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The effect of agricultural abandonment and mountain terrace degradation on soil organic carbon in a Mediterranean landscape

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ABSTRACT

Extensive areas of arable land have been abandoned in many countries around the world, especially in the Mediterranean region. The overall goal of this study is to assess the effects of agricultural land abandonment on soil organic carbon (SOC) concentrations and stocks in a Mediterranean mountain environment. The specific objectives are (i) to quantify differences in SOC concentrations in top 25-cm soil in productive agricultural areas, abandoned agricultural areas and state forests; (ii) to quantify SOC stocks in productive and abandoned terraced vineyards up to the bedrock or to a maximum depth of 80 cm and (iii) to analyze the effect of time of abandonment on the SOC stocks of the vineyards. Top soil SOC concentrations from 826 sampling points covering 2374 km^2 of mountainous areas (Troodos Mountains, Cyprus) with a variety of land covers were used. SOC stocks were determined from soil samples, which were collected up to the bedrock, where possible, from 24 productive and abandoned terraced vineyards (paired-sites). The Loss-on-Ignition method and an elemental carbon analyzer were used for SOC concentrations. Coarse fragment corrections were made for SOC stock calculations. Time of abandonment was estimated with aerial photos taken in 1963 and 1993. The average SOC concentration in the top soil (0–25 cm) ranged between 1.7% in state forests to 1.0% in productive agricultural land, while the mean value of abandoned fields was 1.3%. Regarding SOC in the top soil (0–10-cm) of paired vineyards, concentrations were higher in abandoned (1.4% SOC) than in productive sites (0.9% SOC), with a statistical significance level < 0.05. Paired t-tests showed that SOC was lower in productive sites (0.9% SOC) compared to abandoned sites, with SOC (%) and statistical significance increasing with time of abandonment: 1.2% SOC in sites abandoned after 1993 (p-value 0.18) and 1.6% SOC in sites abandoned before 1963 (p-value 0.05). However, mean SOC stocks, with coarse fragment correction, were slightly higher for the productive sites (22 Mg ha^{-1}) than for the abandoned sites (21 Mg ha^{-1}) and showed no trend with the time of abandonment (p-value: 0.85). The coarse fragment corrections resulted in 17 to 78% reduction in SOC stocks. Our results showed the importance of deep soil sampling ($>$ 30 cm) and coarse fragment corrections for quantifying SOC stock. Despite higher SOC concentrations for abandoned sites, SOC stock calculations resulted in similar mean SOC stock values for productive and abandoned terraced vineyards, indicating the importance of erosional and depositional processes in such landscapes.

1. Introduction

Soil is considered to be the second largest carbon pool after the oceans (Stockmann et al., 2013). Understanding soil organic carbon (SOC) storage within anthropogenic landscapes is critical for assessing soil's carbon sequestration potential and reducing CO_2 emissions to mitigate its alarming atmospheric levels (Rumpel and Kögel-Knabner, 2011). Semi-arid ecosystems have been found to dominate the positive global terrestrial carbon sink trend and play an important role in the inter-annual variability, despite the fact that the tropical forests account for the largest fraction (Ahlström et al., 2015). Moreover, semi-arid and arid regions account for more than 47% of terrestrial land surface and store 15.5% of the global soil C, thus even small changes in their carbon stocks could have profound consequences for global climate (Lal, 2004).

Conversion of natural vegetation to cultivated land in the Mediterranean region has led to dramatic losses of SOC (Seddaiu et al., 2013; Aguilera et al., 2013, 2018). Amongst the diverse agricultural landscapes, vineyards have been often reported to have the lowest SOC levels and have therefore received considerable attention (Eldon and

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Gershenson, 2015; García-Díaz et al., 2017; Novara et al., 2018). Conversely, due to changing socioeconomic conditions (Vinatier and Arnaiz, 2018), extensive areas of arable land have been abandoned in many countries around the world (Ramankutty et al., 2010; Kalinina et al., 2019), including vineyards in the Mediterranean region (e.g. Novara et al, 2014; Zambon et al, 2018). Several studies in Mediterranean environments showed that abandonment of agricultural land and the subsequent recolonization by natural vegetation caused an increase in SOC (Acín-Carrera et al., 2013; De Baets et al., 2013; Novara et al., 2014; van Hall et al., 2017).

Measurement of SOC (% or g kg^{-1}) in bulk soil alone is not representative of the carbon storage (Mg ha^{-1}) in a landscape and might be easily misinterpreted (Eldon and Gershenson, 2015). A significant increase in the SOC concentration in the soil surface layer does not imply a significant overall change in the total SOC storage (or stock: Mg ha^{-1}) due to changes in soil bulk density and depth, related to tillage or soil erosion (e.g. Throop et al, 2012). Sampling of surface soil alone (10 or 20 cm) and sampling to predetermined depths instead of the whole soil column are common in the literature and are not providing a complete picture of soil carbon storage (Rumpel and Kögel-Knabner, 2011). Currently, there are few scientific studies that compared SOC stocks, instead of only SOC concentrations, between productive vineyards and natural vegetation or abandoned vineyards in Mediterranean regions (Williams et al., 2011; Novara et al., 2012; Francaviglia et al., 2017; van Hall et al., 2017; Novara et al., 2018).

The overall goal of this study is to assess the effects of agricultural land abandonment on SOC (%) and SOC stocks (Mg ha^{-1}) in Mediterranean mountain environments with a hypothesis that these would change with the abandonment. The specific objectives are (i) to quantify differences in SOC concentrations in the top 25-cm soil in productive agricultural areas, abandoned agricultural areas and forests; (ii) to quantify SOC stocks in productive and abandoned terraced vineyards up to the bedrock or to a maximum depth of 80 cm; (iii) to analyze the effect of time of abandonment on the SOC stocks of the vineyards. To obtain a broad understanding of SOC concentration changes after agricultural abandonment, with forest as a reference land use system, data from the Geochemical Atlas of Cyprus (Cohen et al., 2011) were used (objective 1). These data represent SOC concentrations (%) of the top 25-cm soil at a sampling density of 2.2 km × 2.2 km in the study area. For refining the understanding of SOC changes after abandonment, samples from productive and abandoned vineyard terraces were collected up to the bedrock, where possible, and SOC stocks were quantified (objective 2 and 3). The current study contributes to knowledge of SOC sequestration potential after abandonment of agricultural terraces, a phenomenon that is widespread in the mountains of Cyprus, as in other areas of the Mediterranean (Varotto et al., 2019).

2. Methodology

2.1. Study area

The Troodos Ophiolite Complex, henceforth referred as Troodos study area, is located in the island of Cyprus and covers an area of 2374 km^2 (Fig. 1). Its stratigraphic units are plutonics (harzburgite, dunite, wehrlite, pyroxenite, gabbro and plagiogranites), intrusives (sheeted dyke complex – diabase) and volcanics (pillow lavas) with an average slope of 34% (Figs. 1 and 2). The average annual precipitation from 61 stations in the study area was 596 mm and temperature ranges from an average daily minimum of −2 °C in January and February (from a meteorological station at the highest elevation of 1725 m a.s.l.) to an average daily maximum of 32 °C in July and August (from a station at the lowest elevation of three m a.s.l.) (1980–2010) (Cyprus Department of Meteorology).

The main land cover is coniferous forest and sclerophylous vegetation (1600 km^2) (Fig. 2). Most of the forested areas have been clear cut or destroyed by fire at some point in time. Significant efforts to restore and maintain the forests in a natural state have been put in place during the British colonial period (1878–1960) and since then the Cyprus Forestry Department continues these efforts (Chapman, 1952; Hadjikyriakou, 2017). The second largest land cover in the study area is agriculture (450 km^2) based on the 2006 CORINE inventory (Büttner and Kosztra, 2007). In 2016, the registered agricultural plots that were eligible to receive subsidy payments from the Cyprus Agricultural Payments Organization (CAPO, 2016) sum up to a total surface area of 260 km^2 (Fig. 3). Agriculture in the Troodos Mountains consists of small, terraced plots cultivated mainly for family use (Zoumides et al., 2017). The main crops are grapes and fruit trees. Abandonment of agriculture on mountain terraces is ubiquitous. The area cultivated with grapes, which are almost exclusively grown in the mountains, dropped from more than 50,000 in 1970 to 25,000 ha in 1990 down to 6000 in 2017 (FAOSTAT, 2019). Although the main change in land use occurred in the early 1980s, the abandonment of agricultural land in Troodos area probably already occurred in different periods before 1940s, as documented by Christodoulou (1959), who provided verbal descriptions, statistics and maps on the evolution of rural land use pattern in Cyprus.

Soil organic carbon in Cyprus is relatively low, similar to other semi-arid areas (e.g., Ballabio et al., 2019; Batjes, 2019). A comprehensive soil mapping study (sampling and analysis) for the Geochemical Atlas of Cyprus found an average 1.5% SOC in the top 25-cm soil at country level and 1.7% for forests and semi-natural areas (Cohen et al., 2011,2012; Zissimos et al., 2019). However, analysis of the possible reasons for the highly variable SOC rates in the Troodos Mountains was beyond the scope of this mapping program. Zissimos et al. (2019) estimated a total top-soil SOC stock of 27 Mt for the country (5500 km^2) of which 6 Mt was in forested areas (1180 km^2). The country-wide SOC estimates were similar to the mean SOC values from the modelling-based studies of Lugato et al. (2014) and Ballabio et al. (2014) for Cyprus, but lower than the average SOC (1.75%) from the 22 soil top 20-cm soil samples analyzed by the GEMAS project (Reimann et al., 2014).

2.2. Soil organic carbon in agricultural, abandoned and forest areas

For quantifying the differences in SOC concentrations in top soils of productive agricultural areas, abandoned agricultural areas and forests, data from the Geochemical Atlas of Cyprus (Cohen et al., 2011) were used. The authors used the same sampling protocols as those of the FOREGS Geochemical Atlas of Europe (Salminen et al., 1998). In the Geochemical Atlas of Cyprus, a total of 929 sampling points in the Troodos study area were identified using a grid-based sampling scheme (2.2 km × 2.2 km) and the top soil layer (25 cm) was sampled between 2006 and 2008. SOC was quantified with an Eltra CS-800 elemental analyzer (Eltra, Germany).

For the present study, the original sampling points from the Geochemical Atlas of Cyprus were first classified by land use with the help of the 2006 CORINE land cover map and the state forest boundaries (mostly coniferous forests). All points that were classified as agriculture (CORINE main class 2) were cross-checked with the plots registered for single area payments in 2008, under the Common Agricultural Policy (CAPO, 2016), to ensure their status as productive agricultural land use in the sampling year. The points that were neither classified as productive agricultural land nor state forest were visually checked by the first author for signs of agricultural abandonment with aerial photos taken in 1963 and 1993, available at a scanned resolution of 1:1128 in the online portal of the Cyprus Department of Lands and Surveys (DLS, 2019). The sampling points that were located in urban or bare areas and points without distinguishable agricultural features such as plough lines, terraces, fruit trees or field borders were not classified and removed from the analysis. The remaining 826 sampling points were subsequently grouped in five classes: (i) productive agriculture, (ii) agriculture abandoned after 1993 (iii) agriculture abandoned

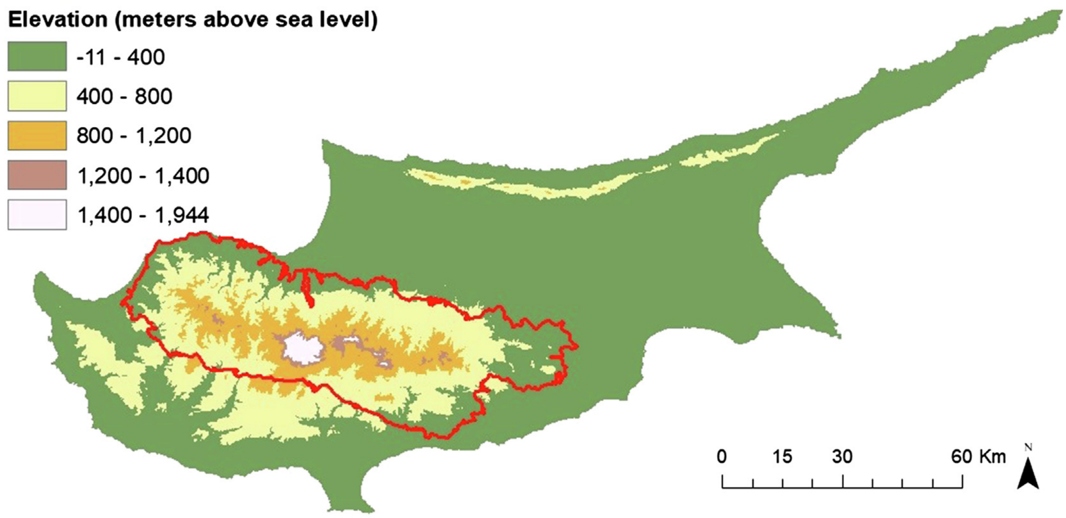

Fig. 1. Cyprus digital elevation model with Troodos study area bordered red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

between 1963 and 1993, (iv) natural vegetation without agriculture since 1963 and (v) state forests.

2.3. Soil organic carbon in terraced vineyards

2.3.1. Sampling design

A paired-site approach (Conteh, 1999) was chosen to investigate the effects of terraced vineyard abandonment on soil organic carbon stocks. One paired-site has two members (i.e. sites) adjacent to each other: one productive vineyard and one abandoned vineyard.

The criteria for two adjacent plots to be a paired-site is that they should have the same climate, geology, natural slope gradient, slope aspect, elevation and upslope drainage, apart from the land use change caused by the abandonment. The vineyards registered with CAPO for the single area support measures in 2016 were assumed to be productive (Fig. 3). The CAPO database contained 6470 productive vineyard plots in the Troodos study area, with an average plot area of 1555 m^2 and median area of 1067 m^2, totaling to an area of 10.06 km^2. To obtain a representative sample, 4% of the plots were randomly selected (258 plots). Their potential to be a member of a paired-site was verified on Google Earth by checking if an abandoned or natural vegetation plot was present next to the terraced vineyard plot, along the same mountain slope. From the 258 plots, 61 were identified to have potential to be a paired-site (abandoned plot next to a productive plot with same geology, slope gradient and slope aspect and similar upslope drainage area). Field-visits were performed for inspecting these potential sites. Twenty four of the 61 potential paired-sites were found to fulfill the criteria and constitute the study sites from where the soil samples were collected (Fig. 3).

2.3.2. Site characteristics

Photos were taken at each plot in addition to GPS point recordings of each sample center location. A site characteristics table, modified from Cools and De Vos (2010), was filled for each site to collect information on parameters that affect SOC stocks. This table included general site characteristics and observations on soil forming factors and soil physical properties. Density of grape vines, tree composition and state of upslope terrace walls (visual assessment of percentage of collapsed terrace walls) were added to the table (see Supplementary Information: Site Characteristics Table). In addition to on-site evaluation, the time of abandonment was estimated by the first author with the aerial photos of 1963 and 1993 (DLS, 2019). The geological unit of the sampling location was obtained from the geological map of Cyprus (Fig. 2). Slope length was measured on-site from the sampling location to upstream drainage lines (roads, drainage channels or structures) and for sites without obvious drainage lines the slope length was obtained by drawing a transect from the sampling location to the drainage divide identified on Google Earth.

2.3.3. Soil sampling procedure

Soil sampling locations in the 24 paired-sites were based on LUCAS field sampling (2013) and sampling depths and quantities were based on Cools and De Vos (2010). First, the center of the productive vineyard was located. The center of the neighboring abandoned site was taken at the same elevation as that of the productive site. Secondly, four locations with 2-m distance from the center point were marked to form a cross, thus creating a total of five subsample locations per site. The subsample locations were at least one meter away from tree stems and disturbances. Soil depth was measured at all five locations by hammering an 80-cm metal rod with a diameter of 16 mm into the soil as deep as possible. These values are referred to as “measured depth”.

Disturbed soil subsamples were collected from each location along the entire depths of 0–10 cm, 10–20 cm, 20–40 cm, 40–80 cm with a hand-auger (Eijkelkamp, Holland), between May and June 2018. However, when augering was made impossible by rocks or bedrock, the soil was sampled up to the depth of the limiting horizon. This depth was noted as “sampled depth”. A percussion drilling set (Eijkelkamp, Holland) with a gasoline powered percussion hammer (Cobra TT) was used in May 2019 for the sites where the average measured soil depth, as determined with the metal rod for both sites of the pair, was more than 60 cm and where no samples below 40 cm depth could be collected with a hand-auger (five paired-sites). The profiles taken by the drill showed the presence of rocks below 40 cm and weathered bedrock below 60 cm depth.

Subsamples (around 100 g) from the five point locations were mixed for obtaining one composite sample for each depth increment per site, resulting in a minimum of 500 g composite sample per depth. For cases with a variable lower depth, the mass of each subsample was proportional to the thickness of the sampled layer. The organic layer at the soil surface was sampled separately from the underlying mineral soil. The organic layer includes: litter (OL), fragmentation horizon (OF) and/or humus (OH) and was sampled in a frame of 25 cm × 25 cm and weighted in the laboratory. A visual assessment of the volumetric fraction of rock fragments (%) and dominant size and abundance of roots was performed by extracting soil from a surface area of 20 cm × 20 cm up to a depth of 30 cm (modified from FAO, 2006).

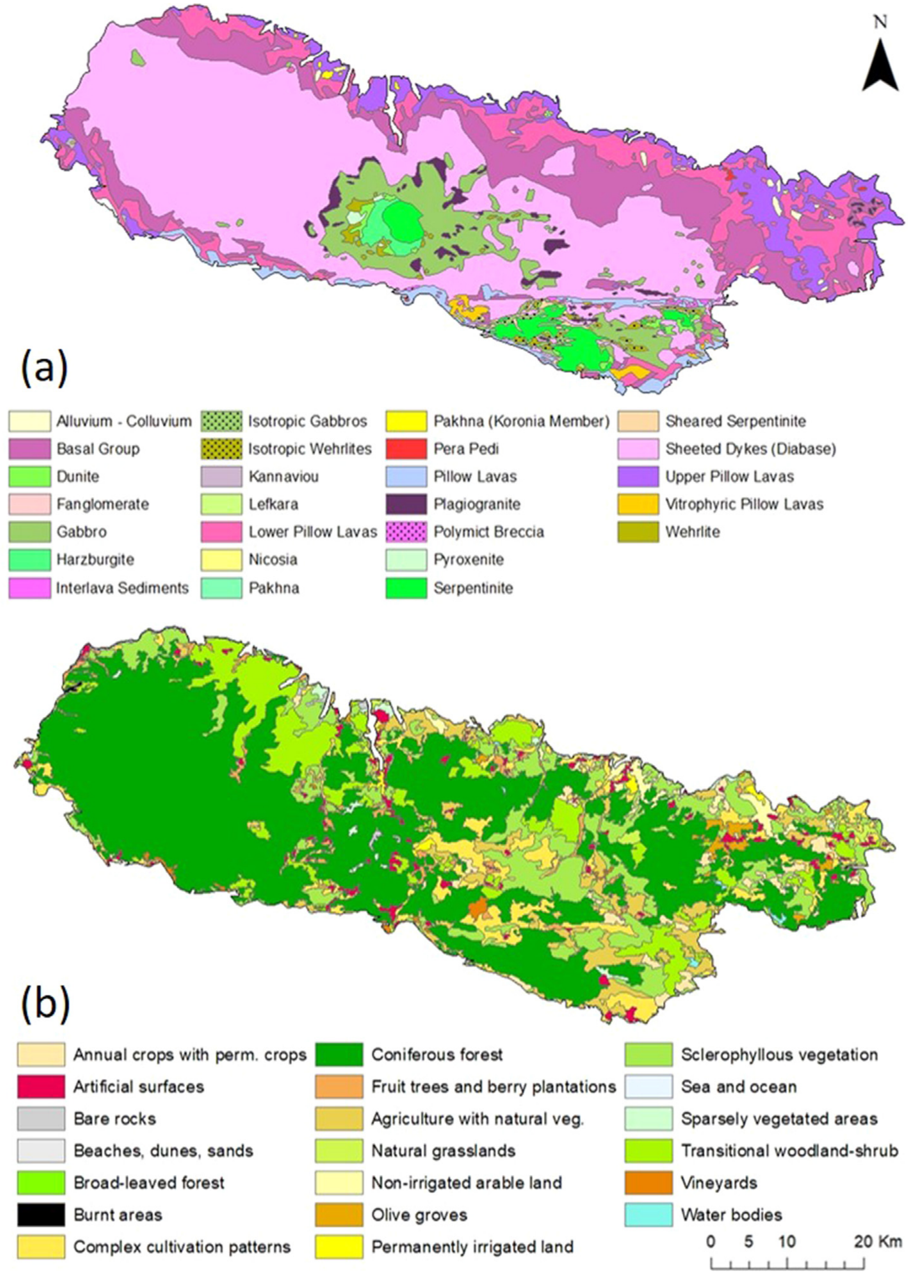

Fig. 2. Geological formations (a) (Cyprus Geological Survey Department, 1995) and land use (Büttner and Kosztra, 2007) (b) of the Troodos study area.

One set of soil bulk density samples was collected from the center point. In 18 of the 24 paired-sites, bulk density samples were taken from a subsample location with the deepest soil, as the center point had shallower soil depths. The samples were collected with a sample ring kit (Eijkelkamp) with 100-cm^3 rings from the mid-point of the four depth intervals.

2.3.4. *Laboratory analyses*

The loss-on-ignition (LOI) method, based on Kasozi et al. (2009) and Hoogsteen et al. (2015) was used for quantifying soil organic matter. Composite samples were dried at room temperature and sieved with a 2-mm sieve. Slightly more than 20 g sub-sample was taken in triplicates from the soil with particle size less than 2 mm and placed in porcelain crucibles, weighted and dried at 105 °C for 24 h. Remaining samples were stored at room temperature. The subsamples in the crucibles were placed in a furnace at 550 °C for 3 h and after the ignition they were cooled in a desiccator and weighted. The mean range of the triplicate SOC results of LOI laboratory analyses (minimum value subtracted from maximum value) was 0.1%. This laboratory measurement range did not show any relation with the depth or land use of the samples, indicating reasonable repeatability of the laboratory methodology.

To convert soil organic matter to SOC, a linear regression relation was established between results obtained with the LOI method and an elemental carbon analyzer (Fig. 4), similar to methodologies used in the literature (e.g., Westman et al., 2006; Abella and Zimmer, 2007; da Silva Dias et al., 2013). Six soil samples from different depths and sites with varying clay content (< 10% and 40–60%, hand-feel method) and soil organic matter percentages (3.7–9.4%, LOI method) were used for the linear regression, which resulted in a satisfactory coefficient of determination value (R^2 = 0.85). For the elemental carbon, the samples were analyzed with an Eltra CS-800 (Eltra, Germany) elemental analyzer at the laboratories of the Cyprus Geological Survey Department. Total carbon (TC) was measured on 2 g of an oven-dried soil by the elemental analyzer. In parallel, an additional 2 g of soil was entered in a

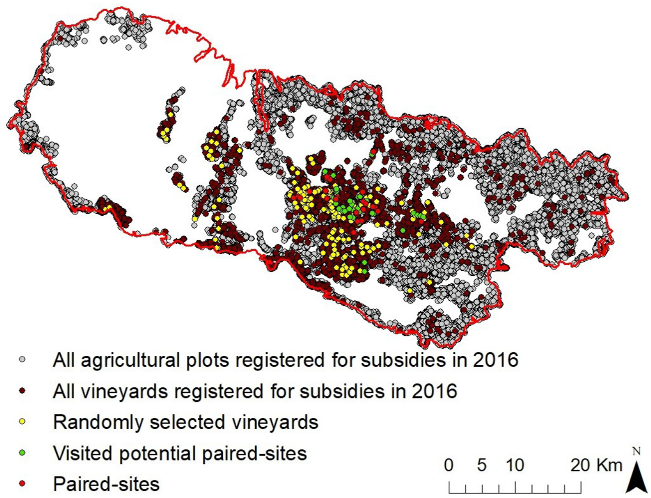

Fig. 3. Agricultural plots, vineyards and selection of paired-sites (sampling locations) in the Troodos study area.

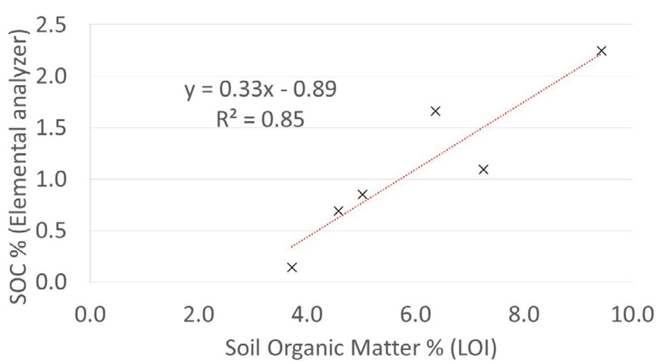

Fig. 4. Linear regression between soil organic matter obtained with loss-on-ignition (LOI) and soil organic carbon obtained with elemental carbon analyzer.

high temperature muffle furnace for the removal of Total organic carbon (TOC) and other organic debris at 500 °C for 4 h and then introduced to the CS automatic analyzer for measurement of inorganic carbon (IC). TOC was subsequently obtained by subtracting IC from TC as a modified method described by Rawlins et al. (2008) and used by Zissimos et al. (2019).

Due to the geology (Ophiolite) soil carbonate is extremely rare in Troodos mountains, pH values of the top 25 cm mainly range between 5.0 and 8.0 in diversity of land cover units (Cohen et al., 2012) and soils are dominated with coarse (> 2 mm) fragments (Camera et al., 2017). The pH measurements, presence of carbonates and texture analyses (< 2mm) were made for the entire soil depths for the first ten sites; five productive and five abandoned. At each of these 10 sites, presence of carbonates (no carbonates) and texture analyses (clay and silty clay loam) were the same for the entire soil depth. The pH value for soil depth 10–20 cm (min: 5.7, max: 7.9) deviated between 0.0 and 0.6 from the pH values of the 0–10 cm (min: 5.8, max: 7.4) and 20–40 cm depths (min: 5.6, max: 7.9) and showed no statistically significant differences (p-values: 0.5 and 0.8, respectively). Considering that these parameters do not affect the SOC related calculations, for the remaining paired-sites the pH measurements, presence of carbonates and texture analyses were made for the 10–20 cm soil depth only. The method for analyzing the pH of the soil was based on ISO 10390, described by Cools and De Vos (2010). A representative sub-sample (fraction < 2 mm) of soil was mixed with deionized water, at a ratio of 1:5 (volume fraction). The measurement was made by placing a pH electrode (HI-1611D from Hanna Instruments, United States of America) in the suspension immediately after shaking. The pH value was noted after stabilization of the value was reached.

The method for determining the presence of carbonates in the soil samples was based on ISO 10693, following Cools and De Vos (2010). Hydrochloric acid (HCl) with a concentration of 4 mol l^{-1} was diluted at a ratio of 340 ml HCl to 1000 ml deionized water. Some hydrochloric acid was added to a portion of the soil and the carbonate content of the sample was estimated on the basis of the intensity and duration of effervescence.

The soil textural class was estimated by hand-feel based on Schlichting et al. (1995), as described by Cools and De Vos (2010). Soil samples were sieved for removing the fragments > 2 mm before the hand-feel estimations.

2.3.5. Soil organic carbon stock and soil loss calculations

The SOC stock (Mg ha^{-1}) per site was calculated as (Cools and De Vos, 2010):

$$SOC\quad Stock = \sum_{j=1}^{j=n} SOC_j x FES_j \tag{1}$$

where j is the sampled soil layer number, n is the number of the deepest soil layer sampled, SOC is the soil organic carbon of the sampled layer (%) and FES is the fine earth stock of the sampled layer (Mg ha^{-1}). The FES is computed as:

$$FES_j = 10 \times BD_j \times d_j \tag{2}$$

where BD_j is the soil bulk density of sampled layer j (kg m^{-3}) and d_j is the average thickness of sampled layer j (m) (average of the five sub-sample locations). In case no bulk density sample could be taken, the value of the soil layer above the missing depth was used. For the sites where no bulk density value is available, the average value for the respective depth and land use was used.

Soil bulk density and FES calculations were based on Cools and De Vos (2010). They suggest a "combined approach" for improving the determination of bulk density and FES at locations with a high content of coarse gravel and the presence of stones and boulders. With this method, the quantity of bulk density of both fine earth and coarse fragments was sampled and estimated in the field. From this method, 3 cases were used according to the conditions (i.e. coarse fragment content and size) at each sampling site. Table 1 presents each case and the respective required parameters.

Table 1
Coarse fragment content and size per case and required parameters for fine earth stock calculations (Cools and De Vos, 2010).

Case Number	Explanation	Parameters
1	Coarse fragments (> 2 mm) < 5% content	Dry mass (kg) and volume (m^3) of the soil bulk density were obtained from the core sample
2	Coarse fragments between 2 and 20 mm and more than 5% content	Dry mass (kg) and volume (m^3) of the fine earth, and volume (m^3) of the coarse fragments were obtained from the core sample. Volume of the coarse fragments was derived by dividing the mass with density of the coarse fragments, measured by water displacement method
3	Coarse fragments > 20 mm and more than 5% content	Dry mass of coarse fragments between 2 and 20 mm were obtained from the core sample; volume of fragments > 20 mm was visually estimated on site (%)

2.4. Statistical evaluation of the results

The grouping of sampling points (objective 1) and estimation of time of abandonment (objective 1 and 2) were performed by the first author using aerial photos and his estimates were used in the results. The precision of these estimates was evaluated with an observers' agreement test. The abandonment time of the abandoned sites of the 24 pairs were visually assessed by all five co-authors using the available aerial photographs (taken in 1963, 1993 and 2008) The level of agreement between the six researchers (first author and five co-authors) was subsequently calculated with Fleiss' Kappa (Fleiss, 1971) (see Supplementary information II: Fleiss Kappa Calculations). The Kappa values range between −1 (perfect disagreement) and 1 (perfect agreement) (Landis and Koch, 1977). Kappa values were reported per time of abandonment class as an indication of the precision of the visual estimation method.

A *t*-test was used to analyze statistical significance of the differences between site characteristics, pH values and SOC values of the abandoned and productive vineyard pairs, per depth interval. The normality of the distribution of the sampled datasets was tested using the Kolmogorov–Smirnov test (Massey, 1951) and homogeneity of variances was analyzed using the Levene test (Levene, 1960). All data sets followed a normal distribution (Kolmogorov-Smirnov test p-values > 0.05) and had similar variances (Levene test p-values > 0.05). Therefore, two-sample t-tests for equal variances were used.

The SOC concentrations were analyzed by depth interval for all 24 paired sites, including sites where sampled soil layer thickness were less than the depth interval in any of the five subsampling locations. A second analysis was made for a subset of the 24 sites for which the entire depth intervals were sampled in both fields of the paired site for all five subsampling locations.

As the soil depth is an important parameter in SOC stock calculations (equation (1) and (2)), scatter plots between the soil depth and other site characteristics (slope length, slope gradient and percentage of degraded terrace walls upslope from the sampling location) were made. The Pearson's correlation coefficient (r) and the *t*-test were used to evaluate possible relations.

3. Results

3.1. Soil organic carbon in agricultural, abandoned and forest areas

The productive land includes mostly complex cultivation patterns with vineyards, fruit trees and nuts at higher elevations and some non-irrigated arable land with olive groves and cereals at lower elevations. Abandoned agricultural areas mostly include garrigue vegetation, i.e., low shrubs with a few higher shrubs and trees: *Pistacia* sp. and *Pinus brutia*. Natural vegetation areas mostly include areas with maquis vegetation, i.e., shrubs of varying heights (1–5 m) mixed with lower shrubs, herbs and isolated trees: *Juniperus phoenicea*, *Pistacia lentiscus*, *Olea europea*, *Cistus spp*., *Salvia fruticosa* and occasional *Pinus brutia* and at a higher elevation *Quercus alnifolia*, *Q. coccifera*, *Pistacia terebinthus*, *Crataegus sp*., *Arbutus andrachne*). The state forest areas are dominated by the coniferous *Pinus brutia* and *Pinus nigra* trees.

Fig. 5 shows SOC values in productive agriculture areas, in abandoned areas, in areas with natural vegetation and state forests. The highest mean SOC value was for state forest (1.7%, median: 1.4%) and the lowest was for productive agricultural land (1.0%, median: 0.9%). The mean SOC value of productive areas was similar to the mean SOC values of areas abandoned after 1993 (1.1%) and areas abandoned between 1963 and 1993 (1.2%). The level of agreement regarding the assessment of the aerial photographs indicates a low level of precision (Landis and Koch, 1977) for assigning time of abandonment for areas abandoned between 1963 and 1993 (Fleiss kappa: 0.1) and after 1993 (Fleiss kappa: 0.3) (see Section 3.2.3). If the two abandoned classes are grouped with the natural areas without agriculture since 1963 (SOC mean 1.4%, median: 1.1%), assuming that these areas could have been abandoned agricultural areas too, the mean SOC of this group (n: 187) becomes 1.3% (median: 1.1%).

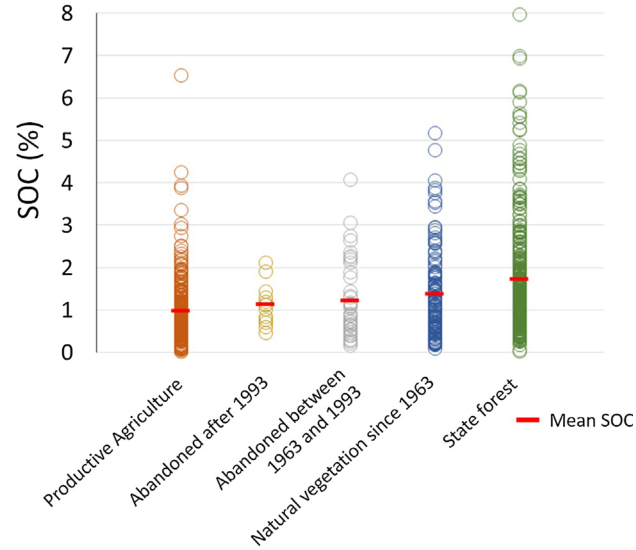

Fig. 5. SOC (%) values in top 25-cm soil in productive (n = 301) and abandoned agricultural land (n = 13 for abandonment after 1993, n = 41 for abandonment between 1963 and 1993), in areas with natural vegetation (n = 133) and in state forest (n = 368).

3.2. Soil organic carbon in terraced vineyards

3.2.1. Paired-site characteristics

The paired-sites were located on different geological formations. From the 24 paired-sites, 14 were on sheeted-dyke (diabase), 9 were on gabbro and 1 was on plagiogranite. The productive vineyards of the paired-sites had, on average, 7200 grape vines per ha (min: 1600, max: 16,000) and had no undergrowth (shallow-ploughed or cleared with herbicide application). Abandoned sites were almost entirely covered with natural vegetation (annuals and perennials). Perennial species included sumac (*Rhus coriaria*), rock-rose (*Cistus creticus*), golden oak (*Quercus alnifolia*), and pine trees (*Pinus brutia*). Abandoned sites had more roots in most of the paired-sites (13 out of 24). Fine roots (< 2 mm diameter) of the seasonal plants were more common in the abandoned sites than in the productive sites in the top 20 cm of soil. Roots of the grape vines in the productive sites and roots of perennial plants (pine, oak, and sumac) (> 5 mm) in the abandoned sites were dominant below 20 cm soil depth. An organic surface layer was present only in five paired sites. In three paired sites it was present in the abandoned site only, in one paired site it was present in the productive site and in one paired site it was present in both sites of the pair.

Table 2 summarizes the main characteristics of the paired-sites. The measured soil depth at the productive sites was greater than at the abandoned sites (p-value: 0.01). In 14 out of the 24 paired sites, the soil was deeper in the productive sites than in the abandoned sites, in seven paired sites abandoned sites had deeper soil and in three paired sites the soil depths were the same for the two land uses. The mean slope length was 66 m (min: 9 m and max: 264 m). Surface rock cover percentage did not differ between productive and abandoned sites. However, the abandoned plots had more coarse fragments in the top 30-cm soil. The soil depth was negatively correlated with slope gradient (r: −0.26) and with percentage of degraded terrace walls upslope from the sampling location (r: −0.03) and positively correlated with slope length (r: 0.23), but no correlation was statistically significant (p-values > 0.05).

Table 3 presents the soil texture and pH of the top soil for the productive and abandoned sites. The soil texture of the productive and

Table 2
Summary of main characteristics of productive (P) and abandoned (A) paired sites (n = 24).

	Elevation (a.s.l)	Slope (%)	Measured soil depth (cm)(1)		Sampled soil depth (cm)(1)		Surface rock cover (%)		Coarse fragments (%)		Degraded terrace walls (%)(2)	
			P.	A.	P.	A.	P.	A.	P.	A.	P.	A.
Mean	1183	26	70	59	45	35	46	44	34	42	51	60
Min	497	10	43	28	22	9	5	2	5	5	0	0
Max	1361	40	80	80	80	75	10	10	70	90	100	100

(1) Mean soil depths at five sub locations. At any site, the mean depth can be made up of a composite of fewer than five samples (minimum of two), if the soil was not present or could not be sampled at any of the five points. The soil depth was considered to be 80 cm for locations with soil depth > 80 cm as the measurement rod had a length of 80 cm.
(2) Percentage of degraded terrace walls upslope from the sampling location to the slope top or drainage line.

Table 3
Soil texture and average pH of productive and abandoned sites.

	Number of sites per soil texture classes (% clay content)				pH
	US, LS, SL* (< 25)	SCL, CL, SiCL* (20–40)	SC, C, SiC* (35–60)	HC* (> 60)	
Productive	2	11	10	1	6.2
Abandoned	5	8	10	1	6.4

*US: Unsorted sand, LS: Loamy sand, SL: Sandy loam, SCL: Sandy clay loam, CL: Clay loam, SiC: Silty clay loam, SC: Sandy clay, C: Clay, SiC: Silty clay, HC: Heavy clay

abandoned sites was similar and mostly had clay contents between 20% and 60%. The pH of the productive vineyards was slightly lower than the pH of the abandoned sites, but this was not significant (p-value: 0.19). None of the samples showed effervescence with the HCl application, which indicates the absence of carbonates as expected due to the geology of the Troodos study area.

3.2.2. Soil organic carbon differences in productive and abandoned sites

Fig. 6 presents mean SOC percentages per depth interval in productive and abandoned sites for the 24 sites and for the subset for which the entire depth intervals were sampled in both fields of the paired site for all five subsampling locations. The SOC concentrations of the 24 sites and those of the subset were similar up to 20-cm depth, indicating that the incomplete sampling depth intervals has little influence on the SOC outcomes. The comparison for the layers below 20-cm depth was not possible due to the lack of sites where entire depth intervals were sampled for the deeper layers.

The SOC percentages of the top 0–10 cm soil layer were significantly different (p-value < 0.05) between productive and abandoned sites, both for the set with all samples and for the subset with the samples for the entire depth, showing higher SOC values for the abandoned sites. The differences were smaller and not statistically significant (p-value > 0.05) for the deeper soil layers.

Mean bulk density values for the four depth intervals and two land uses, measured with the sample rings without correction of coarse fragments are presented in Table 4. The mean bulk density values at each depth were very similar for both productive and abandoned sites. All sites had coarse fragments (> 2mm) exceeding 5% of their soil volume. Twenty three productive sites and twenty one abandoned sites had coarse fragments greater than 20 mm (Case 3, in Table 1).

Table 5 presents mean SOC stock values with and without coarse fragment correction for productive and abandoned sites. On average, productive sites showed slightly higher stock, due to their deeper soils, than the abandoned sites but the difference was not statistically significant (p-value > 0.05). However, the SOC percentages were significantly higher (p-value < 0.05) for the abandoned sites, compared to the productive sites (Fig. 6). Average SOC stock values were 57%

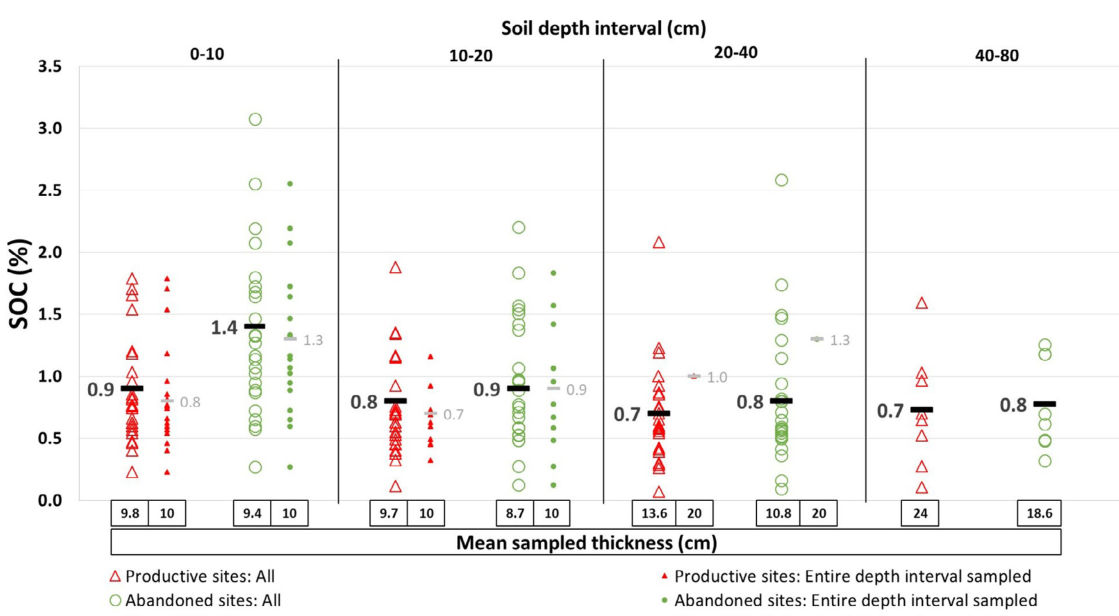

Fig. 6. SOC percentages per soil depth interval with mean sampled soil thicknesses for all productive and abandoned sites and for subsets of the sites where entire depth intervals were sampled.

Table 4
Mean bulk density values and number of samples (n) per depth in productive and abandoned sites.

Depth interval (cm)	Productive		Abandoned	
	Bulk density (kg m^{-3})	n	Bulk density (kg m^{-3})	n
0–10	1.5	19	1.5	19
10–20	1.6	15	1.5	9
20–40	1.4	7	1.5	4
40–80	1.5	2	n.a.	0

Table 5
Average total SOC stock of the 24 productive and abandoned sites with and without coarse fragment correction.

	SOC stock without coarse fragment correction (Mg ha^{-1})			SOC stock with coarse fragment correction (Mg ha^{-1})		
	Productive	Abandoned	p-value	Productive	Abandoned	p-value
Mean	50	49	0.89	22	21	0.85
Min	7	7		3	3	
Max	131	122		65	61	

lower with the coarse fragment corrections.

The use of the percussion drill resulted in greater mean sampling depths compared to the hand-augered depths, but the drill was still not able to sample the entire probe-measured depths. For the five sites where the drill was used, the mean probe-measured depth was 76 cm for the productive and 71 cm for the abandoned sites, hand-augered sampled depth was 37 cm for productive and 27 cm for the abandoned sites and drill sampled depth was 70 cm (85% of the missing depth) for productive and 55 cm (64% of the missing depth) for abandoned sites. The SOC concentrations of the drill-sampled soil from the extra depths were 0.7% for productive sites and 0.8% for the abandoned sites. For these five sites, total stock values increased, on average, from 30 Mg ha^{-1} to 43 Mg ha^{-1} for productive and 20 Mg ha^{-1} to 34 Mg ha^{-1} for abandoned sites (with coarse fragment corrections). If a similar percentage increase for the sampled-depth was assumed for the 19 none-drilled sites, an average increase of 20 cm could be expected for the productive sites (based on the missing depth of 24 cm) and an average increase of 16 cm for the abandoned sites (based on the missing depth of 25 cm). Such increase in depths would result in an average coarse-fragment corrected SOC stock value of the 24 sites of 31 Mg ha^{-1} for productive and 29 Mg ha^{-1} for abandoned sites.

3.2.3. Effects of time of abandonment on soil organic carbon

Fig. 7 presents SOC percentages of the top 10-cm soil and total SOC stock (with coarse fragment correction) in the productive and abandoned paired-sites, by time of abandonment, as classified by the first author with the aerial images. The difference in SOC percentages between the productive and abandoned sites was greater for the sites with older abandonment time (p-values for the pairwise comparison with productive sites: 0.18 for sites abandoned after 1993, 0.11 for sites abandoned between 1993 and 1963 and 0.05 for sites abandoned before 1963). However, such relation was not found for the SOC stock values, due to, on average, shallower soil depths and higher coarse fragment content of the abandoned sites, compared to the productive sites (Table 2) (p-values > 0.2).

Concerning the precision of abandonment-time estimations, the majority of the five aerial-photo assessors agreed with the first author on the abandonment time class for thirteen sites, for seven sites the majority disagreed and for four sites the six assessors were split equally. Fig. 8 shows example sets of aerial paired-site photos taken in 1963, 1993 and 2008 and field photos of paired-sites taken in 2018 for which all five assessors agreed with the first author. Fleiss kappa for the overall agreement of the 24 sites was 0.3 indicating a fair agreement. Per time category the respective values were: 0.1 for the sites abandoned between 1963 and 1993, 0.3 for the sites abandoned after 1993 and 0.5 for the sites abandoned before 1963. Thus, the assessors' agreement for categorizing sites abandoned before 1963 were higher than for the other categories. This might be due to the effect of vegetation cover, which tends to increase with prolonged abandonment, and is thus more obvious for the sites with older abandonment (before 1963) (Fig. 8: D and E).

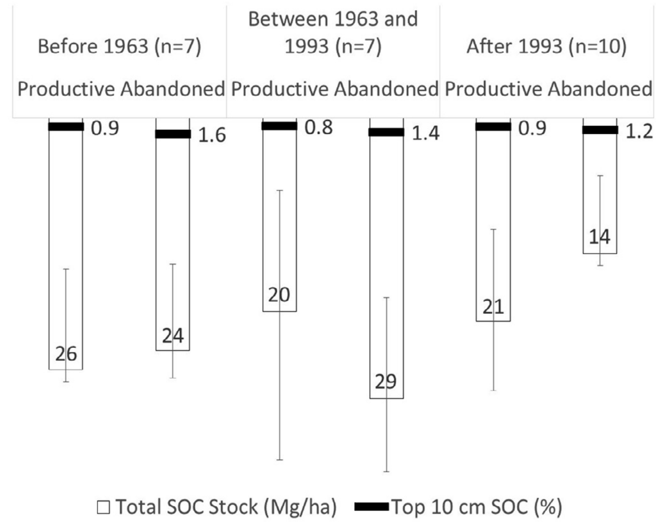

Fig. 7. Number of paired-sites (n) per time of abandonment (of the abandoned sites of the pair), with average SOC percentage of top 10-cm soil and total SOC stock, calculated up to the deepest sampled layer (the whiskers indicate the first and third quartiles).

4. Discussion

4.1. Soil organic carbon in agricultural, abandoned and forest areas

The largest difference in mean SOC percentage was between agriculturally productive land (1.0%) and the state forests (1.7%) (Fig. 5). The state forests, dominated by pine trees, are considered as climax vegetation community along the slopes of the Troodos Mountains (Tsintides and Kourtellarides, 1998). According to Ciesla (2004), garrigue and maquis vegetation in Cyprus are primarily of human origin resulting from forest destruction and after the abandonment the successional order garrigue > maquis > pine forest would be followed and eventually pine forest would be re-established. If similar successional patterns for the studied abandoned agricultural fields are considered then the SOC concentrations indicate that abandonment of agricultural plots could increase the mean SOC concentrations from 1.0% to 1.3% and after the full succession to pine forests the mean SOC could reach to 1.7%. Nevertheless, higher SOC concentrations in pine forest do not necessarily mean higher SOC stocks, as Eliades et al. (2018) measured an average soil depth of 14 cm in the *Pinus brutia* forest on the diabase formation along the northern slopes of the Troodos Mountains.

A variety of results have been presented in the literature for similar environments. Zethof et al. (2019) found, after sampling top-10 cm soil in gently sloping (around 10% slope) productive and abandoned agricultural fields with different degrees of succession and afforestation, that in a semi-arid southeastern Spain, under secondary succession on abandoned fields, soil quality can improve non-linearly and only marginally over a time of 40 years (from 1.9% SOC to 2.0% SOC). Van Hall et al. (2017) found much higher increases of SOC after 25 to 50 years of

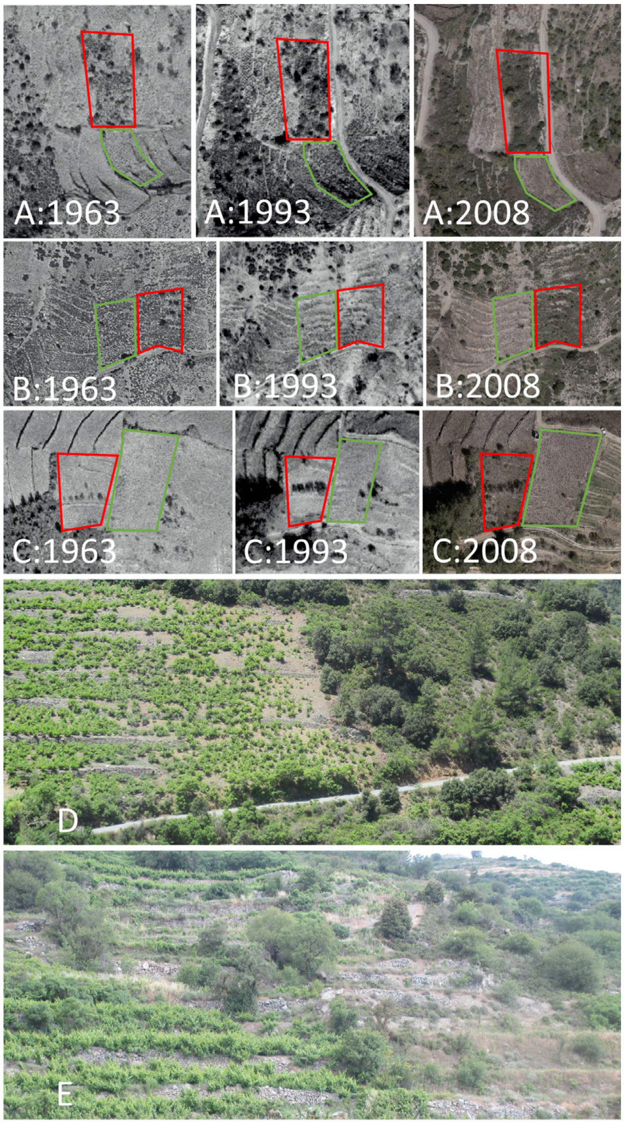

Fig. 8. Aerial photos taken in 1963, 1993 and 2008 with productive sites (green framed) and abandoned sites (red framed) (Scale 1:1128) (DLS, 2019); categorized as abandoned before 1963 (A), abandoned between 1963 and 1993 (B) and abandoned after 1993 (C). Photos D and E were taken in the field in 2018 and represent paired-sites; productive site (left) next to an abandoned site (right) categorized as abandoned before 1963 (D) and abandoned after 1993 (E). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

abandonment (from 1.6% SOC to 5.6% SOC), for the same sampling depth and similar slopes as Zethof et al. (2019), but in the humid Mediterranean country of Slovenia. De Baets et al. (2013) found that topsoil (0–10 cm) SOC concentrations were doubled (1.0% SOC compared to 1.98% SOC) for eroded areas; and slightly increased (from 1.78% SOC to 1.98% SOC) for depositional areas in the first 10–50 years after cropland abandonment in a mountainous area in southeast Spain. Alternatively, Romero-Díaz et al. (2017) showed ecosystem evolution in abandoned fields in three different regions in Spain (Valencia, Murcia and Andalucia). In particular, the vegetation recovery patterns after abandonment evolved from herbs as the dominant species the first 5 years, to dwarf shrubs (10 years), to shrubs (maquis), which were the most widespread vegetation until 50 years after abandonment, and finally a mixture of Aleppo pine and oak developed a forest after 100 years. They found that such succession increased soil organic matter concentrations from 1% to 7% for the sites in Valencia, from 1.46% to 1.63% for the sites on limestones in Murcia and from 1.66% to 3.50% for the sites on metamorphic rocks in Murcia. However, for the sites in Murcia, where erosional processes following abandonment were important for terraced areas on marls, a decrease in soil organic matter from 0.87% to 0.71% was found.

4.2. Soil organic carbon in terraced vineyards

4.2.1. Soil organic carbon concentrations

Our SOC concentrations found in in the top 10-cm soil in paired terraced vineyards (0.9% for productive and 1.4% for abandoned sites) were comparable to the concentrations reported in the literature in the Mediterranean region. In semi-arid Pantelleria Island (Italy), SOC values of the top 15-cm soil on productive terraced vineyards were reported to range between 1.0% and 2.2% in comparison to 1.7% and 2.7% for 60 to 100 year abandoned terraces (Novara et al., 2013, 2014; Badalamenti et al., 2019). In Cap de Creus Peninsula in northeast Spain, a value of 0.25% was reported for productive terraced vineyards compared to 1.8% and 3.8% for 60–100 year abandoned terraces (Emran et al., 2012; Pardini and Gispert, 2012). The above studies had fewer sampling locations than our study and none used a paired-site approach as sampling strategy. Therefore, SOC differences might be affected by other environmental factors than those affected by the abandonment.

It is remarkable that in our study the ratio of the SOC concentrations of the 25-cm top soil of the grid-based samples of abandoned (n = 187) over productive sites (n = 301) (ratios of 1.3) was similar to the ratio of SOC concentrations (20-cm top soil) of the 24 randomly selected, paired-site data (ratio of 1.4). Observing similar ratios by two different methods increases the confidence in our results.

4.2.2. Soil organic carbon stocks, effects of time of abandonment and the importance of sampling depths

Despite our findings and overall agreement in the literature that abandonment increases SOC concentrations, SOC stocks show varying results after abandonment mostly due to differences in soil depths. Mean SOC stocks in our study showed slightly higher values for productive sites (50 Mg ha^{-1} without coarse fragment correction and 22 Mg ha^{-1} with the correction) than the abandoned sites (49 Mg ha^{-1} without the coarse fragment correction and 21 Mg ha^{-1} with the correction) with a considerable variation among the sites. The observed shallower soil depths in abandoned compared to productive vineyards (mean depth difference of 23 cm) could be the result of greater erosion rates due the degradation of dry-stone terrace walls after abandonment (the percentage of degraded terrace walls upslope from the sampling location was 60% for abandoned and 51% for productive sites). The effect of terrace degradation on soil erosion was quantified by Camera et al. (2018) in a vineyard in the Troodos Mountains. These authors found found that degraded walls delivered 3.8 times more sediment than standing walls, based on 2-year observations with sediment traps located in the mid-hillslope. However, it should be noted that in terraced slopes measurement of soil depth in the middle section of the slope is not always expected to reflect the erosional processes as soil deposition could also occur as a result of intact terraces, vegetation recovery or local slope gradient (Djuma et al., 2017; Rodrigo-Comino et al., 2018; Stavi et al., 2018). This might explain the occurrence of seven out of twenty-four sites where abandoned sites had deeper soils than productive sites (mean depth difference of 9 cm). The inconsistent depth differences reflect the variability of such landscapes in our SOC stock results.

SOC stocks reported in the literature for similar environments were higher for abandoned than productive sites when the top 30-cm soil was sampled, but became similar or even lower than the productive sites when deeper soil sampling was performed (e.g., Williams et al., 2011; De Baets et al., 2013; Nadal-Romero et al., 2016). Badalamenti et al. (2019) sampled soil in Pantelleria Island (Italy) to a depth of 30 cm in a productive vineyard, in three stages of plant succession (high maquis, maquis-forest, and forest-maquis), and in an old growth forest. They concluded that along the 100 year old secondary succession, SOC stocks increased considerably from 33 Mg ha^{-1} in the vineyard to about 69 Mg ha^{-1} in old growth forest (no coarse fragment corrections applied). Similarly, Rodríguez Martín et al. (2019) sampled soil to a depth of 30 cm in agricultural fields in Majorca (Spain) and found SOC concentrations of almost 2% (two times more than our values) and a mean SOC stock value of 68 Mg ha^{-1} with the inclusion of coarse fragment correction (mean value of 20%). They further found that 11 years of abandonment increased SOC stock values by 30% in mountain terraces. SOC stock difference between abandoned and productive sites becomes less when soil deeper than 30 cm was sampled. Williams et al. (2011) sampled soil to a depth of 100 cm in wildlands and vineyards in northern California and reported 89.3 Mg ha^{-1} SOC stock for wildlands and 84.1 Mg ha^{-1} for vineyards. De Baets et al. (2013) sampled soil in southeast Spain up to the bedrock or a maximum depth of 1 m in productive and 10–50 year old abandoned cropland and made a distinction of erosional and depositional areas. They found out that erosional cropland areas showed increased SOC stock values after the abandonment from 13 Mg ha^{-1} to 25 Mg ha^{-1} with standard deviation of 4 Mg ha^{-1} and 19 Mg ha^{-1}, respectively. For depositional areas the stock values for both abandoned and productive areas were similar (around 30 Mg ha^{-1}) showing again high variability.

The lack of research on the deeper SOC stocks (> 30 cm up to the bedrock) was acknowledged by a recent review article by Lorenz et al. (2019) focusing on the suitability of the SOC stock as an indicator for monitoring land and soil degradation with regard to the Sustainable Development Goals framework. Nadal-Romero et al. (2016) also pointed out the importance of soil sampling depth and effects on SOC stock calculations in their research about SOC stock change after cropland abandonment in humid Mediterranean mountain areas. They concluded that when only the upper mineral soils (0–10 cm) were included the afforestation of abandoned land with pine forests would have significantly improved SOC stocks. However, when the whole soil profile was taken into account, the afforestation effects decreased and only small differences were observed showing even higher SOC stocks in pasturelands than in pine forest sites. Similarly, our results showed that the SOC concentrations of the top 10-cm soil increased with time of abandonment in the paired-sites. However, when the full sampled soil profiles were compared, stock values did not show significant differences between productive and abandoned sites (Fig. 7). Therefore, in such landscapes with steep slopes and agricultural terraces, land abandonment might increase the SOC concentrations with time. However, stocks are also affected by erosional and depositional processes, which might play an important role during the time after the abandonment.

5. Conclusions

This study presents information on the effects of agricultural land abandonment on SOC concentrations and stocks in an Eastern Mediterranean environment (Troodos Mountains, Cyprus). Abandoned agricultural fields (abandoned before 1963, between 1963 and 1993 and after 1993) had SOC concentrations of 1.3% in the top-25 cm soil, productive fields had 1.0% and pine forests had 1.7%. This indicates that the SOC concentrations increase after agricultural abandonment but require long time to reach the concentrations found in soils covered with climax vegetation. This supports the hypothesis that SOC (%) changes with the abandonment. Despite different SOC concentrations (%) for abandoned sites compared to productive sites, SOC stock (Mg ha^{-1}) calculations for the sampled soil profile resulted in similar mean SOC stock values for productive and abandoned terraced vineyards, disproving the hypothesis and indicating the importance of erosional and depositional processes in such landscapes. Moreover, coarse fragment correction for stock calculations is important, especially in stony mountainous environments, as it resulted in 17 to 78% reduction in SOC stocks of the vineyards. Concerning the research methodology, similar top-soil SOC ratios for abandoned over productive terraced vineyards were found for 24 paired sites (ratio: 1.4) and for 488 samples from a grid-based survey (ratio: 1.3) with different land cover types. These results also indicate that a stepwise, random selection and identification of paired sites, as used in this study for the terraced vineyards, could offer a resource-efficient approach for SOC studies. Aerial photos taken in different years helped to identify abandoned and productive agricultural areas but estimating time of abandonment based on these photos can be imprecise. Findings from this study indicate that SOC accumulation in a mountainous Mediterranean environment is a slow process and that erosion control strategies should be applied after agricultural abandonment to maintain and increase SOC stocks.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2020.104741.

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