N$ signature at the reference site could be partially due to the input of litter N
from the natural legumes and to the closed N cycling which characterize natural forest ecosystems. The trend in ^{15}N
315   enrichment with soil depth, as found in the reference site, is a common observation in forest and grassland sites, which has
been related to different mechanisms, including ^{15}N isotope discrimination during microbial N transformations, differential
preservation of ^{15}N-enriched soil organic matter components during N decomposition, and more recently, to the build-up of
microbial ^{15}N-enriched microbial necromass (Huygens et al., 2008). However, there still remains the need for a careful
calibration against an undisturbed reference site and a better understanding of the influence of different vegetation between
320   the reference and the studied area in the change of the $\delta\ ^{15}N$ signal for its further use as an additional tool to determine soil
degradation.

5 Conclusions

1- The results indicate that erosion and deposition within the investigated old olive orchard have created a significant
difference in soil properties along a catena, which is translated into different soil C_{org}, P_{avail} and N_{org} contents and $\delta\ ^{15}N$, and
325   thus soil quality status.

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2- This variability was smaller than that of the natural area, which indicated a severe depletion of SOC as compared to the natural area and a redistribution of available organic carbon among the different SOC fractions.

3- The results suggest that δ ^{15}N has the potential for been used as an indicator of soil degradation. More investigation under different agroecosystems would be required for confirming this statement at larger scale.

330   4- This investigation highlights that proper understanding and management of soil quality and C_{org} content in olive orchards require considering the on-site spatial variability induced by soil erosion/deposition processes.

6 Acknowledgements

References

Álvarez, S., Soriano, M.A., Landa, B.B., and Gómez, J.A.: Soil properties in organic olive groves compared with that in natural areas in a mountainous landscape in southern Spain, Soil Use and Manage., 23, 404–416, https://doi.org/10.1111/j.1475-2743.2007.00104.x, 2010.

340   Anderson, J.M., and Ingram, J.S.I. (Eds.): Tropical soil biology and fertility: A handbook of methods, CAB International, Wallingford, UK, 1993.

Andrews, S.S., and Carroll, C.R.: Designing a soil quality assessment tool for sustainable agroecosystem management, Ecol. Appl., 11, 1573–1585, https://doi.org/10.1890/1051-0761(2001)011[1573:DASQAT]2.0.CO;2, 2001.

Bameri, A., Khormali, F., Amir, K., and Dehghani, A.: Spatial variability of soil organic carbon in different hillslope
345   positions in Toshan area, Golestan Province, Iran: Geostatistical approaches, J. Mt. Sci., 12, 1422–1433, https://doi.org/10.1007/s11629-014-3213-z, 2015.

Barthes, B., and Roose, E.: Aggregate stability as an indicator of soil susceptibility to runoff and erosion: validation at several levels, Catena, 47, 133–149, https://doi.org/10.1016/S0341-8162(01)00180-1, 2002.

Beaufoy, G.: EU Policies for olive farming-Unsustainable on all Counts, Brussels, WWF & BirdLife Joint Report, 20 pp.,
350   2001.

Bouyoucos, G.J.: Hydrometer method improvement for making particle size analysis of soils, Agron. J., 54, 179–186, http://dx.doi.org/10.2134/agronj1962.00021962005400050028x, 1962.

Deckers, J., Spaargaren, O., and Dondeyne, S.: Soil survey as a basis for land evaluation, in: Land Use, Land Cover and Soil Sciences, Volume II: Land Evaluation, Encyclopedia of Life Support Systems, edited by: Verheyen, W., EOLSS-UNESCO
355   Publ.,Oxford, UK, 29-58, 2004.

Dell, C.J., and Sharpley, A.N.: Spatial variation of soil organic carbon in a Northeastern U.S. watershed. J. Soil Water Conserv., 61, 129–136, https://doi.org/10.1007/s11676-014-0533-3, 2006.

De Gryze, S., Six, J., Bossuyt, H., Van Oost, K., and Merckx, R.: The relationship between landform and the distribution of soil C, N and P under conventional and minimum tillage, Geoderma, 144, 180–188, https://doi.org/10.1016/j.geoderma.2007.11.013, 2008.

Dlugoß, V., Fiener, P., Van Oost, K., and Schneider, K.: Model based analysis of lateral and vertical soil carbon fluxes induced by soil redistribution processes in a small agricultural catchment, Earth Surf. Proc. Land., 37, 193–208, https://doi.org/10.1002/esp.2246, 2012.

FAOSTAT (Food and Agriculture Statistics of FAO) Publications: http://www.fao.org/faostat/en/#home, last access: January 2019.

Gargouri, K., Rigane, H., Arous, I., and Touil, F.: Evolution of soil organic carbon in an olive orchard under arid climate, Sci. Hortic., 152, 102–108, https://doi.org/10.1016/j.scienta.2012.11.025, 2013.

Gómez, J.A., Álvarez, S., and Soriano, M.A.: Development of a soil degradation assessment tool for organic olive groves in southern Spain, Catena, 79, 9–17, https://doi.org/10.1016/j.catena.2009.05.002, 2009a.

Gómez, J.A., Sobrinho, T.A., Giráldez, J.V., and Fereres, E.: Soil management effects on runoff, erosion and soil properties in an olive grove of Southern Spain, Soil Tillage Res., 102, 5–13, https://doi.org/10.1016/j.still.2008.05.005, 2009b.

Gómez, J.A, Burguet, M., Taguas, M.E., Perez, R., Ayuso, J.L., Vanwallgehem, T., Giraldez, J.V., and Vanderlinden, K.: Distribution of soil organic carbon in two small agricultural Mediterranean catchments, EGU General Assembly, Vienna, Austria, 22–27 April 2012, EGU2012-4232, 2012.

Gómez, J.A., Infante-Amate, J., González de Molina, M., Vanwalleghem, T., Taguas, E.V., and Lorite, I.: Review: Olive cultivation, its impact on soil erosion and its progression into yield impacts in Southern Spain in the past as a key to a future of increasing climate uncertainty, Agriculture, 4, 170–200, https://doi.org/10.3390/agriculture4020170, 2014.

Harris, D., Horwath, W., and Kessel, C.: Acid fumigation of soils to remove carbonates prior to total organic carbon or Carbon-13 isotopic analysis, Soil Sci. Soc. Am. J., 65, 1853–1856, https://doi.org/10.2136/sssaj2001.1853, 2001.

Hassink, J., and Whitmore, A.P.: A model of the physical protection of organic matter in soils, Soil Sci. Soc. Am. J., 61, 131–139., https://doi.org/0.2136/sssaj1997.03615995006100010020x, 1997

Huang, J., Pedrera-Parrilla, A., Vanderlinden, K., Taguas, E.V., Gómez, J.A., and Triantafilis, J.: Potential to map depth-specific soil organic matter content across an olive grove using quasi-2d and quasi-3d inversion of DUALEM-21 data, Catena, 152, 207–217, https://doi.org/10.1016/j.catena.2017.01.017, 2017.

Huygens, D., Denef, K., Vandeweyer, R., Godoy, R., Van Cleemput, O., and Boeckx, P.: Do Nitrogen isotope patterns reflect microbial colonization of soil organic matter fractions? Biol. Fert. Soils, 44, 955–964, https://doi.org/10.1007/s00374-008-0280-8, 2008.

Lal, R.: Soil erosion and the global carbon budget, Environ. Int., 29, 437–450, https://doi.org/10.1016/S0160-4120(02)00192-7, 2003.

Lal, R.: Cover cropping and the "4 per Thousand" proposal, J Soil Water Conserv., 70, 141A, https://doi.org/10.2489/jswc.70.6.141A, 2015.

Lal, R.: Accelerated soil erosion as a source of atmospheric CO_2, Soil Tillage Res., 188, 35–40, https://doi.org/10.1016/j.still.2018.02.001, 2019.

Lugato, E., Paustian, K., Panagos, P., Jones, A., and Borrelli, P.: Quantifying the erosion effect on current carbon budget of European agricultural soils at high spatial resolution, Global Change Biol., 22, 1976–1984, https://doi.org/10.1111/gcb.13198, 2016.

Mabit, L., Benmansour, M., and Walling, D.E.: Comparative advantages and limitations of Fallout radionuclides (^{137}Cs, ^{210}Pb and [7]Be) to assess soil erosion and sedimentation, J. Environ. Radioact., 99, 1799–1807, https://doi.org/10.1016/j.jenvrad.2008.08.009, 2008.

Mabit, L., Benmansour, M., Abril, J.M., Walling, D.E., Meusburger, K., Iurian, A.R., Bernard, C., Tarján, S., Owens, P.N., Blake, W.H., and Alewell, C.: Fallout ^{210}Pb as a soil and sediment tracer in catchment sediment budget investigations: A review, Earth-Sci. Rev., 138, 335–351, https://doi.org/10.1016/j.earscirev.2014.06.007, 2014.

Mabit, L., and Bernard, C.: Spatial distribution and content of soil organic matter in an agricultural field in Eastern Canada, as estimated from geostatistical tools, Earth Surf. Proc. Land., 35, 278–283, https://doi.org/10.1002/esp.1907, 2010.

Mabit, L., and Bernard, C.: Relationship between soil inventories and chemical properties in a small intensively cropped watershed, CR Acad. Sci. II A, 327, 527–532, https://doi.org/10.1016/S1251-8050(99)80034-2, 1998.

Mabit, L., Chhem-Kieth, S., Toloza, A., Vanwalleghem, T., Bernard, C., Infante-Amate, J., González de Molina, M., and Gómez, J.A.: Radioisotopic and physicochemical background indicators to assess soil degradation affecting olive orchards in southern Spain, Agr. Ecosyst. Environ., 159, 70–80, https://doi.org/10.1016/j.agee.2012.06.014, 2012.

Matisoff, G.: [210]Pb as a tracer of soil erosion, sediment source area identification and particle transport in the terrestrial environment, J. Environ. Radioact., 138, 343–54, https://doi.org/10.1016/j.jenvrad.2014.03.008 ,2014.

Meusburger, K., Mabit, L., Park, J.-H., Sandor, T., and Alewell, C.: Combined use of stable isotopes and fallout radionuclides as soil erosion indicators in a forested mountain site, South Korea., Biogeosciences, 10, https://doi.org/10.5194/bg-10-5627-2013, 2013.

Milgroom, J., Soriano, M.A., Garrido, J.M., Gómez, J.A., and Fereres, E.: The influence of a shift from conventional to organic olive farming on soil management and erosion risk in southern Spain, Renew. Agr. Food Syst., 22, 1–10, https://doi.org/10.1017/S1742170507001500, 2007.

Olsen, S.R., and Sommers, L.E.: Phosphorus, in: Methods of soil analysis, Part 2. Chemical and microbiological properties, edited by: Page, A.L., Miller, R.H., and Keeney, D., ASA & SSSA, 403–430. Madison WI, USA, 1982.

Poeplau, C., and Don, A.: Sensitivity of soil organic carbon stocks and fractions to different land-use changes across Europe, Geoderma, 192, 189–201, https://doi.org/10.1016/j.geoderma.2012.08.003, 2013.

Rajan, K., Natarajan, A., Kumar, K.S.A., Badrinath, M.S., and Gowda, R.C.: Soil organic carbon - the most reliable indicator for monitoring land degradation by soil erosion, Curr. Sci., 99, 823–827, 2010.

425 Robison, D.: δ^{15}N as an integrator of the nitrogen cycle, Trends Ecol. Evol., 16, 153–162, https://doi.org/10.1016/S0169-5347(00)02098-X, 2001.

Ruíz de Castroviejo, J.: Explotación de olivares en asociación con trébol subterráneo, Agricultura, 443, 135–139, 1969.

Scheidel, A., and Krausmann, F.: Diet, trade and land use: A socio-ecological analysis of the transformation of the olive oil system, Land Use Policy, 28, 47–56, http://dx.doi.org/10.1016/j.landusepol.2010.04.008, 2011.

430 Six, J., Callewaert, P., Lenders, S., De Gryz, S., Morris, S. J., Gregorich, E. G., and Paustian, K.: Measuring and understanding carbon storage in afforested soils by physical fractionation, Soil Sci. Soc. Am. J., 66, 1981–1987, https://dx.doi.org/10.2136/sssaj2002.1981, 2002.

Soriano, M.A., Álvarez, S., Landa, B.B., and Gómez, J.A.: Soil properties in organic olive orchards following different weed management in a rolling landscape of Andalusia, Spain, Renew. Agr. Food Syst., 29, 83–91, 435 https://doi.org/10.1017/S1742170512000361, 2014.

Stevenson F.J.: Nitrogen-Organic forms, in: Methods of soil analysis, Part 2. Chemical and microbiological properties, edited by: Page, A.L., Miller, R.H., and Keeney, D., ASA & SSSA, 625–641. Madison WI, USA, 1982.

Stewart, C.E., Paustian, K., Conant, R.T., Plante, A.F., and Six, J.: Soil carbon saturation: Implications for measurable carbon pool dynamics in long-term incubations, Soil Biol. Biochem., 41, 357–366, 440 https://doi.org/10.1016/j.soilbio.2008.11.011, 2009.

Van Oost, K., Govers, G., Quine, T.A., Heckrath, G., Olesen, J.E., De Gryze, S., and Merckx, R.: Landscape-scale modeling of carbon cycling under the impact of soil redistribution: The role of tillage erosion, Global Biogeochem. Cy., 19, GB4014, doi:10.1029/2005GB002471, https://doi.org/10.1029/2005GB002471, 2005.

Vanwalleghem, T., Infante Amate, J., González de Molina, M., Soto Fernández, D., and Gómez, J.: Quantifying the effect of 445 historical soil management on soil erosion rates in Mediterranean olive Orchards, Agr. Ecosyst. Environ., 142, 341–351, https://doi.org/10.1016/j.agee.2011.06.003, 2011.

Vicente-Vicente, J.L., García-Ruiz, R., Francaviglia, R., Aguilera, E., and Smith, P.: Soil carbon sequestration rates under Mediterranean woody crops using recommended management practices: A meta-analysis, Agr. Ecosyst. Environ., 235, 204–214, https://doi.org/10.1016/j.agee.2016.10.024, 2016.

450 Vicente-Vicente, J.L., Gómez-Muñoz, B., Hinojosa-Centeno, M.B., Smith, P., and García-Ruiz, R.: Carbon saturation and assessment of soil organic carbon fractions in Mediterranean rainfed olive orchards under plant cover management, Agr. Ecosyst. Environ., 245, 135–146, https://doi.org/10.1016/j.agee.2017.05.020, 2017.

Walkley, A.: A critical examination of a rapid method for determining organic carbon in soils – effect of variations in digestion conditions and of inorganic soil constituents, Soil Sci., 63, 251–264, https://doi.org/10.1097/00010694-194704000-455 00001, 1947.

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Figure 1: Site location and associated sampling. Left: Location map of the sampling area in Montefrío, Southern Spain. Reference site limited by the white line within a protected archaeological site (yellow line). Yellow arrows indicate the sampled transect within the olive orchard. Right: Location of the sampled points in transect at the olive orchard. Numbering starts in the points at higher elevation. Europe map designed by Freepik, and air images source Google Earth (© Google 2018).

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475 **Figure 2: Comparison of average soil organic carbon concentration in bulk soil by soil depth between: A) reference site vs. olive orchard; B) eroded and deposition areas within the olive orchard. Labels in bars indicate the p-value according to a one-way ANOVA between treatments for the same soil depth.**
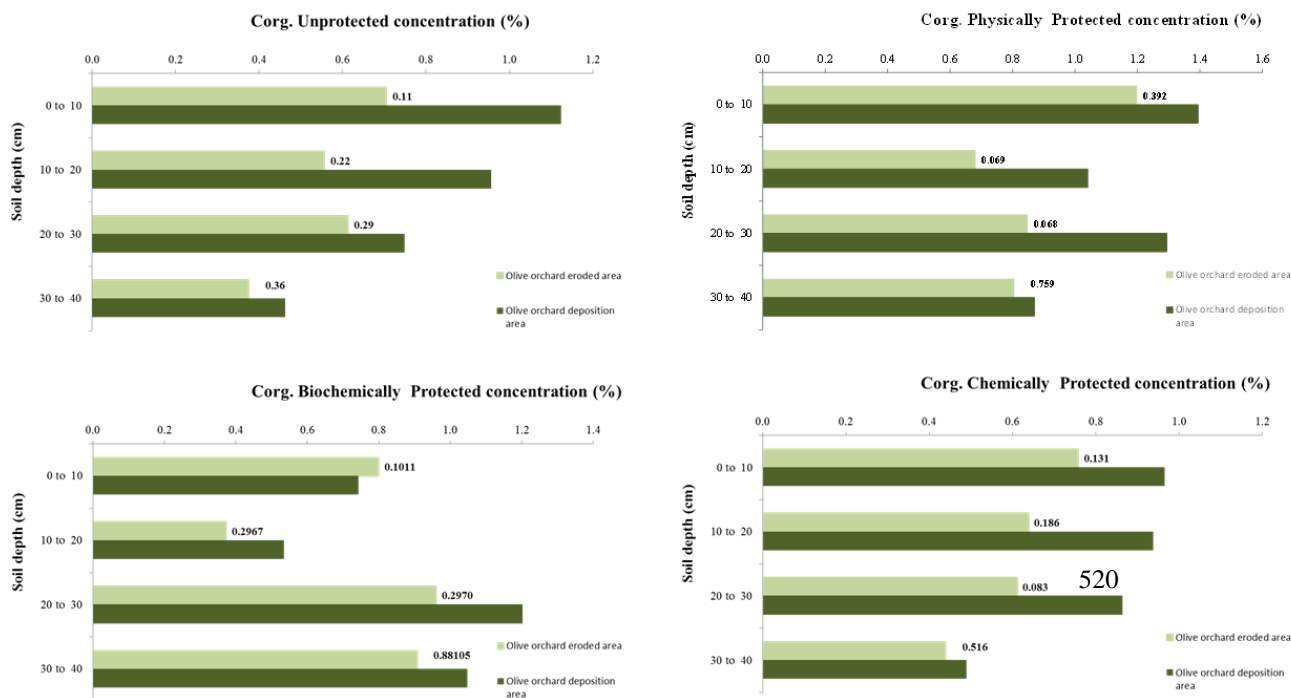
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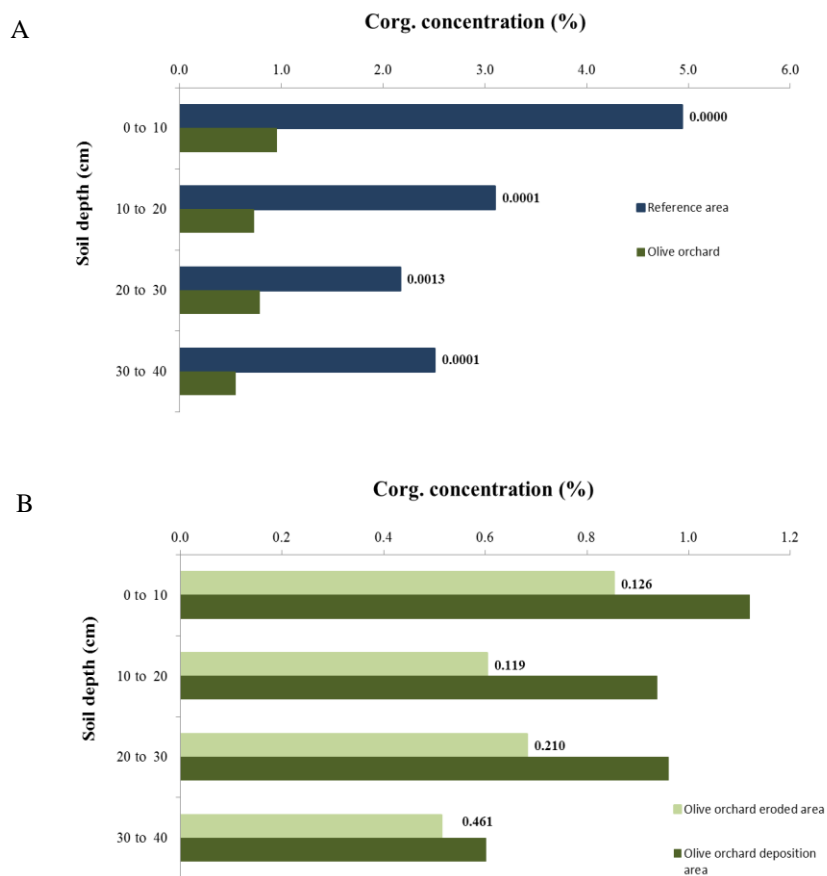
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Figure 3: Organic carbon concentration in the different soil organic carbon fractions at each depth comparing reference site vs. olive orchard. Labels in bars indicate the p-value according to a one-way ANOVA comparing treatments for the same soil depth.

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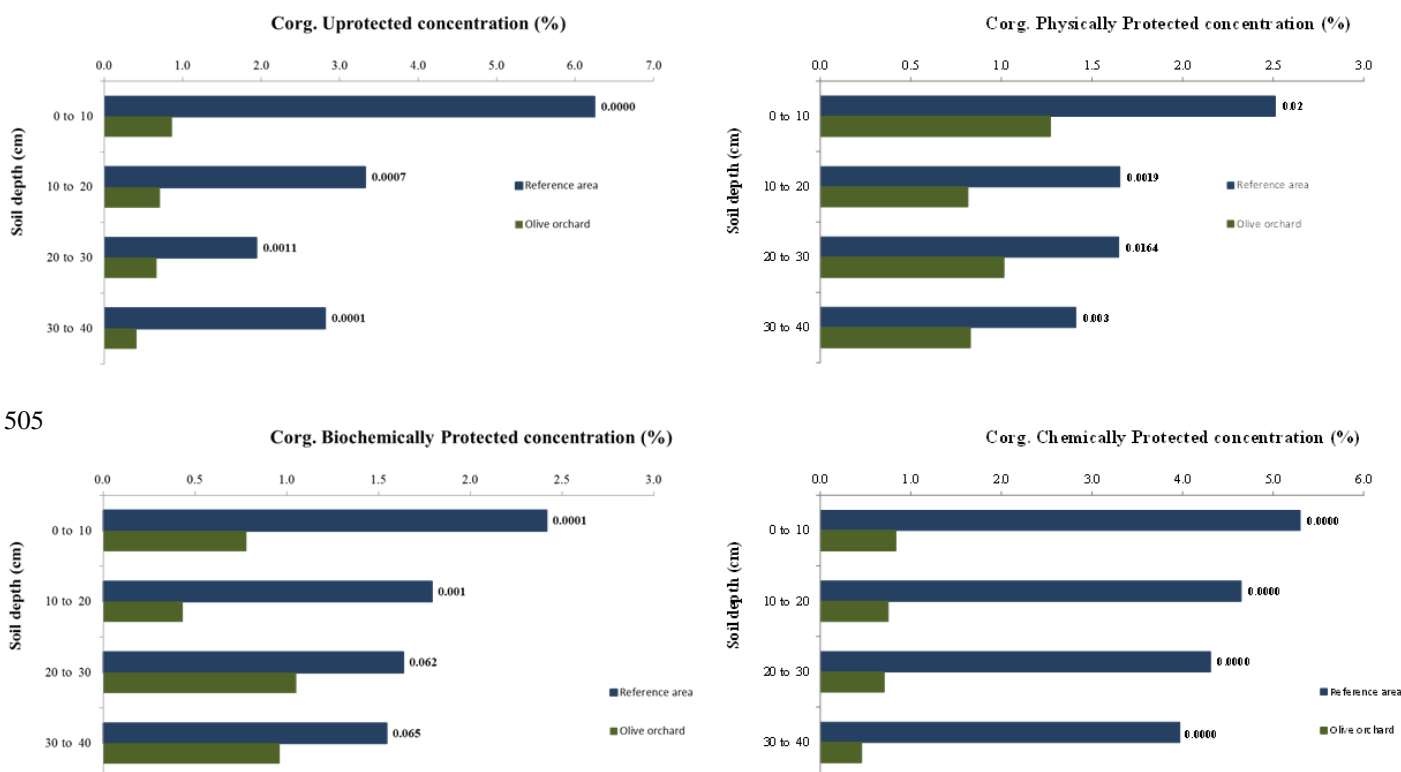
Figure 4: Organic carbon concentration in the different soil organic carbon fractions by depth comparing erosion vs. deposition
510 **areas within the olive orchard. Labels in bars indicate the p-value according to a one-way ANOVA comparing areas for the same soil depth.**
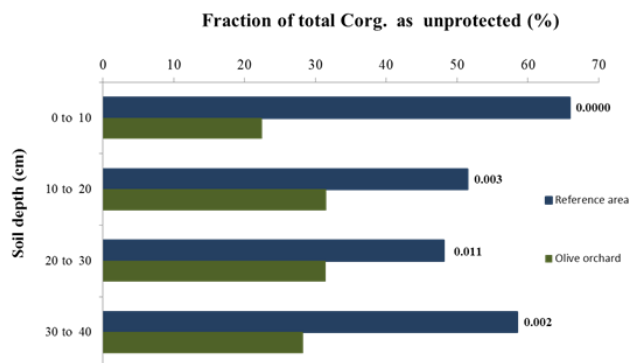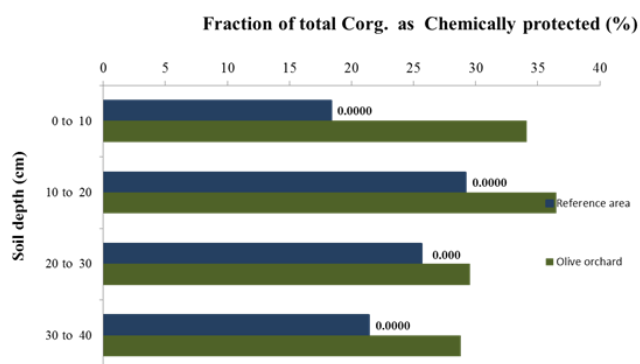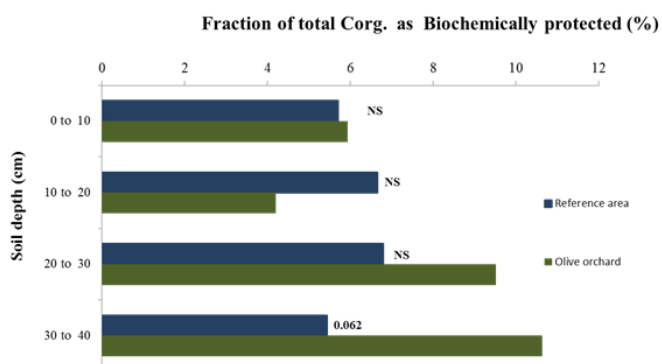

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Figure 5: Fraction of total organic carbon stored in the different fractions by depth comparing reference site vs. olive orchard. Labels in bars indicate the p-value according to a one-way ANOVA comparing areas for the same soil depth.
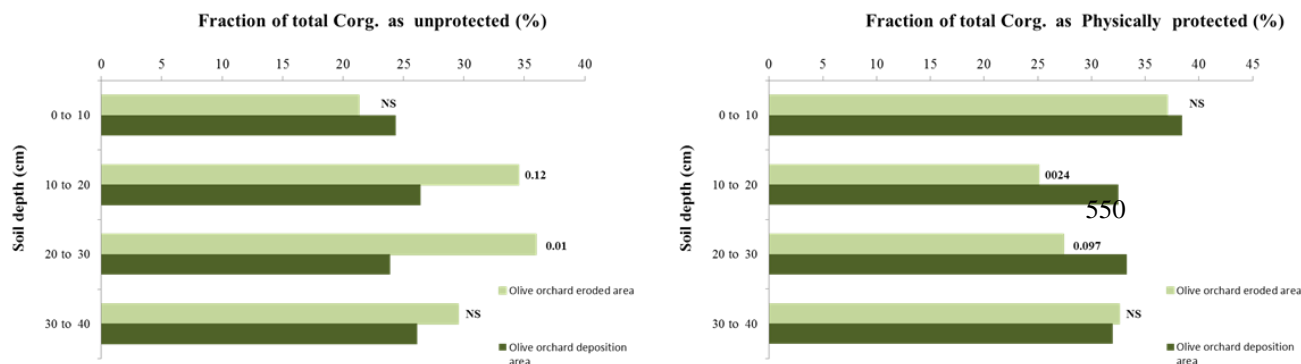
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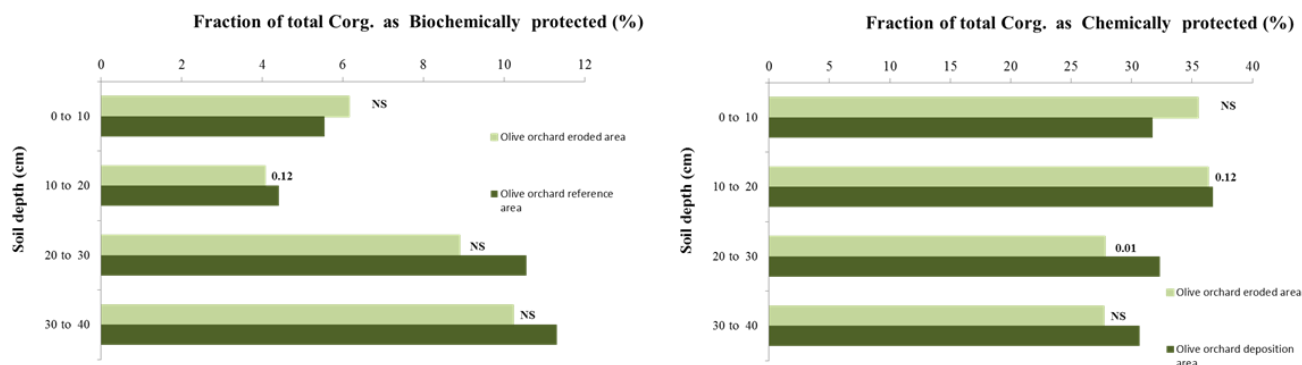535

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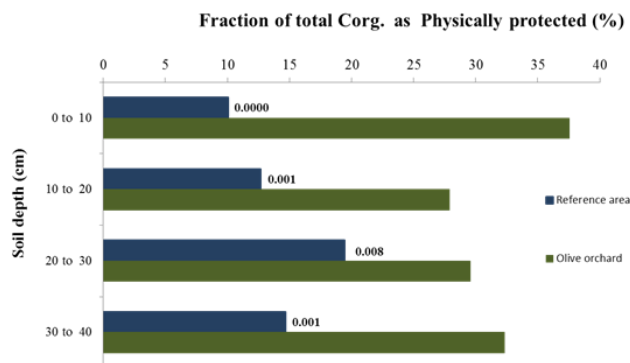
Figure 6: Fraction of total organic carbon stored in the different fractions by depth comparing erosion vs. deposition areas within the olive orchard. Labels in bars indicate the p-value according to a one-way ANOVA comparing areas for the same soil depth.
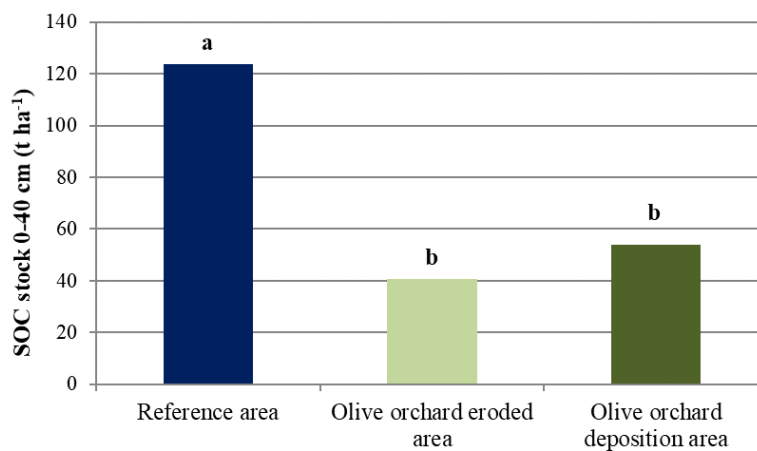
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Figure 7: Total soil organic carbon (SOC) stock at the top 40 cm of the soil in the reference site and in the erosion and deposition areas of the olive orchard. Different letters above bars means statistically significant differences (Kruskal-Wallis test at $p<0.05$).

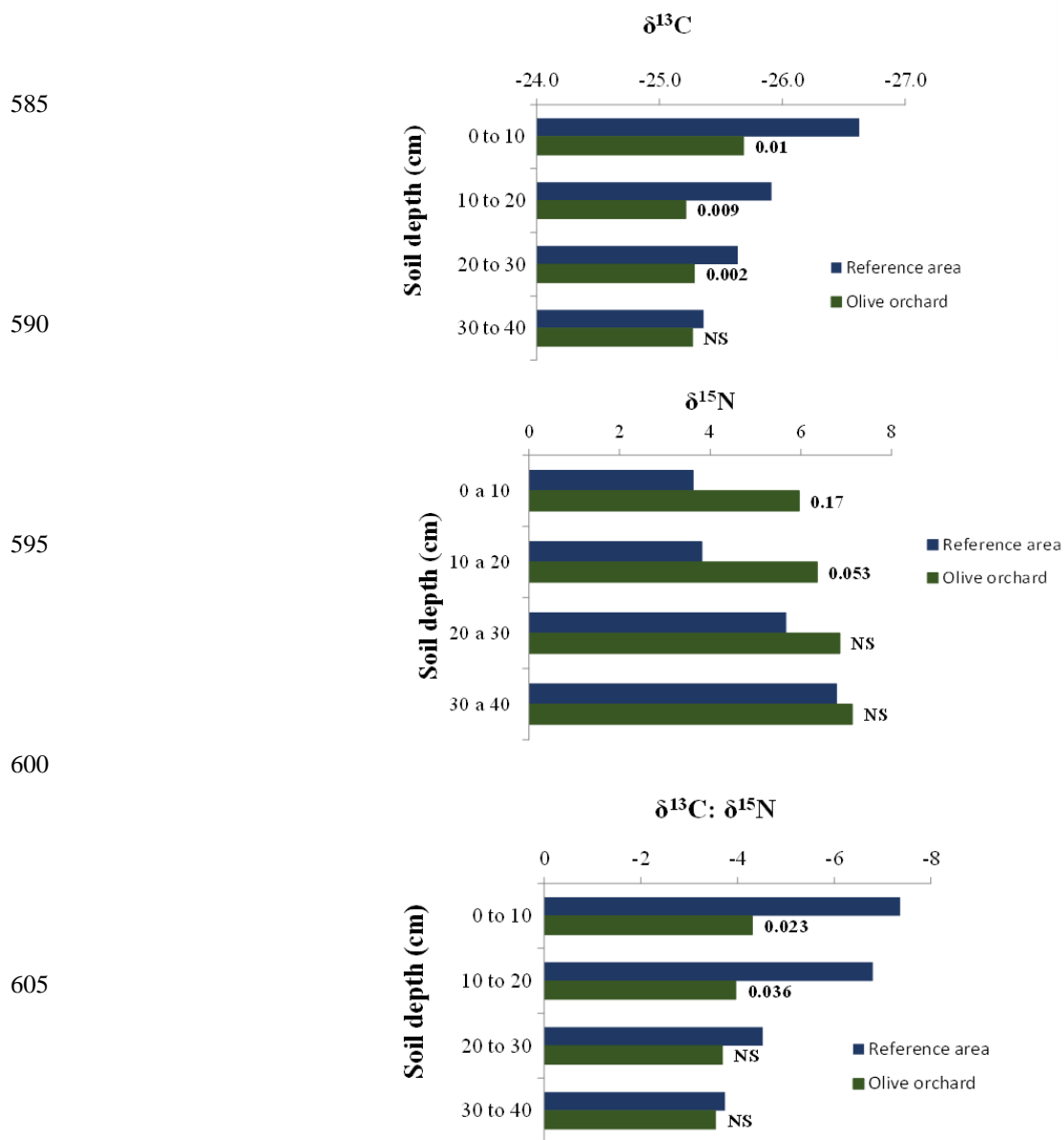580 **Figure 8: ^{13}C and ^{15}N isotopic signal of soil by depth comparing reference site vs. olive orchard. Labels in bars indicate the p-value according to a one-way ANOVA comparing treatments for the same soil depth.**

Figure 9: ^{13}C and ^{15}N isotopic signal of soil by depth comparing erosion vs. deposition areas within the olive orchard. Labels in bars indicate the p-value according to a one-way ANOVA comparing area treatments for the same soil depth.
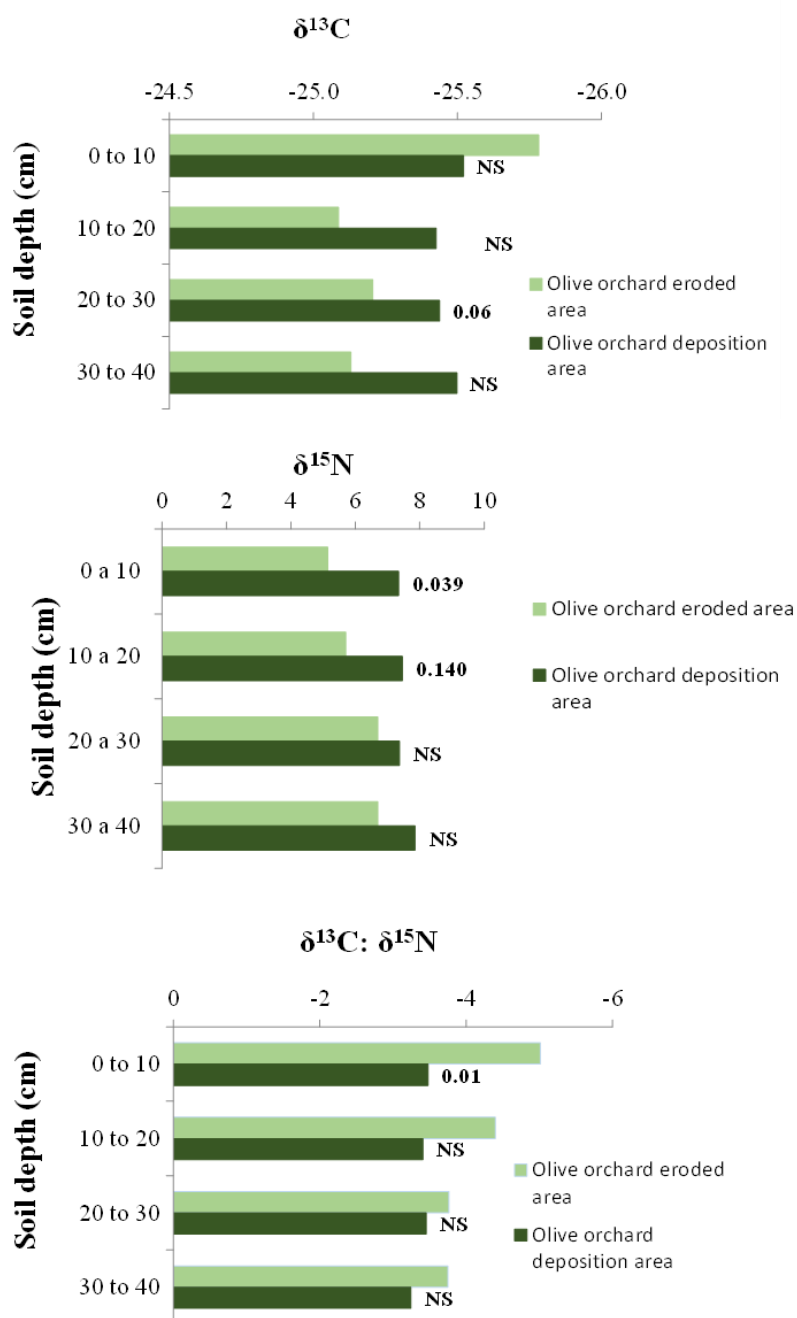
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Figure 10: Soil available phosphorus (P$_{avail}$), organic nitrogen (N$_{org}$), aggregate stability (W$_{sagg}$) and Soil Degradation Index (SDI)l by depth comparing eroded vs. deposition areas within the olive orchard. Labels in bars indicate the p-value according to a one-way ANOVA comparing areas for the same soil depth.

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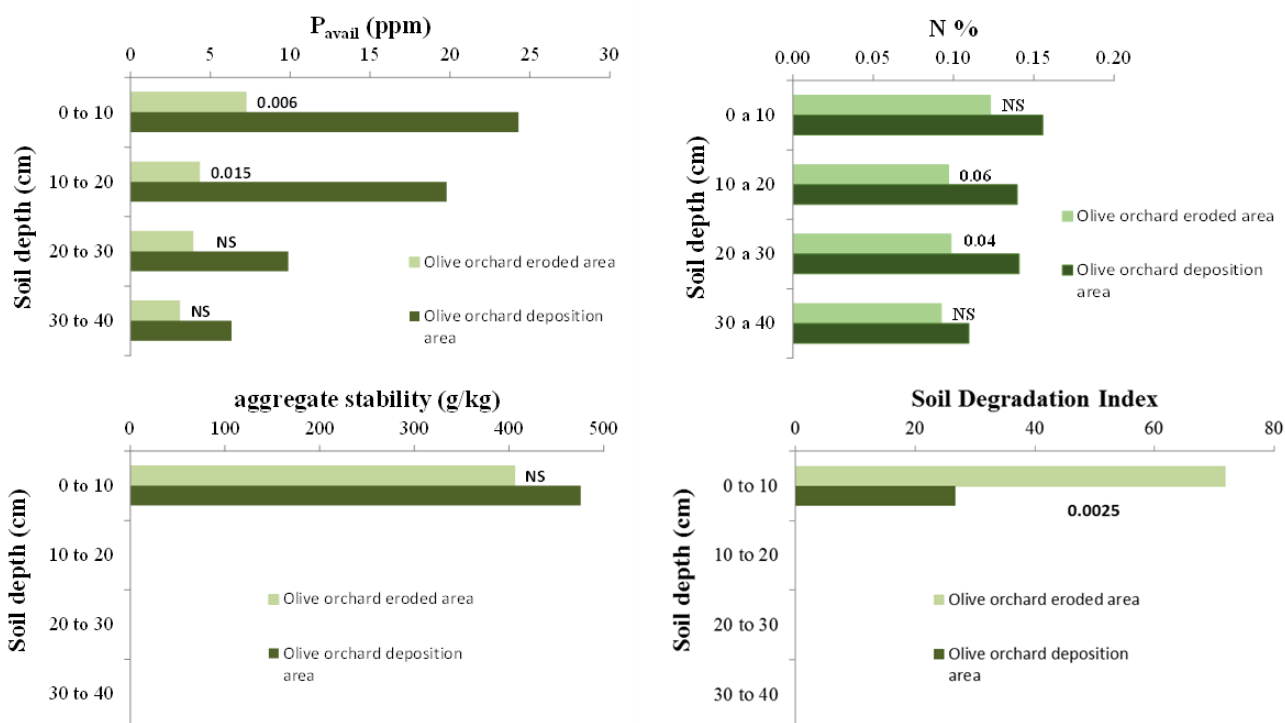
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670 **Table 1: Location of the sampling points along the transect and associated soil redistribution rates derived from the ^{137}Cs technique (adapted from Mabit et al., 2012). Negative values indicate net erosion and positive values net deposition.**

Point #	Code	Distance in transect (m)	Elevation (m)	Erosion/deposition rate (t ha^{-1} yr^{-1})
1	Cs1	0	1044	-5.2
2	Cs3	66.4	1032.8	-17.8
3	Cs5	125.0	1017.8	-7.1
4	Cs7	179.0	1006.8	-16.3
5	Cs12	312.2	986.8	-15.2
6	Cs13	338.1	984.8	5.9
7	Cs15	388.8	981.8	24.7
8	Cs17	429.5	979.8	8.8

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Table 2: Results of the two-way ANOVA analysis of soil organic carbon concentration, C$_{org}$, in different fractions and in bulk soil. In A) area refers to reference site vs. olive orchard and in B) area refers to eroded vs. deposition areas in the olive orchard. NS stands for Not Significant.

690 **A)**

Model	Bulk soil	C$_{org}$ fraction			
		Not protected	Physically protected	Chemically protected	Biochemically protected
Area (A)	0.0000	0.0000	0.0000	0.0000	0.0000
Depth (D)	0.0023	0.0022	0.0061	0.0190	NS
A x D	NS	NS	NS	NS	0.0300

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700 **B)**

Model	Bulk soil	C$_{org}$ fraction			
		Not protected	Physically protected	Chemically protected	Biochemically protected
Area (A)	0.0198	0.0400	0.0077	0.0299	NS
Depth (D)	0.0081	0.0070	0.0058	0.0055	0.0847
A x D	NS	NS	NS	NS	NS

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Table 3: Results of the two-way ANOVA analysis of the distribution of the total soil organic carbon content in the soil among the different fractions of soil organic carbon, C_{org}. In A) area refers to reference site vs. olive orchard and in B) area refers to eroded vs. deposition areas in the olive orchard. NS stands for Not Significant.

715 **A)**

Model	C_{org} fraction			
	Not protected	Physically protected	Chemically protected	Biochemically protected
Area (A)	0.0000	0.0000	0.0000	NS
Depth (D)	NS	NS	0.0640	NS
A x D	NS	0.0059	NS	NS

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B)

Model	C_{org} fraction			
	Not protected	Physically protected	Chemically protected	Biochemically protected
Area (A)	0.091	0.0881	NS	NS
Depth (D)	0.051	0.0214	NS	0.033
A x D	NS	NS	NS	NS

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Table 4: Results of the two-way ANOVA analysis of the stable isotopes signal. In A) area refers to reference site vs. olive orchard and in B) area refers to eroded vs. deposition areas in the olive orchard. NS stands for Not Significant.

A)

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Model	δ ^{13}C	δ ^{15}N	δ ^{13}C : δ ^{15}N
Area (A)	0.0001	0.002	0.002
Depth (D)	0.0026	0.0175	0.029
A x D	NS	NS	NS

B)

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Model	δ ^{13}C	δ ^{15}N	δ ^{13}C : δ ^{15}N
Area (A)	NS	0.01	0.01
Depth (D)	NS	NS	NS
A x D	NS	NS	NS

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Table 5: Results of the two-way ANOVA analysis of some soil physical and chemical properties comparing eroded vs. deposition areas in the olive orchard. NS stands for Not Significant.

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Model	N_{org}	P_{avail}	Bulk density
Area (A)	0.0000	0.01	NS
Depth (D)	0.0009	NS	NS
A x D	NS	NS	NS

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