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Original Research Article

Spatial variability of soil organic carbon stock in an olive orchard at catchment scale in Southern Spain

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A B S T R A C T

Orchards have a high potential for carbon sequestration. However, little research is available on the spatial variability at catchment scale and on the difference between the tree area and the lanes. We analyzed theik spatial variability of soil organic carbon stock, SOC_{stock} at 90 cm depth in an 8-ha catchment in Southern Spain with olives on a vertic soil. Results showed higher soil organic carbon concentration, SOC, in the tree area as compared to the lane up to 60 cm depth, but its impact on SOC_{stock} was negligible since it was compensated by the higher soil bulk density in the lane. SOC at different depths was correlated with that in the top 0–5 cm. The overall SOC_{stock} of the orchard was 4.14 kg m^{-2}, ranging between 1.8 and 6.0 kg m^{-2}. This SOC_{stock} is in the mid-lower range of values reported for olive orchards, measured at smaller scale, and similar to those other intensive field crops and agroforestry under comparable rainfall conditions. The spatial variability in SOC_{stock} was correlated to several geomorphological variables: elevation, cumulative upstream area, topographic wetness index, sediment transport index, and tillage erosion. Differences in SOC and SOC_{stock} are driven by the sediment redistribution downslope, mainly by tillage erosion, and higher soil water availability in lower areas allowing higher biomass production. These topographic indexes and the correlation between SOC in the topsoil and SOC_{stock} up to 90 cm should be further explored in other typology of olive orchards for facilitating the mapping of SOC_{stock}.

1. Introduction

Olive tree is one of the dominant crops in Mediterranean countries with approximately 97% of the world acreage, 10.3 Mha (FAO, 2021), located in Mediterranean countries like Spain, Tunisia, Morocco or Italy which crop 2.6, 1.6, 1.1 and 1.1 Mha, respectively (FAO, 2021). As such, any environmental or social issue related to olive cultivation has a large national and regional relevance. To be adapted to Mediterranean rainfed cropping, characterized by limited rainfall availability, olive cultivation has historically been based on low tree density, control of tree canopy size by regular pruning and soil management based on bare soil (Gómez, 2016). However, concerns regarding environmental damage associated with soil degradation, water erosion and offsite contamination led to a shift from bare soil-based management (based on regular tillage and/or herbicide use) into more sustainable management practices based on temporary cover crops during the rainy period and/or mulching with pruning residues (Gómez et al., 2021). Although, to our knowledge, there are no reliable statistics on the extension of these alternative management practices, several local studies suggest a significant expansion. Gómez et al. (2021), based on detailed farm surveys in two olive growing areas in Southern Spain, reported that 63% of the farmers used some kind of cover crop while 80% a mulch of pruning residues.

This change from bare soil to mulch- or cover crop-based management results not only in large reductions of erosion rates and a moderate reduction in runoff generation but also in an increase in soil organic carbon, hereafter OC, content (*e.g.* Bombino et al., 2021; Gómez et al., 2014; Vicente-Vicente et al., 2017). The possibility of increasing soil OC in a widely cultivated crop in

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Mediterranean regions has spurred several initiatives to increase and monitor soil OC in olive orchard soils as part of adaptation and mitigation strategies to climate change (*e.g.*, Olive, 2021). However, most of the available literature on the evolution of soil OC under mulching- or cover crop-based management practices in olive orchards show moderate increments in the top 5 or 10 cm of the soil (Castro et al., 2008; Gómez et al., 2014; Vicente-Vicente et al., 2017). This research focused mainly on the hillslope scale and on the soil in the orchard's lanes, although preceding studies highlighted already significant differences in soil OC and other soil properties between the lane and the olive tree canopy projection areas (*e.g.* Gómez et al., 2009; 2014). The higher SOC measured in these studies in the olive tree canopy projection area as compared to the lane area can be explained by the carbon inputs due to fallen leaves and fruits, roots and dissolved organic carbon in stemflow and throughfall (Lombardo et al., 2017). Soil management has a major impact on top SOC. As a general trend, the use of cover crops, temporary to minimize risk for water competition, use of a mulch of chopped pruning residues and/or organic amendments provide an increase of SOC in the topsoil as compared to management based on bare soil by tillage and/or herbicide (e.g. Gómez et al., 2014; Vicente-Vicente et al., 2017). Vicente-Vicente et al. (2017) in a survey of different olive orchards in Southern Spain demonstrated a great variability in soil OC content in cover crop managed orchards. They found OC contents ranging from 0.5 to 2.5% in the top 15 cm, in accordance with the large variability observed in biomass production by cover crops along the lanes (between 0.65 and 2.53 t ha^{-1} $year^{-1}$), yielding an average annual input of organic carbon of 0.56 t ha^{-1} $year^{-1}$. This large variability in biomass production by cover crops was already observed by Castro et al. (2008) who compared different cover crop- and bare soil-based systems. Castro et al. (2008) also reported how systems based on low intensity tillage resulted in insignificant differences in weed biomass production and soil OC content as compared to some cover crops systems. This was due to moderate biomass production of the cover crop and the fact that adventitious vegetation was allowed to grow during a few months between tillage operations.

The number of studies on soil OC stock, hereafter SOC_{stock}, in olive orchards that focus also on the subsoil are less frequent. In a study based on soil pits, Lozano-Garcia and Parras-Alcántara (2014) measured the SOC_{stock} in the top 1 m along a toposequence in a traditional regularly tilled rainfed olive orchard in Jaén (Southern Spain). Their study was carried out in the orchard lanes, since it was based on sampling in soil pits, and yielded an overall SOC_{stock} of 6.6 kg m^{-2} with no significant differences among the three different slope positions, summit, backslope and toeslope. Gómez et al. (2020) measured different soil properties and long-term erosion rates along a 430 m catena in a mature olive orchard and found a significant increase in topsoil quality (top 10 cm) in the downslope deposition area of the catena, as compared to the actively eroding upslope area. However, they did not find significant differences between different slope positions in SOC_{stock} for the top 0.6 m of the soil, with an average value of 3.90 kg m^{-2}. These SOC_{stock} were significantly lower than those measured by Massaccesi et al. (2018) for the top 0.9 m of the soil in two olive orchards of different age (7 and 30 year) with permanent cover crop and addition of chopped pruning residues, in central Italy. Also measuring in the orchard lanes, these authors determined a SOC_{stock} of approximately 7 and 13 kg m^{-2} for the 7 and 30 years old orchards, respectively. González-Rosado et al. (2020), in a toposequence in Jaén (Southern Spain) with the same methodology used by Lozano-Garcia and Parras-Alcántara (2014), measured the effect of management on SOC_{stock} change, comparing conventional tillage against no tillage with spontaneous cover crop- and chopped pruning residue mulching, two years after the introduction of both managements. Averaging both management systems, SOC_{stock} increased along the toposequence with 3.4, 3.5 and 5.2 kg m^{-2} for the summit, backslope and toeslope positions, respectively. These authors found no significant differences in SOC_{stock} between tillage and cover crop-based management systems overall, with SOC_{stock} of 4.14 and 3.91 kg m^{-2} for the tillage and cover crop-based management systems, respectively. Only locally, for the backslope position, 4.01 *vs* 2.98 kg m^{-2}, differences were significant. Huang et al. (2017) mapped soil organic matter concentration across the 0—0.7 m soil depth profile in a 6.7 ha olive orchard in Southern Spain using electromagnetic induction sensing, showing also a large spatial variability, with a CV between 30 and 57%, depending on the soil depth interval measured. All these studies have noted the potential impact of topography on soil organic carbon content in olive orchards. Several of these studies have also noted the need of a careful evaluation of the soil bulk density, which can also present a significant spatial variability due to management and tree influence (*e.g.* Reyna-Bowen et al., 2020), for a reliable determination and understanding of $SOC_{stock.}$ However, to the best of our knowledge, there is no published study that evaluates the relevance of these topographical factors on SOC_{stock} at the field scale beyond a catena, as published for other agricultural systems, *e.g.* cereal based rotations in Germany (*e.g.* Aldana et al., 2016) or China (e.g. Li et al., 2006). Some of these studies on redistribution of SOC have used simulation model like WATEM/SEDEM, which is an empirical, spatially distributed model of soil erosion, considering detachment, transport and deposition, which is used to estimate long-term mean annual soil erosion rates (*e.g.* Quijano et al., 2016). We have not found either, to our knowledge, any attempt to evaluate the potential impact on SOC_{stock} in olive orchards of the trees' effect on increasing soil organic carbon content in their surrounding as compared to the lane areas beyond the small plot scale. This impact has been demonstrated for analogous agroforestry systems in Mediterranean conditions (*e.g.* Cardinael et al., 2015; Reyna-Bowen et al., 2020).

Proper understanding of the heterogeneity of soil organic carbon in forest and agricultural systems is capital for a reliable estimation of SOC_{stock}. Mishra and Riley (2015) evaluated the impact of 13 topographical attributes at different scales, from 50 up to 10000 m. They found that five of them: elevation, slope steepness, slope aspect, soil wetness index and sediment transport index were significant predictors of SOC_{stock} at different scales. They also found that while elevation was a relevant predictor across all the scales evaluated, slope-related indicators were significant only at 10 km scale while soil wetness and sediment transport index were significant only at the smaller scale, 50 m. These results are in line with those found by Aldana et al. (2016) in a high resolution horizontal and vertical mapping of SOC in a 5-ha field on a rolling arable land. They found that the topsoil SOC was mainly controlled by erosion processes (water and tillage) and correlated to topographical attributes driving these erosion processes. They found the variation in the shape of the SOC distribution along the soil profile, down to 0.95 m, was related to plan curvature and slope steepness.

All these results fit into the overall analysis of the processes driving carbon cycling in eroding landscapes (Dlugoß et al., 2012; Doetterl et al., 2012) where geomorphic processes and soil carbon turnover are closely coupled, and part of the eroded carbon transported to the deposition areas remains buried and partially stabilized. While soil erosion and carbon redistribution have received a lot of attention over the last decades, there is still considerable uncertainty and conflicting results (Wilken et al., 2017), especially in Mediterranean agroecosystems and at catchment scale.

This manuscript presents a study aimed to provide insight into.

1 Spatial variability in SOC_{stock} at field and small catchment scale, in a mature olive orchard in an eroding landscape to stablish a baseline for future mapping in a long-term experiment.
2 The effect of the olive tree canopy on SOC distribution and overall SOC_{stock}.
3 The correlations between the spatial distributions of SOC and SOC_{stock} and topographical attributes in this orchard, in order to elucidate the controlling processes.

2. Materials and methods

2.1. Study area

The study was carried out in a commercial olive orchard, “La Conchuela”, located in South-Western Spain (37° 49′ 4.6″ N, 4° 53’ 45.6″ W, Fig. 1). It has a total extension of 12 ha, with 8 of them forming a small catchment draining into an ephemeral stream (Fig. 1). Catchment elevation ranges from 122 to 163 m.a.s.l. and its average slope is 9%, ranging from 0 to 45%. The type of climate is Mediterranean, with an average annual rainfall of 642 mm of which 76% occurs from October to March. Average annual temperature is 17.5 °C, with a maximum average daily temperature in July of 27.8 °C, and minimum in January of 8.1 °C. The average annual cumulative potential evapotranspiration is 1411 mm, with daily average values ranging from 7.5 in July to 1.2 mm day^{-1} in December. The soils in the catchment are formed on Miocene marls and have been classified as Typic Haploxerert (Soil Survey Staff, 2002), or Vertisol according to the FAO classification. These soils are relatively deep, with a 0.56-m thick Ap horizon and a total depth up to at least 2.2 m. These soils are highly plastic when wet, and crack as they dry due to their high content of smectite clay.

The olive orchard was planted in 1993 with a 6 × 7 m tree spacing. Tree lines and traffic are orieneeted in the E-W direction, see Fig. 1. Average ground cover by the time of our sampling was approximately 35%, although tree size varied in the catchment (Fig. 1) because of severe infestation by *Verticillium dahliae*, which has required periodical replanting of dead trees since 1996 (Pedrera-Parrilla et al., 2014). After replanting, shoulders were formed around the tree planting lanes, running in a North to Northwest direction. Soil management in the catchment until 2008

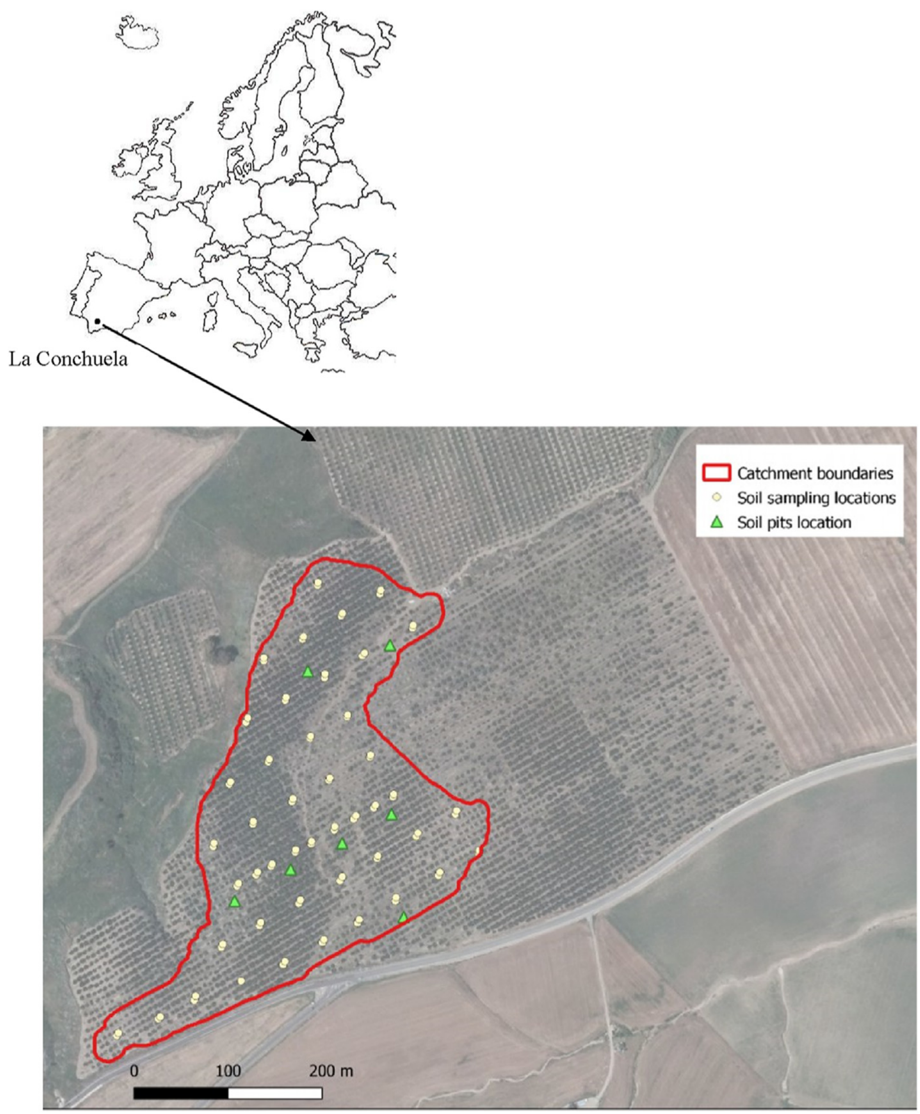

Fig. 1. Location map and air view of the sampled orchard, “La Conchuela”. Dots mark the sampling points for determination of soil organic carbon and other properties, and the green triangles the location of the soil pits for soil description. The red line shows the catchment boundaries.

was based on bare soil by regular tillage. After that year, soil management consisted in maintaining spontaneous vegetation along the lanes controlled by mowing and applying herbicide (glyphosate) occasionally to control their growth in late spring and a selective herbicide for broad leaves species to promote the expansion of grasses within the flora community. Occasionally, surface tillage was performed at selected areas within the catchment to cover rills and small gullies obstructing machinery traffic. Olive trees were deficit irrigated, using a drip irrigation system, from April to September with an amount equivalent to 200 mm. Harvesting is semi-mechanized using tree-shakers, and is done from late November to mid-February, with the specific dates for a given year varying as a function of climate conditions and fruit ripening.

2.2. Soil sampling

Soil sampling took place during late May and early June 2010, when the soil presented a relatively homogeneous soil moisture profile close to field capacity. Analysis of the samples taken showed a very low correlation between gravimetric soil moisture and bulk density, $r^2 = 0.008$, indicating a very low effect of the variation of soil moisture on our bulk density assessment. Firstly, seven soil pits (Fig. 1) were dug for soil profile description, according to the NRCS guidelines (Soil Survey Staff, 2002) within the catchment containing the orchard, hereafter orchard. Afterwards we sampled 90 paired points (45 along the lanes and 45 below olive tree canopy areas, hereafter called respectively lane and tree area) distributed in different transects across the orchard. Sampling depths were 0–5, 5–10, 15–20, 0–30, 30–60 and 60–90 cm. At each sampling point, the top three depths were sampled in duplicate at each depth using a hand sampler (5 cm high and 5 cm in diameter) for determination of bulk density, while the other three depths were sampled using a powered driller with a sampling tube of 5 cm diameter. The coordinates of the sampled points were recorded with a GPS with sub-metric resolution. Samples were kept in sealed bags and transported to the laboratory for analytical determination.

2.3. Soil analysis

Gravimetric moisture content was calculated for all the samples after oven drying at 105 °C, using one of the duplicated samples for the three topsoil (0–5, 5–10 and 15–20 cm) and a representative, approximately a 10 g samples, for the two deepest layers (30–60, 60–90 cm). Soil bulk density was determined for all the depths using the volume, the total weight and the gravimetric soil moisture content of each sample. Topsoil (0–5, 5–10, 15–20 cm) samples were analyzed for organic carbon content and soil particle composition, and those at 30 cm interval (0–30, 30–60, 60–90 cm) were analyzed for organic carbon content, soil particle composition, electrical conductivity (EC) at 1:5 soil:water ratio, and pH at 1:2.5 soil:water ratio. Soil organic carbon was determined by wet oxidation (Nelson & Sommers, 1982), particle size analysis by the hydrometer method (Gee & Bauder, 1986) and available Phosphorous, available Potassium, carbonates, electrical conductivity and pH as described in MAPA (1994).

2.4. Mapping of soil properties

The data were spatially visualized in QGIS (3.16.6 version Madeira). This GIS used a digital elevation model at a 1-m square grid from a high-resolution photogrammetric flight carried out in June 2003. From this digital elevation model, we derived the maps of topographical features such as slope aspect and inclination, cumulative flow area, soil wetness index and sediment transport index (Mishra & Riley, 2015) using the QGIS tools. Maps of the measured soil properties were plotted from the soil samples measurements and using the inverse of the squared distance from a shapefile containing the weighted average values for the 45 sampled paired points into a raster file at 0.5 m square grid. Lane and tree points were assigned weights of 0.65 and 0.35, respectively, according to the average ground cover of the olive tree canopy at the time of sampling (35%).

Soil organic carbon stock, SOC_{stock} (kg m^{-2}) was determined for the 0–90 cm depth using

$$SOC_{stock} = \sum_{i=1}^{5} SOC_i \; d_i \;\; bd_i \; (1 - stone) \text{ x } 1000, \quad (1)$$

where SOC is soil organic carbon concentration of soil (in fraction, 0–1), d is the sampling depth (m), bd is bulk density (t m^{-3}), and stone (in fraction, 0–1) refers to the fraction of coarse material larger than 2 mm in soil samples. Depths considered were 0–5, 5–10, 10–30, 30–60 and 60–90 cm. For the 10–30 cm depth, we considered as representative of the average SOC and bd, the one determined from the 15–20 cm sample.

2.5. Modelling of soil erosion at catchment scale

To evaluate the possible effect of long-term sediment movement due to erosion within the catchment, we determined the spatial distribution of long-term water and tillage erosion by applying the WATEM/SEDEM model (Van Oost, Govers, van Muysen, & Quine, 2000, b) in the catchment. WATEM/SEDEM is an empirical, spatially distributed model of soil erosion, considering detachment, transport and deposition, which is used to estimate long-term mean annual soil erosion rates. The model has two components, one simulating water erosion and another one simulating tillage erosion. The water erosion component is based on the Revised Universal Soil Loss Equation, RUSLE (Renard et al., 1997). The RUSLE model calculates potential soil loss (Mg ha^{-1} yr^{-1}) as the product of six independent factors: rainfall erosivity (R, MJ mm ha^{-1} h^{-1} yr^{-1}), soil erodibility (K, Mg h MJ^{-1} mm^{-1}), slope length (L, dimensionless), slope steepness (S, dimensionless), cover and management (C, dimensionless) and a conservation support practices (P, dimensionless). The available sediment calculated is then routed downslope according to the topography until a stream cell is reached. Sediment transport by overland runoff is modeled according to a transport capacity equation (TC, t yr $^{-1}$),

$$TC = k_{tc} R\, K \left(LS - 4.1\; S_g^{0.8} \right), \quad (2)$$

with R, K, L and S as the RUSLE factors already defined, k_{tc} a transport capacity coefficient, and S_g is the slope gradient. Although theoretically this transport capacity coefficient can be spatially distributed, in most studies using WATEM/SEDEM it is used as a uniform parameter calibrated according to soil properties and average sediment loss rates (<u>Van Oost, Govers, van Muysen, & Quine, 2000</u>, b) or from local erosion deposition rates when available (Quijano et al., 2016). At any given raster cell, sediment deposition will occur when the transport capacity of the cell is smaller than the amount of sediment that reaches the cell; otherwise, the sediment generated is recirculated during the computation.

Tillage erosion, the downslope transport of soil as a result of ploughing, is modeled as a diffusion-like process. Tillage erosion is controlled by the change of the slope gradient, with erosion taking place on convex areas and soil accumulation occurring mainly on concave zones. It is defined by

$$Q_{s,t} = k_{till}\, S_g \,, \tag{3}$$

where $Q_{s,t}$ is the net downslope flux due to tillage, k_{till} is a tillage transport coefficient and S_g is the local slope gradient.

We used the 1 m grid DEM for running the model, from which L, S and S_g were determined during simulations. The model was calibrated for our analysis as follows. R was determined from available sources for the location (ICONA, 1998), K, and C from soil and management data following Gómez et al. (2003), k_{till} was taken from previous analysis from olive orchards (Vanwalleghem et al., 2011) while k_{tc} was fitted to provide net water losses in the range to that measured in the catchment during a 5 year period (Gómez et al., 2014). The values used for the calibration were: R, 850 MJ mm $ha^{-1}\ h^{-1}\ yr^{-1}$; K, 0.035 Mg h $MJ^{-1}\ mm^{-1}$; C, 0.3; k_{tc}, 175 m; k_{till}, 600 kg m^{-2}.

2.6. Statistical analysis

Differences between average values of soil properties by depths and locations were evaluated using a non-parametric Kruskal-Wallis test. Correlation between different parameters were evaluated using Pearson correlation test. When significant correlations where identified ($P < 0.05$) we developed statistical models using simple and multiple linear regression. All the statistical analyses were performed with STATA (ver. 15.1).

3. Results and discussion

3.1. Soil profile description and overall bulk density

Table 1 summarizes the soil properties from the seven soil pits distributed within the catchment. It shows a soil with a high clay content and good cation exchange capacity CEC and available Potassium K_{aval} values, and moderate available Phosphorous P_{avail} and organic carbon C_{org} concentration. Relatively large rooting depths for Mediterranean soils on sloping terrain were observed, with the B and BC horizon reaching the 1.10–1.38 m depth without the presence of any restricting layer across the soil profile, according to the soil profile description, and a smooth transition to the C horizon formed by marls.

The overall bulk density by soil depth and in relation to the tree, under the olive tree canopy and in the lane area, is summarized in Fig. 2. The results show increasing values with depth and a significantly larger bulk density in the lanes down to 0.6 m depth. This can be explained by the cumulative compaction due to machine traffic in the lane area. This can apparently not be overcome by the self-mulching of the vertic soil due to the cracking and swelling cycle during the year, described for this type of soils (*e.g.* Taddese et al., 2007). In the tree area, it can also be expected that the action of the tree roots reduces bulk density. Differences in topsoil (down to 0.2 m depth) bulk density between the lane and tree area have been widely reported in olive orchards (*e.g.* Gómez et al., 1999; 2004) but our data suggests that this differential compaction can be transmitted much deeper, to a depth within the range observed for other agricultural soils by the transmission of pressure load by agricultural equipment, down to 0.5–0.66 m (Lindstrom & Voorhees, 1994). This relatively deep differential compaction might be relevant for determination of the SOC_{stock}, but also for other soil related processes like, for instance, rainfall infiltration or redistribution of soil water. Bulk density, bd, showed a moderate variability across the catchment (coefficient of variation within each soil depth and location class in the range of 6–10%), with more compacted areas located in the less sloping areas of the catchment located in the Southern and Northern areas of the catchment, Supplementary Material Fig. 1. This variability in bulk density tended to be maintained across the soil profile, with a significant correlation among the topsoil bulk density and that at deeper soil layers, Table 2. This correlation might be useful values in studies aimed to determine SOC_{stock} using remote sensing from which only SOC concentration from the top soil could be calculated.

3.2. Soil organic carbon concentration

Fig. 3 presents the variability in soil organic carbon concentration, SOC, among different soil depths and location with respect to the tree. The results show decreasing SOC with depth and a significantly higher SOC at the tree area as compared to the lane area up to 60 cm depth. This can be explained by the higher biomass return by leaves, fruit and roots in the olive tree canopy area as compared to the lane where only a modest biomass return by adventitious vegetation can be expected as described for olive orchards in the region by Vicente-Vicente et al. (2017). This was verified during 2011 in our studied orchard by Gimeno (2011) appraising the variability of ground cover by vegetation in the lane areas. The lower erosion rate in the olive tree canopy area as compared to the lane area, measured by Guzmán et al. (2013) in this orchard, also contributes to these differences between the two areas. Spatial variability of SOC by depth and area was higher than that of bulk density, with coefficient of variation at each soil depth and location class in the range of 19–53% increasing with soil depth (Supplementary Material Table 1). This higher variability can be explained by the fact that SOC is determined by a more complex combination of several processes determining biomass return and fate as compared to bulk density. The shape of the SOC distribution varied with depth, tending to be positively skewed for the 0–5 and 60–90 cm depth, and negatively skewed for the other soil depths (Supplementary Material Table 1 and Fig. 2). The spread of the distribution curves of SOC varied also with depth. SOC distribution at the top 0–5 cm tends to be wider than a normal distribution, while for all the other depths (except the tree area at 60–90 cm) tends to be narrower than a normal distribution (Supplementary Material Table 1 and Fig. 2). We have found only one other study in olive orchards measuring spatial variability of SOC at a similar scale, namely by Huang et al. (2017) in a 6.7 ha orchard in Malaga (Spain), which showed a similar coefficient of variation at each depth. There was a clear correlation between the SOC between the lane and olive tree canopy area for all the analyzed depths (Fig. 4), indicating that there was a general trend in the spatial variability of SOC across the catchment on which the relative differences

Table 1
Average, with standard deviation between brackets, soil profile description from the seven soil pits made in the orchard. OC: organic carbon, P_{avail}: available Phosphorous, K_{avail}: available Potassium, CEC: cation exchange capacity, CO_3: carbonates.

Horizon	Depth (cm)	Textural class	OC (%)	P_{avail} (ppm)	K_{avail} (ppm)	CEC (meq $100g^{-1}$)	CO_3 (%)
A	0–56	Clay	0.54 (0.16)	4.80 (3.10)	360 (87)	26.2 (2.8)	25.4 (2.8)
B	56–110	Clay	0.39 (0.07)	1.75 (0.46)	249 (58)	27.4 (3.8)	27.4 (10.3)
BC	110–138	Clay-loam	0.27 (0.10)	1.96 (0.78)	191 (54)	23.8 (5.3)	32.8 (10.2)
C	>138	Clay-loam	0.14 (0.03)	2.10 (1.04)	168 (69)	19.2(4.2)	32.6 (7.6)

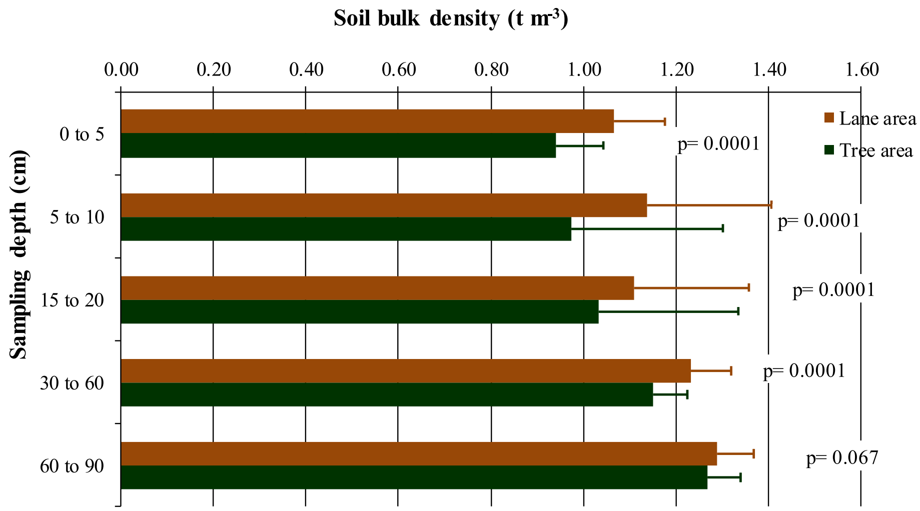

Fig. 2. Summary of bulk density ($t \cdot m^{-3}$) values by depth (cm) and in relation to olive tree canopy projection. Tree below the olive canopy; lane in the orchard alley outside the olive canopy projection. Bars indicate average values and error bars standard deviation. P values correspond to a comparison of differences between samples from both areas at each depth using a non-parametric Kruskal-Wallis test.

Table 2
Summary statistics of correlation between bulk density (Bd) at different depths (tree and lane areas samples combined; 90 samples in total). First figure is the Pearson's coefficient of correlation, the second is the statistical significance of the correlation and the third one is number of samples.

		Bd ($t\ m^{-3}$)				
	Depth (cm)	0–5	5–10	15–20	30–60	60–90
Bd ($t\ m^{-3}$)	**0–5**	1.0000, 0.0000, 90				
	5–10	0.5079, 0.0000, 90	1.0000, 0.0000, 90			
	15–20	0.4677, 0.0000, 90	0.7413, 0.0000, 90	1.0000, 0.0000, 90		
	30–60	0.3305, 0.0147, 90	0.4610, 0.0000, 90	0.4004, 0.0009, 90	1.0000, 0.0000, 90	
	60–90	0.2279, 0.3074, 90	0.2206, 0.3669, 90	0.1782, 0.9280, 90	0.5029, 0.0000, 90	1.0000, 0.0000, 90

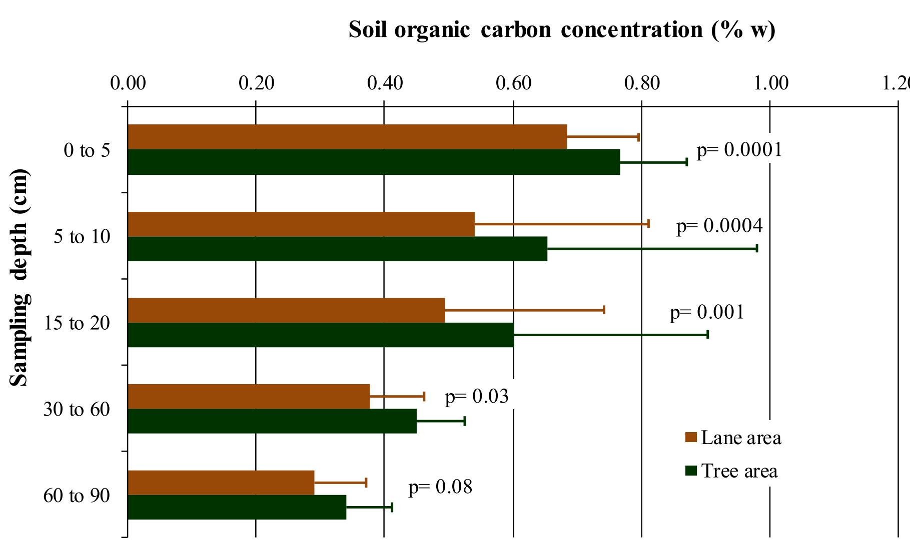

Fig. 3. Soil organic carbon concentration (% by weight) by depth (cm) and in relation to olive tree canopy projection. Tree below the olive canopy; lane in the orchard alley outside the olive canopy projection. P values correspond to a comparison of differences between samples from both areas at each depth using a non-parametric Kruskal-Wallis test.

between the lane and the tree area are superposed. We have not found a description of this phenomena in olive orchards, but it has been previously described in agroforestry systems. For instance, Cardinael et al. (2015) described it in their maps of SOC_{stock} in a hybrid walnut-durum wheat system in Southern France. As it can be expected from the previous discussion, there was a significant correlation between SOC in the topsoil and all the other soil depths (Table 3). This might have implications for the mapping of SOC at larger scales in olive orchards, where the combination of higher resolution measurements in the topsoil, where a more intense sampling or the use of remote sensors based on VIR-NIR (*e.g.* Reyna-Bowen et al., 2018) with a reduced number of samples across the

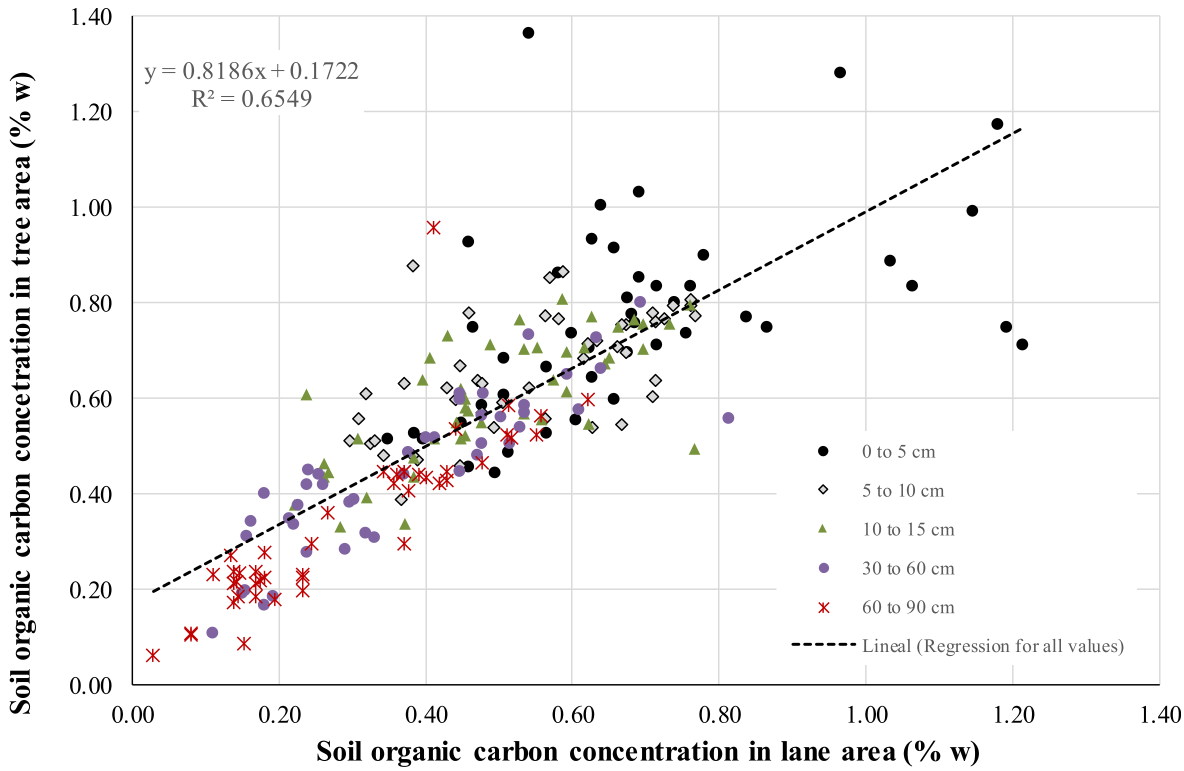

Fig. 4. Comparison between tree and lane area soil organic carbon concentration (% by weight). The lineal regression shown has been calculated for all the data points.

Table 3
Summary statistics of correlation between soil organic carbon concentration, SOC (% by weight) at different depths (tree and lane areas; 90 samples in total). First number is the Pearson's coefficient of correlation, the second is the statistical significance of the correlation and third is number of samples.

		SOC (% w)				
	Depth (cm)	0–5	5–10	15–20	30–60	60–90
SOC (%)	**0–5**	1.0000, 0.0000, 90				
	5–10	0.6227, 0.0000, 90	1.0000, 0.0000, 90			
	15–20	0.6126, 0.0000, 90	0.9061, 0.0000, 90	1.0000, 0.0000, 90		
	30–60	0.5156, 0.0000, 90	0.7752, 0.0000, 90	0.7816, 0.0000, 90	1.0000, 0.0000, 90	
	60–90	0.4821, 0.0000, 90	0.6736, 0.0000, 90	0.7170, 0.0000, 90	1.0000, 0.0000, 90	1.0000, 0.0000, 90

full soil profile depth might be the only feasible way to determine SOC and SOC_{stock} beyond the plot scale. This approach has been shown successful in estimating SOC and SOC_{stock} distribution in complex landscapes in field crops, *e.g.* Aldana et al. (2016).

Fig. 5 depicts the map of SOC distribution across the orchard at 0–5 and 60–90 cm depth. As expected from the above-mentioned correlation in SOC across depths, similar patterns were found, with lower SOC values in the Northern, Southern and middle Western area of the orchards, and highest values in the Eastern part and in a cluster in the upper Eastern part.

3.3. *Soil organic carbon stock*

Fig. 6 summarizes the soil organic carbon stock by depth and location to the tree. The results show a significant increase of SOC_{stock} with depth, especially below 10 cm. Surprising is the lack of differences in SOC_{stock} between the lane and tree area, which can be understood because the differences in SOC (higher in the tree area) are compensated by the differences in bulk density (higher in the lane area). This compensating phenomenon was not observed by Cardinael et al. (2015) in their study of an agroforesty walnut-durum wheat system, probably because the durum wheat growing area was subjected to a less intensive machine traffic than the lanes of olive orchards. One of the periods of heavier traffic in olive orchards is during the harvest season in the late fall-early winter period which is the rainy period in Mediterranean area. This can exacerbate the risk of soil compaction since on many occasions it is unavoidable to traffic under suboptimum conditions to prevent soil compaction. However, the intensity of traffic in olive orchards can vary widely for different orchard types. For small and low intensity orchards, harvested manually with the fruit retired in small containers, the intensity of the traffic, and as such the risk of compaction, can be very small. On the contrary, in large intensive orchards that need to be harvested mechanically with heavier machines, as is the case of the orchard studied in this manuscript, the compaction risk in the lanes can be large. This is a reminder that the compensating effect discussed above should always be appraised in the characterization of soil bulk density that must always be made for a for reliable determination of SOC_{stock} (*e.g.* Penman et al., 2003).

We combined each paired tree-lane point to determine the overall SOC_{stock} for the orchard (Supplementary Material Table 2). Fig. 7 depicts the map of spatial distribution of SOC_{stock} at 90 cm depth indicating a large variability among some areas, with lowest

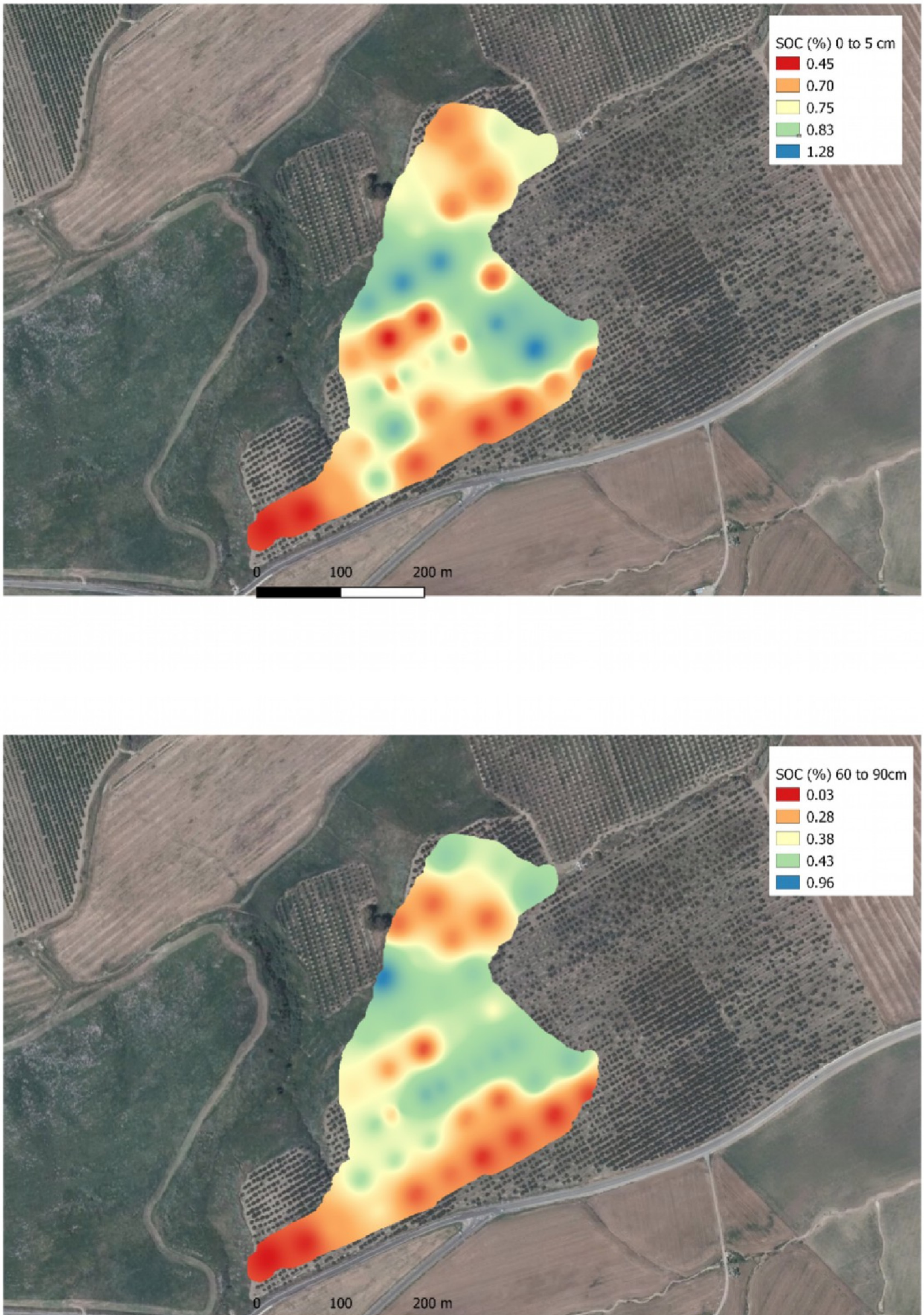

Fig. 5. Maps of spatial distribution of soil organic carbon concentration (%) by weight at 0–5 cm depth (top) and 60–90 cm depth (bottom).

values, in the range of 1.8–3.7 kg m^{-2}, in the Southern and Northwestern part of the orchard and the greater, in the range of 5.1–6.9 kg m^{-2}, in the central and Northeast part of the orchard, coinciding approximately with the spatial distribution of soil SOC shown in Fig. 5. Overall, the orchard has an average SOC_{stock} of 4.41 kg m^{-2} with a moderate coefficient of variation (32%) and a

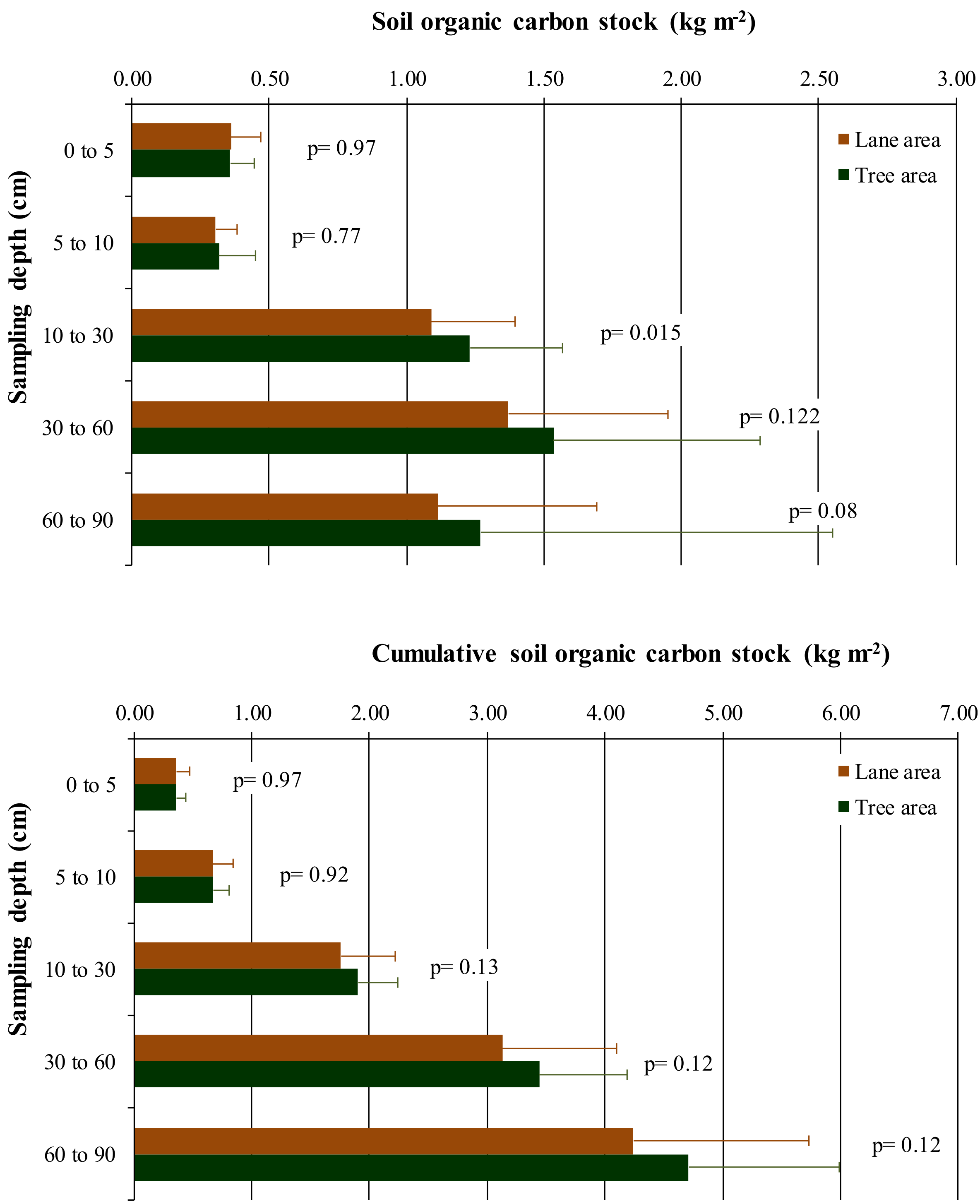

Fig. 6. Soil organic carbon stock (kg·m^{-2}), by depth (top) and cumulative down to that depth (bottom) in relation to olive tree canopy projection. Tree below the olive canopy; lane in the orchard alley outside the olive canopy projection.

centered distribution narrower than a normal distribution, albeit it is a bimodal distribution (Supplementary Material Table 2 and Fig. 3). The average SOC_{stock} found is in the mid-lower range of reported values for olive orchards; less than of 6.58 kg m^{-2} reported by Lozano-Garcia and Parras-Alcántara (2014) in Southern Spain for 0–100 cm depth, or the 7 and 13 kg m^{-2} for 7 and 30 years old orchards respectively in central Italy by Massaccesi et al. (2018) for 0–90 cm soil depth. These lower values in comparison to the Italian study might be explained by the higher biomass return by vegetation in the latter, in which it a permanent vegetation was maintained in the lanes and chopped pruning residues were spread annually. In addition, the smaller slope might also contributed to minimize organic carbon losses by erosion. In the case of Lozano-Garcia and Parras-Alcántara (2014) study, its higher value can be partially explained by the fact that the SOC_{stock} is calculated for a 10% deeper soil. However, even considering this, it remains larger for unexplored reasons as the authors described a conventional management based on mineral fertilization, conventional tillage

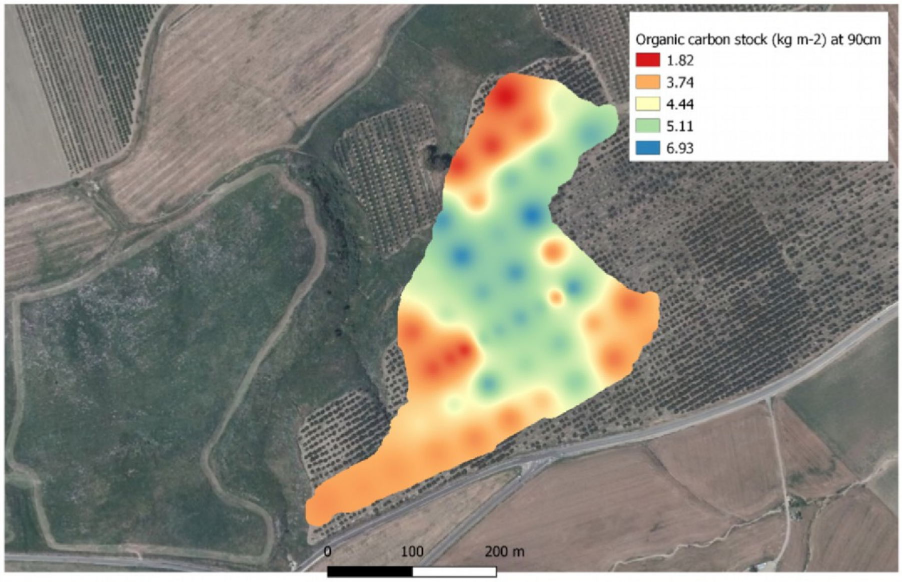

Fig. 7. Map of spatial distribution of soil organic carbon stock ($kg \cdot m^{-2}$) at 90 cm depth.

and no use of chopped pruning residues. Moreover, the reported slope (in the range of 4–14%) was similar to the one of our studied orchard. This is a good reminder of the possibility of large differences in SOC_{stock} in olive orchards at similar regions under apparently similar conditions. González-Rosado et al. (2020) measured 4.01 vs 2.98 kg m^{-2} for tillage and spontaneous cover crop soil managements, respectively, at the top 100 cm soil in a mild slope (1–6%) olive orchard located in Jaén (Sourthern Spain). The variability among orchards in similar soil and climate conditions, without a clear identification of the direct effect of soil managements points towards the persistence of a significant variability in SOC_{stock} among orchards that remains poorly understood and needs to be considered when discussing the potential of olive orchards in soil carbon sequestration schemes. It also notes the need for further experimental studies, at a relevant spatial scale and including commercial farms to ensure that agricultural practices are the ones that farmers carry out in the region. These, aimed to further explore the link between different biomass return to the orchards, orchard age, effect of losses by water and tillage erosion, and its link with soil management and soil characteristics climate and topographic conditions. Overall, the experimental values found in our orchard are in the range of SOC_{stock} for the whole rooting depth for olives in Italy by Caddeo et al. (2019) using CENTURY 5 model simulations, with an average value and standard deviation of 5.2 and 0.16 kg m^{-2}, respectively. However, our SOC_{stock} values, and all the other experimental values discussed above, suggest that the modelling predictions of Chiti et al. (2012) using also the CENTURY 5 model for olive orchards in Italy might be overpredicting actual values, since they reported an average prediction of 5.2 kg m^{-2} considering only the top 0.30-m soil layer. It is complicated to compare these values of SOC_{stock} in olive orchards to other agroforestry systems in Mediterranean conditions since only a limited number of studies is available. Cardinael et al. (2015) found much higher values for a 0–100 cm soil depth, in the range of 10–13.5 kg m^{-2}, for a hybrid walnut-durum wheat in Mediterranean France on a flatland area and with a significantly higher annual rainfall for Mediterranean conditions (873 mm). When compared the maps of SOC_{stock} presented by Cardinael et al. (2015) to the ones presented in Fig. 7, our results show a larger spatial variability which can be explained by the more homogeneous nature of the field at the French site which been in a flat area was subject to a less intense transfer of soil organic carbon by erosion processes.

When compared to experimental studies on SOC_{stock} in other agricultural systems, like field crops, the values found in our study are in the upper range of reported values, *e.g.* Goidts et al. (2009) with values in the range of 3.07–4.17 kg m^{-2} in Southern Belgium. Reyna-Bowen et al. (2020) reported a SOC_{stock} of 3.9 and 5.3 kg ha^{-1} for a 1-m soil profile in Southern Spain for "dehesa", which is an agroforestry system aimed mainly at extensive livestock raising.

We have not found similar studies on the spatial distribution of SOC_{stock} in olive orchards at a similar scale.

3.4. Spatial attributes related to topography and erosion processes

Fig. 8 shows the most relevant topographic features of the orchard. The difference in elevation (Fig. 8A) between the highest elevation points in the southern part and the catchment outlet in the north-eastern part is approximately 35 m. Most of the catchment is oriented towards the north, with the exception of southern oriented slope in the north section of the orchard (Fig. 8B). There are three areas with the steepest slopes located at the northern, eastern and western parts of the catchment (most in the range of 10–25%) connected by thalweg areas of milder slopes (most in the range of 2–10%), with an area of mild slope in almost the entire southern part of the orchard (Fig. 8C).

Fig. 9 depicts two topographic related indexes that have been related to SOC_{stock} distribution on preceding studies (*e.g.* Mishra & Riley, 2015). The orchard map of Sediment Transport Index (hereafter STI, Fig. 9A) reflects the concentration of flow in the catchment due to its topography, with several slopes converging in thalweg areas and flow concentration in the lane areas due to the shoulders built in the tree planting rows, which are breached only in the thalweg area draining the catchment from the South-Eastern boundary to the outlet at the North-Eastern corner. The Topographic Wetness Index (hereafter TWI, Fig. 9B) also reflects this variability due to a combination of the general topography with the

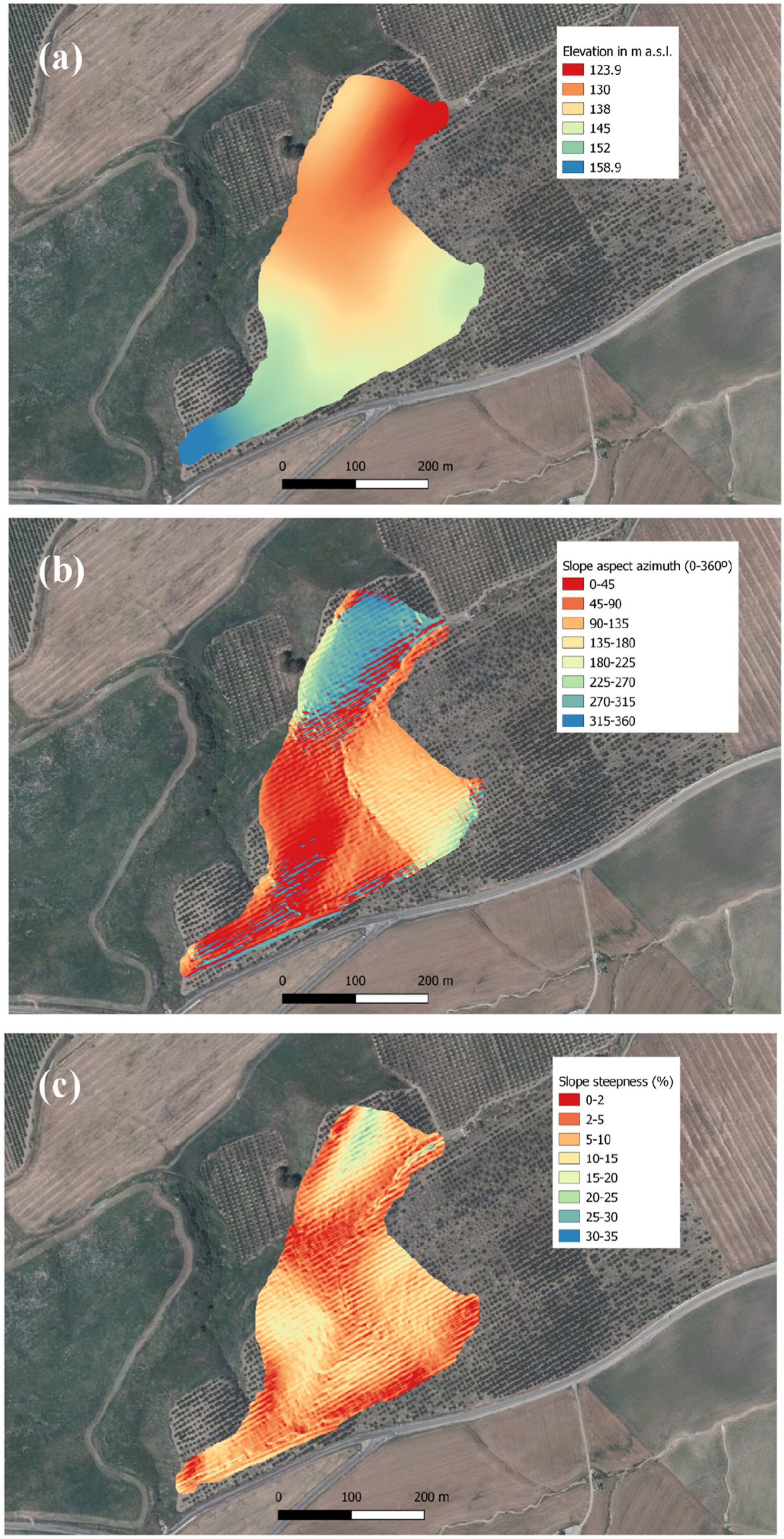

Fig. 8. Maps of spatial distribution of topographic attributes: Elevation (m.a.s.l.) (a), Orientation (sexagesimal degrees) (b) and Slope steepness (%) (c).

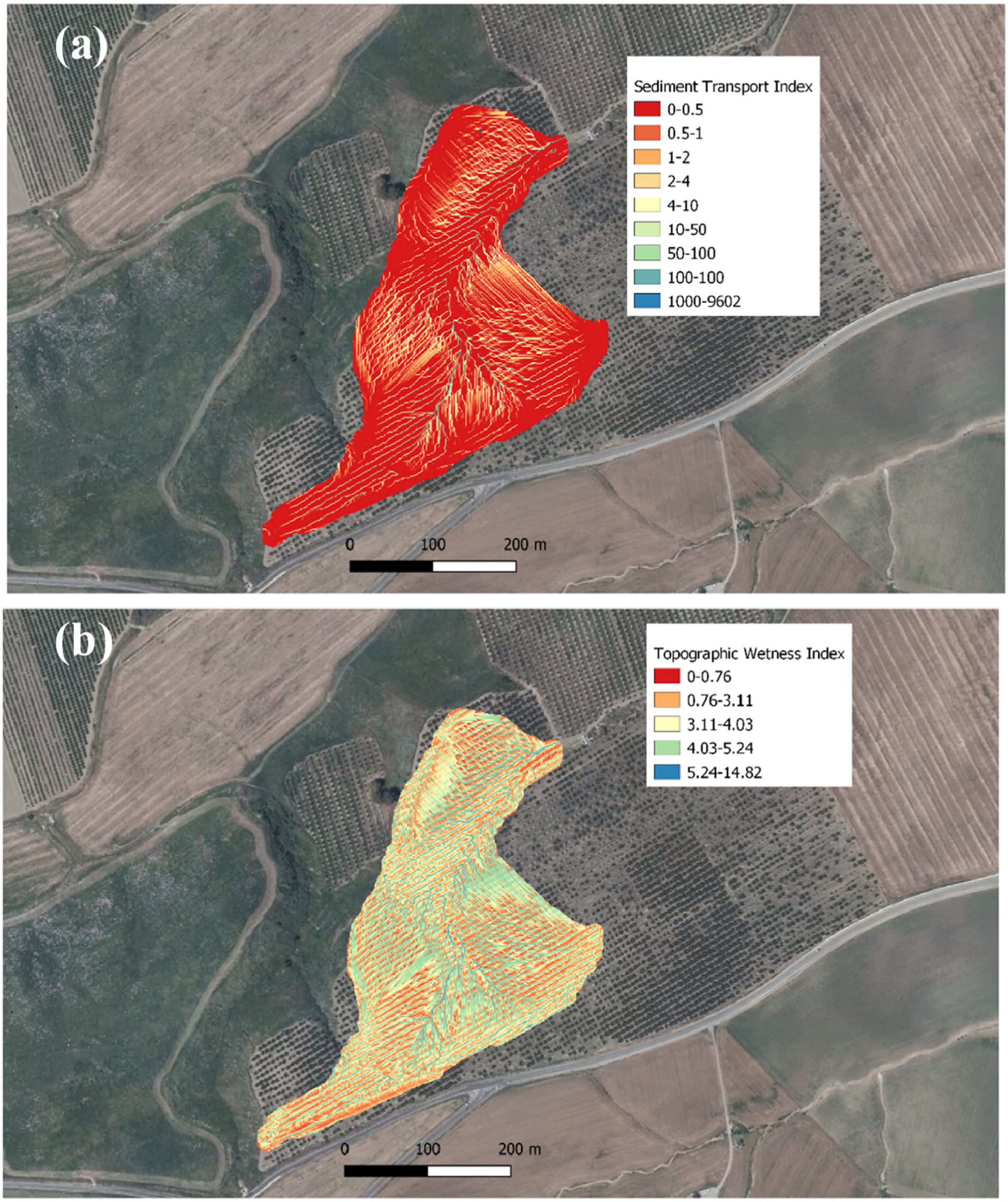

Fig. 9. Maps of spatial distribution of topographic related attributes: Sediment Transport Index (a), Topographic Wetness Index (b).

man-made shoulders. Despite this variability, there is apparently a trend to observe the higher TWI values in the thalweg area draining the catchment from the south-east to the north-east outlet, as well as in the Eastern slope.

Fig. 10 depicts the long-term erosion predictions of water and tillage erosion in the catchment using WATEM/SEDEM. The tillage erosion map (Fig. 10A) predicted areas of significant deposition of sediment from the sloping areas, reflecting the concave-convex topography of the catchment in which the orchard was planted. This process of soil movement towards the convex areas in the catchment was observed by the authors when tillage was implemented in the catchment or occasionally used to cover the ephemeral gullies periodically developed in the draining thalweg area (already commented) during very rainy years. The water erosion map estimated by WATEM/SEDEM appears in Fig. 10B, showing how most of the catchment slopes present a moderate erosion rate (indicating the moderate contributing area despite the relative steep slope) with areas of higher erosion rates in the thalweg area where the overland flow is concentrated. The model predicts some deposition areas of water detached sediment across the thalweg area and the connecting area between this and the slopes. Although no validation of the model spatial predictions was

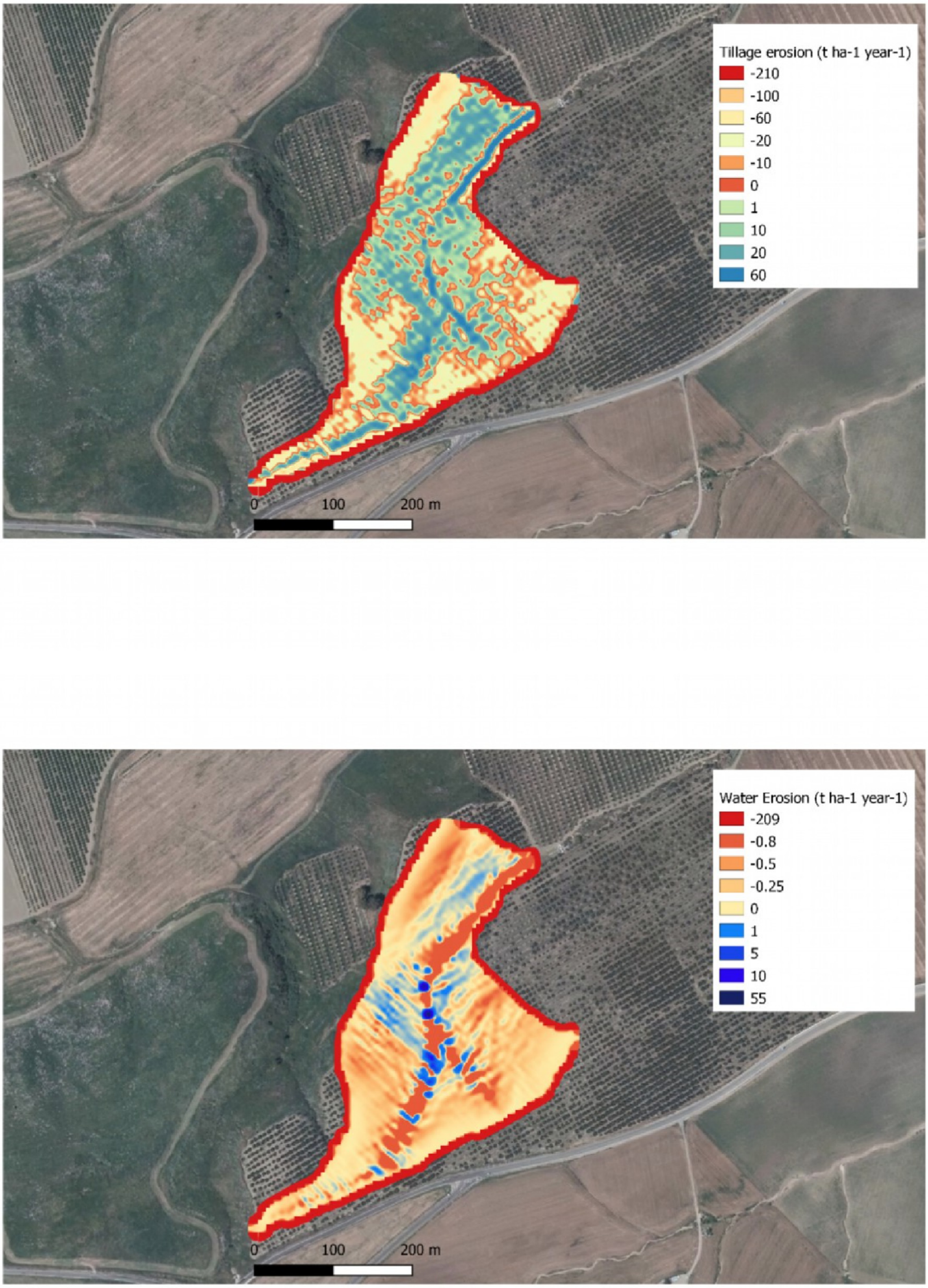

Fig. 10. Map of long-term tillage (top) and water (bottom) erosion ($t \cdot ha^{-1} \cdot yr^{-1}$) calculated with WATEM/SEDEM. Note that positive values indicate net deposition and negative values net erosion.

performed, some of these areas of sediment deposition agreed well with field observations carried out in the catchment after storm periods (Ayala, 2004).

3.5. Correlation between total soil organic carbon stock and landscape features

In order to elucidate the processes influencing the spatial distribution of SOC_{stock}, the relation with topographical attributes and water and tillage erosion rates was evaluated. The variables that were evaluating are related to the redistribution of sediment and carbon, and the spatial distribution of soil moisture within the catchment. Table 6 summarizes the correlation between the SOC_{stock} in the soil profile and the topography-related properties and the erosion and sedimentation predictions by water and tillage within the catchment. Other properties explored but not shown (slope steepness and orientation) did not show a significant correlation with SOC_{stock}. Results in Table 4 indicate a moderate correlation, r in the range of 0.55–0.64, between SOC_{stock} and predicted tillage erosion and deposition, elevation, STI and TWI, but no correlation with predicted water erosion was found. Correlation with the geomorphological variables in Table 6 has been assessed in previous studies on agricultural and forest areas. So, Mishra and Riley (2015) noted how elevation, aspect, SWI and erosion were statistically significant predictors for SOC_{stock} at small (50–100 m) spatial scale, while they detected TWI as a significant predictor at medium (500 m) spatial scale. Aldana et al. (2016) in the study described in previous sections concluded that SOC_{stock} was mainly controlled by erosion processes, with erosion/deposition rates measured using Cs^{137}, and slope curvature and steepness. Gómez et al. (2020) found a similar inverse correlation of SOC and elevation and transition from erosion to deposition areas in a 430 m catena of a mature olive orchard. However, they were not able to detect significant differences in SOC_{stock} for the top 0.6 m of the soil between the eroding and deposition area. Lozano-Garcia and Parras-Alcántara (2014) and González-Rosado et al. (2020), both using soil pits across toposequences in different olive orchards, also found inconclusive results when trying to link differences in SOC_{stock} to topographic position. It is worth noting that these three studies in olive orchards used a smaller number of samples than ours, and so had a lower chance of detecting the statistical significance. In our study, the higher SOC_{stock} occur in the lower areas of the catchment close or in the thalweg draining area. This can be explained as the lower slope and change of slope curvature are areas of deposition by soil transported by tillage erosion from upslope, as well as areas with higher moisture availability as detected by the correlation with the TWI. In semiarid regions these downslope areas have been connected to higher crop yields and higher water availability (Halvorson & Doll, 1991) and they have been described in the study region on wheat fields on vertic soils of similar topography (Tenreiro et al., 2021). The combination of slope change and increase of upslope contributing area in the lower areas of the catchment, reflected by the STI, also in this case its counterintuitive, since an increase in SOC_{stock} in an area where there is potential higher capacity to transport sediment coming upslope by water erosion, is expected. In our study, this probably reflects a correlation with the underlying topographical properties defining this index rather than a connection to water erosion processes, although this phenomenon is relevant in the orchard (Gómez et al., 2014). The lack of correlation between SOC_{stock} and our water erosion predictions can be understood since most of the water erosion in the catchment is driven by rill and gully erosion which seems to be concentrated in a very limited surface area of the orchard and has a high sediment transport capacity, as observed at the hillslope and catchment scale by Guzmán et al. (2013) and Gómez et al. (2014). This also appears from the high degree of overland flow concentration by the drainage network, apparent in the map of STI (Fig. 9A). Rills and ephemeral gullies are obliterated by normal farm operations, even in cover crop systems, and our results suggest that sediment redistribution from the top of the slope to the lower areas, by tillage erosion and by machine traffic, plays a role in the spatial variability of SOC_{stock} although it is not possible to quantify its relevance in comparison to the higher water availability at the lower area. It is worth remembering that in our study different landscape positions did not affect the effective soil rooting depth, as it was the case of other studies (*e.g.* Aldana et al., 2016).

Table 5
Multiple linear regression model to predict SOCstock for 0.9 m of soil depth from cumulative upslope area (CumArea) and topographic wetness index (TWI).

	Coefficient	Standard error	p	95% Confidence interval
Constant	−2.240144	1.98117	0.265	[-6.254376, 1.774087]
CumArea	0.010531	0.0045855	0.027	[0.0012399, 0.0198222]
TWI	1.402629	0.4884163	0.007	[0.4130037, 2.392254]

The variables shown in Table 4 are significantly correlated to SOC_{stock} and so can be useful from an operational perspective in future studies in which we need to cluster areas within orchards for exploring spatial differences in SOC or SOC_{stock}, it will be highly desirable to reduce that number to a minimum. Using stepwise multiple linear regression, we developed a model in which the spatial variability of SOC_{stock} could be described by two variables (TWI and cumulative upslope area) with an r^2 of 0.48 and a mean root square error of 1.01 kg m^{-2} (Table 5 and Supplementary Fig. 4). This, with the previous discussion on the interpretation in semiarid areas as proxy variables for areas of higher water availability and sediment deposition, suggest the potential use of topographic derived indices for orienting clustering of orchards in Mediterranean conditions for best appraisal of SOC and SOC_{stock}. Nevertheless, the determination of threshold values among areas and the calibration of similar models for other conditions remain an open question.

Table 4
Summary statistics of correlation between soil organic carbon stock in the top 90 cm of the soil and some soil properties and erosion rates, as well as between these properties. First number is coefficient of correlation, the second is the statistical significance of the correlation. STI is sediment transport index and TWI is the topographic wetness index. Other topographic related properties not shown did not presented any statistically significant correlation with soil organic carbon stock. * Note that positive values of water and tillage erosion indicates deposition of soil material.

	$SOC_{stock,\ 0-90\ cm}$	Water erosion	Tillage erosion	CumArea	STI	TWI
$SOC_{stock,\ 0-90\ cm}$	1.0000, 0.0000					
Water erosion*	0.2590, NS	1.0000, 0.0000				
Tillage erosion*	0.5577, 0.0067	0.2653, NS	1.0000, 0.0000			
CumArea	0.5459, 0.0038	0.4229, NS	0.6152, 0.0009	1.0000, 0.0000		
Elevation	−0.4968, 0.0187	−0.1744, NS	0.2465, NS			
STI	0.5946, 0.0087	0.3126, NS	0.5518, 0.0080	−0.2515, NS	1.0000, 0.0000	
TWI	0.6423, 0.0003	0.4880, 0.0505	0.6134, 0.0009	−0.4110, NS	0.5089, 0.0287	1.0000, 0.0000

Table 6
Summary statistics of topsoil organic carbon concentration determined for different areas (tree, lane and combined) and depths (0–5, 5–10 and 0–10 cm). Areas were weighted averaged with a 0.35 and 0.65 weighting factor for the lane area respectively. r^2 is square coefficient of correlation, P is statistical significance of the correlation, and RMSE is root mean square error.

	Depth (cm)	Area	n	m	r^2	P	RMSE (kg m^{-2})
SOC (%)	0–5	Lane	1.804	3.806	0.365	0.0000	1.126
		Tree	1.231	4.136	0.363	0.0000	1.128
		Combined	0.807	5.050	0.472	0.0000	1.027
	5–10	Lane	−0.008	8.166	0.728	0.0000	0.738
		Tree	−0.984	8.243	0.533	0.0000	0.966
		Combined	−1.341	9.908	0.794	0.0000	0.632
	0–10	Lane	0.347	6.637	0.613	0.0000	0.879
		Tree	−0.353	6.708	0.515	0.0000	0.985
		Combined	−0.860	8.141	0.704	0.0000	0.768

3.6. Correlation between total soil organic carbon stock and surface soil organic carbon concentration

Table 6 summarizes the regression between the SOC_{stock} in the soil profile and SOC at different depths and location in relation to the tree, showing a significant degree of correlation. This is not surprising given the previous discussion on the spatial variability of SOC, in which we noted a general trend across the catchment maintained along the sampled soil depth (90 cm) on top of which it was superimposed a local variability up to 60 cm depth due to the olive tree influence in relation to the lane area. This might also have operational implications for the determination of SOC_{stock} under similar situations in which high resolution surface determinations of SOC could be combined with calibration using SOC_{stock} in selected points, as made by Aldana et al. (2016). Here, we did not observe differences in the shape of the SOC distribution with depth between the areas with higher and lower SOC_{stock} (data not shown) as it was found by Aldana et al. (2016) on field crops with complex topography in Germany.

4. Conclusions

This study presented, to the best of our knowledge, the first detailed estimation of SOC_{stock} beyond the hillslope scale, in an 8-ha Mediterranean olive orchard catchment. SOC_{stock} was on average 4.14 kg m^{-2} and ranged from 1.8 to 6.0 kg m^{-2}. This average SOC_{stock} is in the mid-lower range of SOC_{stock} reported for olive orchards in preceding studies. It is similar to those reported in other intensive arable crops and agroforestry fields under similar rainfall conditions, but lower than agroforestry systems under higher rainfall availability. A large within-field variability was observed, that highlights the need for further studies at a similar scale to reduce uncertainty in the determination of SOC_{stock} in olive orchards.

Our study documented lower SOC values in the upper sloping areas and higher in the thalweg areas connecting hydrologically the catchment. This pattern in SOC was maintained across the different soil depths, down to 0.9 m, without distinguishing differences in SOC profile with depth between areas with higher or lower SOC_{stock}. On top of this large-scale spatial variability, we detected a superimposed local variability in SOC between the lane and the olive tree canopy area, with higher SOC at the olive tree canopy area down to 0.6 m. This local variability did not result in higher SOC_{stock} in the olive tree canopy area as compared to the lane area due to the higher bulk density at the lanes, as a result of compaction by machine traffic. However, it is important these local differences in SOC and bulk density between lane and olive tree canopy areas are taken into consideration in the determination of SOC_{stock} in olive orchards, since its relevance will vary in relation to the specific management and degree of intensification in the orchard, being a crop with a wide range of farming systems.

SOC_{stock} values across the orchard were correlated with several topography-related indexes (TWI, STI, elevation, cumulative upslope area) and tillage erosion predictions but not with water erosion prediction. Our interpretation is that the differences in SOC and SOC_{stock} in this catchment are driven by the sediment redistribution downslope, mainly by tillage erosion and machine traffic, and the higher soil water availability in the lower areas. These topographic indexes might be of use in future studies to clustering areas within the same catchment/orchard for SOC and SOC_{stock} determination.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.iswcr.2022.12.002.

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