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ORIGINAL ARTICLE

Soil organic carbon sequestration and tillage systems in the Mediterranean Basin: a data mining approach

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Abstract This study has reviewed 66 long-term experimental comparisons on Soil Organic Carbon (SOC) and tillage systems in Mediterranean arable crops (from 15 sites located in Greece, Italy, Morocco and Spain), with the aim to identify the biophysical and agronomic variables most associated with C sequestration rate. Data were organized in a dataset containing basic environmental descriptors (elevation, temperature, rainfall), information on soil tillage system (conventional, minimum, no-tillage), soil attributes (pH, particle size distribution and texture), crop rotation, fertilization, time length of the experiment, initial and final SOC stocks. The collected information were analyzed using a data mining approach including Spearman non-parametric correlations, Principal Component Analysis (PCA), hierarchical clustering and step-wise multiple regression. Tillage, crop rotation, and fertilization were the most significant factors affecting C sequestration rate. Non-parametric correlations reported negative coefficients for initial SOC stock, length of the experiment, mineral fertilization, tillage and production system. C sequestration rate increased significantly under no-tillage. Hierarchical clustering indicates that geographical proximity reflects similarity in biophysical conditions and agronomic practices. PCA outlined a positive correlation of SOC with soil depth, elevation and sites located in Spain and a negative correlation with mean air temperature, mineral fertilization, irrigation, experiment's length and sites located in Greece. C sequestration rate was positively associated with mean air temperature. Finally, a step-wise multiple regression indicated that C sequestration rate increased in sites exposed to colder climate conditions and under no-tillage.

Keywords No-tillage · Long-term experiment · Arable cropping systems · PCA · Hierarchical clustering

Introduction

Soil is the key component of the Earth System and interacts with other environmental compartments such as air and water. It regulates the hydrological and erosive processes, supports the biotic activity within the terrestrial ecosystems and influences the biological and geochemical cycles (MEA 2005). Moreover the soil system contributes with many others provisioning and supporting services to the humankind (Bennett et al. 2010; Keesstra et al. 2012; Berendse et al. 2015; Brevik et al. 2015; Decock et al. 2015; Smith et al. 2015). Ecosystem services are included in the recently

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adopted United Nations Sustainable Development Goals. The importance of soils and soil science in issues such as food security, water scarcity, climate change, biodiversity loss and health threats has been stressed largely (Keesstra et al. 2016). In addition, soil science can be used to expand investigation into a more holistic and therefore richer approach to soil research (Brevik et al. 2015).

Soil carbon sequestration is of special interest in the Mediterranean region, where rainfed cropping systems are prevalent, inputs of organic matter to soils are low and mostly rely on crop residues, while losses are high due to the joint impact of biophysical and anthropogenic factors such as intensive and non-conservative farming practices (Farina et al. 2011). The adoption of reduced or no-tillage systems, characterized by a lower soil disturbance in comparison with conventional tillage, has proved to impact positively Soil Organic Carbon (SOC) and other physical and chemical processes and functions, e.g. erosion (Novara et al. 2011; Lieskovský and Kenderessy 2014; Novara et al. 2015; García-Díaz et al. 2016), compaction (Brevik et al. 2002), ion retention, exchange and buffering capacity (Keesstra et al. 2012), water balance and retention (Cerdá et al. 2014; Walraevens et al. 2015), and aggregate stability (Six et al. 2002). Moreover, a reduced tillage intensity usually improves soil biological and biochemical processes (Laudicina et al. 2011; Balota et al. 2014; Laudicina et al. 2015). SOC varies among environments and management systems, and increases with higher precipitation levels (Burke et al. 1989), lower temperatures (Jenny 1980), and higher clay content (Nichols 1984), crop residue inputs (Franzluebbers et al. 1998), and cropping intensity (Grandy and Robertson 2007). SOC is definitely higher in sites with native vegetation compared with cultivated management (Francaviglia et al. 2014), and with no tillage compared with conventional tillage (Farina et al. 2011). Soil type and management (Muñoz-Rojas et al. 2012; Lozano-García and Parras-Alcántara 2014a), landscape (Salvati et al. 2015), and position and slope (Lozano-García and Parras-Alcántara 2014b; Parras-Alcántara et al. 2015) are additional factors shaping the local-scale spatial distribution of SOC.

Tillage management together with other recommended management practices (RMPs) in Mediterranean cropping systems were relatively poorly studied. Aguilera et al. (2013) did not address arable crops specifically, considering indeed orchards and horticulture together, organic farming, cover crops, and the use of external inputs from organic amendments. Most RMPs significantly increased SOC when compared to conventional management. Apart from Aguilera et al. (2013), meta-analyses in Europe were proposed for arable and permanent crops, grasslands, pasture and forests in France (Arrouays et al. 2002; Chenu et al. 2014), arable crops in Spain (González-Sánchez et al. 2012), and RMPs for woody crops in Mediterranean countries (Vicente–Vicente et al. 2016). Virto et al. (2012) found that the effect of carbon input differences was the only factor explaining the changes of SOC in relation to tillage types, mainly due to the variability of crop production response; unfortunately, the number of field studies in Mediterranean countries was very limited in this study. Additional global meta-analyses of different factors affecting C sequestration rates include references from West and Post (2002), Luo et al. (2010), McDaniel et al. (2014), and Poeplau and Don (2015).

Based on an extensive analysis of recent literature reporting comparisons among tillage systems in typical Mediterranean arable crops, this study proposes an exploratory analysis of latent spatial relationships between C sequestration rate and a number of agronomic, environmental and topographic indicators for 66 field comparisons in the Mediterranean Basin. The present approach may substantially improve understanding of soil C dynamics under traditional and intensive agricultural practices and will contribute to a comprehensive monitoring of soil quality, possibly informing local-scale policies of soil conservation in agricultural-specialized areas.

Materials and methods

Literature review and data selection

We reviewed published articles until July 2016 reporting comparisons among tillage systems in typical Mediterranean arable crops, both as monoculture and rotation: barley (*Hordeum vulgare* L.), corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), durum wheat (*Triticum durum* Desf.), forages, legumes, sunflower (*Helianthus annuus* L.), soybean (*Glycine max* L.). All studies considered here were carried out in areas under a Mediterranean climate type with low summer rainfall; a total of 66 comparisons from 15 studies were available from long-term field experiments in Greece (1), Italy (5), Morocco (1), and Spain (8). Sampling sites were located between 33°00′ and 43°32′ latitude N, 2-860 m a.s.l., with mean annual temperature and rainfall in the range 10.9–19.6 °C and 355–948 mm respectively. The main details of field experiments are shown in Table 1. Based on an aridity index (De Martonne 1926), sites presented the following climate regimes: arid (1), semi-arid (6), sub-humid (6), and humid (3). Data were organized in a dataset containing the main environmental parameters (altitude, temperature, rainfall), soil tillage system information (conventional, minimum and no-tillage), soil parameters (pH, particle size distribution and texture), crop type, rotation, fertilization management, length of the experiment (years), initial and final soil organic carbon stocks (SOCi and SOCf).

SOC data, expressed in Mg C ha^{-1}, have been evaluated in terms of Carbon Sequestration Rate, given by (SOCf-SOCi)/experiment's length. The increase or decrease of C sequestration is complex and site specific and is influenced by climate conditions, soil characteristics and agronomic management. So, to compare C sequestration rate, the difference in raw data given by the increase over conventional tillage (NT–CT and MT–CT) was evaluated as a measure of the effect size (González-Sánchez et al. 2012; Aguilera et al. 2013). Many studies did not report the bulk density (BD) required to calculate SOC stocks. Missing BD values were calculated with the equation proposed by Aguilera et al. (2013), modified from Howard et al. (1995) and standardized using data from Mediterranean soils:

$$\mathrm{BD}\left(\mathrm{Mg\,m^{-3}}\right) = 1.84 - 0.443 \times \log 10 \times \mathrm{SOC}\ \left(\mathrm{g\,C\,kg^{-1}\ soil}\right)$$

If soil organic matter concentration SOM was reported, SOC was calculated using the relationship (SOC = 0.58 × SOM). When only concentration data were provided, SOC stock was calculated with the equation:

$$\mathrm{SOC_{stock}}\left(\mathrm{Mg\,ha^{-1}}\right) = \mathrm{SOC}\ \left(\mathrm{g\ kg^{-1}}\right) \times \mathrm{BD}\ \left(\mathrm{Mg\,m^{-3}}\right) \times \mathrm{depth}\ (\mathrm{m}) \times 10^{-1}$$

Since the IPCC (2006) carbon accounting method estimates the change in SOC storage for the top 30 cm of a soil profile, $\mathrm{SOC_{stock}}$ was calculated for all the soil layers up to the maximum depth reported (15, 20, 30 and 40 cm).

Statistical analysis

A preliminary exploratory data analysis was performed to evaluate the significance of the different parameters on C sequestration rates with the Kruskal–Wallis test. Results were grouped by environmental and agricultural management according to Table 2, and represented by Box-Whisker plots (central point means, and 95% confidence interval). Statistical analysis was performed using Statistica 7.0 (Statsoft, Tulsa, USA).

A data mining approach incorporating Spearman non-parametric correlations, Principal Component Analysis (PCA), hierarchical clustering and step-wise multiple regression was developed using the full sample size composed of 22 quantitative variables including C sequestration rate (Table 2) measured in the 66 comparisons. The analysis' strategy is aimed at assessing the variety of local biophysical conditions (climate, soil, topography, cropping systems and agricultural practices), and identifying the most associated variables with C sequestration rate, intended as the dependent variable. Spearman non-parametric rank tests were run to assess significant pair-wise correlations ($p < 0.05$) between C sequestration rate and 21 candidate predictors. A PCA was run on the data matrix constituted by the 22 variables listed above at each of the 66 comparisons. The PCA investigated latent relationships between variables identifying biophysical factors and agronomic practices associated with high or low C sequestration rate at the field spatial scale. Relevant components were selected according to the eigenvalue extracted by the PCA: components with absolute eigenvalue >2 were extracted and analyzed. The linkage between variables and principal components were studied considering loadings $>|0.5|$. A hierarchical clustering (Euclidean distances, Ward's agglomeration rule) was run on the same data matrix to identify homogeneous groups of experimental sites based on common biophysical factors. A multiple linear regression model was finally developed to identify factors influencing C sequestration rate (dependent variable) in the 66 comparisons using 21 independent variables as predictors.

Table 1 Main details of field experiments

Citation	Country, province	Site name	Site ID	MAT °C	MAP mm	Aridity index class	Soil type (USDA texture)	Latitude, longitude, altitude m	Tillage treatments	Duration years
Álvaro-Fuentes et al. (2014)	Spain Lleida	Agramunt	ES-AGR	13.8	432	Semi-arid	loam	41°48′N, 1°07′W, 330	CT (moldboard plough 25 cm); NT	1-4-11-20
Barbera et al. (2012)	Italy Agrigento	Santo Stefano di Quisquina	IT-SSQ	19.0	481	Semi-arid	clay	37°32′N, 13°31′E, 236	CT (moldboard plough 30–35 cm); MT (chisel dual-layer tillage 40 cm, and 15 cm light tillage); NT	19
Bessam and Mrabet (2003)	Morocco Settat	Sidi El Aydi	MA-SEA	19.6	358	Arid	clay	33°00′N, 9°22′E, 230	CT (no depth reported); NT	11
Blanco-Moure et al. (2013)	Spain Aragona	Peñaflor	ES-PEN	13.3	355	Semi-arid	loam	41°44′N, 0°46′W, 259	CT (no depth reported); MT (no depth reported); NT	19–20
Blanco-Moure et al. (2013)	Spain Aragona	Lanaja	ES-LAN	13.2	433	Semi-arid	clay-loam	41°43′N, 0°21′W, 422	CT (no depth reported); NT	14
Blanco-Moure et al. (2013)	Spain Aragona	Torres de Alcanadre	ES-TDA	12.6	468	Sub-humid	sand	41°57′N, 0°05′W, 431	CT (no depth reported); NT	9
Blanco-Moure et al. (2013)	Spain Aragona	Undués de Lerda	ES-UDL	10.9	676	Humid	clay	42°33′N, 1°07′W, 860	CT (no depth reported); NT	13
Blanco-Moure et al. (2013)	Spain Aragona	Artieda	ES-ART	11.3	741	Humid	loam	42°35′N, 0°59′W, 526	CT (no depth reported); NT	21
Eleftheriadis and Turrión (2014)	Greece Kilkis	Filyria	EL-FIL	15.0	506	Sub-humid	clay	40°54′N, 22°28′E, 170	CT (deep plowing 30–40 cm); MT (plowing 20–30 cm)	25-34-72
Farina et al. (2011)	Italy Ancona	Agugliano	IT-AGU	14.4	700	Sub-humid	silty-clay	43° 32′N, 13° 22′E, 88	CT (moldboard plough 40 cm); NT	11
Hernanz et al. (2005)	Spain Madrid	Alcalá de Henares	ES-ADH	13.1	430	Semi-arid	loam	40°29′N, 3°22′W, 610	CT (moldboard plough 25 cm); MT (chisel plough 15-20 cm); NT	13
Hernanz et al. (2009)	Spain Madrid	Alcalá de Henares	ES-ADH	13.1	430	Semi-arid	loam	40°29′N, 3°22′W, 610	CT (moldboard plough 25 cm); MT (chisel plough 15–20 cm); NT	21
López-Bellido et al. (2010)	Spain Córdoba	Córdoba	ES-COR	17.5	584	Sub-humid	clay	37°46′N, 4° 31́W, 280	CT (moldboard plough 25–30 cm); NT	21
López-Fando and Pardo (2009)	Spain Toledo	Santa Olalla	ES-SOL	14.5	400	Semi-arid	sandy-loam, sandy-clay-loam	40°3′N, 4°26′W, 461	CT (moldboard plough 25–30 cm); MT (chisel plough 18–22 cm); NT	6
López-Fando and Pardo (2011)	Spain Toledo	Santa Olalla	ES-SOL	14.9	428	Semi-arid	sandy-loam	40°3′N, 4°26′W, 450	CT (moldboard plough 25–30 cm); MT (chisel plough 18–22 cm); NT	17

Table 1 continued

Citation	Country, province	Site name	Site ID	MAT °C	MAP mm	Aridity index class	Soil type (USDA texture)	Latitude, longitude, altitude m	Tillage treatments	Duration years
Mazzoncini et al. (2011)	Italy Pisa	San Piero a Grado	IT-SPG	15.0	900	Humid	loam	43°40′N, 10°19′E, 1	CT (moldboard plough 30–35 cm); NT	15
Mazzoncini et al. (2016)	Italy Pisa	San Piero a Grado	IT-SPG	14.5	948	Humid	loam	43°40′N, 10°19′E, 1	CT (moldboard plough 30–35 cm); NT	28
Sombrero and de Benito (2010)	Spain Castille-Leon	Burgos	ES-BUR	11.2	448	Sub-humid	silty-clay-loam	42°13′17″N, 4°22′45″W, 785	CT (moldboard plough 25–30 cm); MT (chisel plough 10 cm); NT	11
Troccoli et al. (2015)	Italy Foggia	Foggia	IT-FOG	15.8	534	Sub-humid	loam	41° 27′ 59″N, 15° 30′ 21″E, 79	CT(moldboard plough 40 cm); NT	14

MAT mean annual temperature, *MAP* mean annual precipitation, USDA texture according to Soil Survey Staff (2011), *CT* conventional tillage, *MT* minimum tillage, *NT* no-tillage

Predictors were included in the model when the *p*-level associated to the respective Fisher–Snedecor test was below 0.01. Results of the regression model were illustrated using standardized coefficients and tests of significance for each variable (an overall Fisher–Snedecor's F-statistic testing for the null-hypothesis of non-significant model and a Student's t-statistic testing for the null hypothesis of non-significant regression coefficient). A Durbin–Watson statistic testing for the null hypothesis of serially uncorrelated errors was applied separately to regression residuals.

Results and discussion

C sequestration rate (Fig. 1) was influenced significantly by the different tillage systems ($p = 0.003$), crop rotation ($p = 0.05$), and fertilization type ($p = 0.02$). Average values for conventional tillage CT, no-tillage NT and minimum tillage MT were respectively −0.17, 0.30 and −0.12 Mg C ha^{-1} $year^{-1}$. The negative value found for MT indicates that this type of tillage in some sites induced a high soil disturbance associated to the deep tillage depth (up to 30 cm, as in Eleftheriadis and Turrión 2014, Table 1), so that in the present dataset, MT was similar to CT as average. As a consequence, to avoid SOC depletion MT depth should be limited to 10–15 cm as a maximum (see Hernanz et al. 2009; Sombrero and de Benito 2010, Table 1). The average differences between C sequestration rates were 0.47 and 0.05 Mg C ha^{-1} $year^{-1}$ for NT–CT and MT–CT respectively. The lower C sequestration rate observed under CT may be associated to the higher soil organic matter mineralization than under NT. As a consequence C sequestration rate under NT can be higher even with lower yield and crop residue production. No-till can perform best under rainfed conditions in dry climates (Pittelkow et al. 2015), or in temperate climates when rainfall is a limiting factor during the grain filling period, matching conventional tillage yields on average (Mazzoncini et al. 2008).

Luo et al. (2010) found that conversion from tillage to no-tillage resulted in significant topsoil SOC enrichment, but did not increase the total SOC stock in the whole soil profile. A difference in the distribution of SOC, with higher concentrations near the surface in conservation tillage and higher concentrations in deeper layers under conventional tillage was shown also by Baker et al. (2007).

Table 2 Site, environmental, crop management and soil variables considered in the statistical analysis*

Variable	Unit
Site	
Greece	Yes/No (1/0)
Italy	Yes/No (1/0)
Spain	Yes/No (1/0)
Environment	
Elevation	m
Rainfall	mm
Temperature	°C
Agricultural management	
Productive system	Yes/No (1/0; Conventional: 1; Conservative: 0)
Tillage_1	Yes/No (1/0; NT: 1; CT:0)
Tillage_2	Yes/No (1/0; CT: 1; MT-NT: 0)
Rotation_1	Yes/No (1/0; Monoculture:1; Other: 0)
Rotation_2	Yes/No (1/0; two-years:1; Other: 0)
Fertilization_1	Yes/No (1/0; Mineral + other: 1; Other: 0)
Fertilization_2	Yes/No (1/0; Mineral: 1; Other: 0)
Irrigation	Yes/No (1/0)
Duration	Years
Soil	
Sampling depth	cm
Sand	%
Clay	%
Ph	0–14
SOC_i	Mg C ha^{-1}
SOC_f	Mg C ha^{-1}
C sequestration rate	Mg C ha^{-1} $year^{-1}$

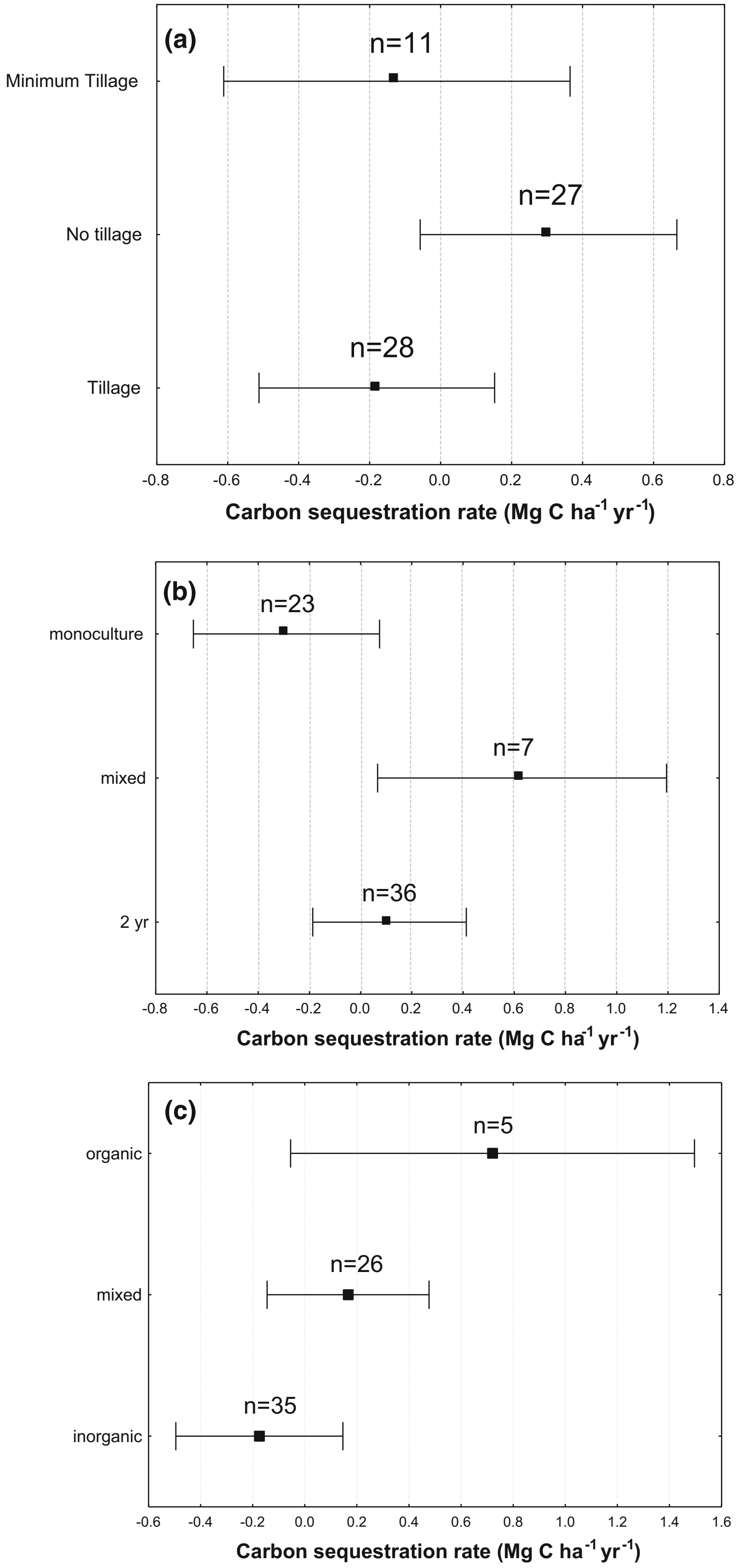
* Source: see Table 1

Crop rotation effect on C sequestration rate was weakly significant being negatively affected by monoculture (–0.28 Mg C ha^{-1} $year^{-1}$), and positively by 2-year and mixed (i.e. >2-year) crop rotations (0.11 and 0.63 Mg C ha^{-1} $year^{-1}$ respectively). The high value of mixed crop rotation was probably due to the limited number of comparisons available ($n = 7$). As average, NT–CT and MT–CT differences in Mg C ha^{-1} $year^{-1}$ were 0.48 and 0.02 with monoculture, 0.38 and 0.04 with 2-year rotations, and 0.72 and 1.06 in mixed rotations (>2-year).

The average effect of fertilization type was negative under mineral fertilization (−0.17 Mg C ha^{-1} $year^{-1}$), positive with the application of mixed fertilization (mineral + crop residues, or mineral + cover crop adoption) and organic fertilization with external inputs (0.17 and 0.72 Mg C ha^{-1} $year^{-1}$ respectively). As average, NT–CT and MT–CT differences in Mg C ha^{-1} $year^{-1}$ were 0.73 and 0.23 with mineral fertilization, −0.11 and −0.16 with mixed fertilization, and 0.80 with organic fertilization (NT–CT). The negative values observed in NT and MT with mixed fertilization may be related firstly to the presence of bare-fallow in rotation with cereals (see Blanco-Moure et al. 2013) in four sites (−0.88 Mg C ha^{-1} $year^{-1}$ as average), and secondly to the recent land use change from the native vegetation in one site of the same study (−3.18 Mg C ha^{-1} $year^{-1}$). This finding is supported by Gregory et al. (2016) showing that the land use change from native vegetation to arable crops and bare fallow may result in a SOC loss by 65–78% in the topsoil.

Climate effect on the increase of C sequestration rate when CT is converted to NT was higher in sub-humid and humid conditions (0.49 Mg C ha^{-1} $year^{-1}$) and lower in semi-arid and arid climates

Fig. 1 Carbon sequestration rate grouped by **a** tillage system ($p = 0.003$), **b** crop rotation ($p = 0.05$), and **c** fertilization type ($p = 0.02$)



(0.39 Mg C ha^{-1} year^{-1}). These results are in agreement with some literature reviews. Six et al. (2004) reported SOC sequestration rates under humid and dry climates of 0.22 and 0.10 Mg C ha^{-1} year^{-1}, respectively. Franzluebbers (2010), showed a lower C sequestration rate for NT in drier climate in Texas (0.36 Mg C ha^{-1} year^{-1}) than in the wetter climates in Alabama or Georgia (0.62 Mg C ha^{-1} year^{-1} as average). No significant differences in CO_2 emissions and SOC changes between untilled and tilled soils were found in arid and humid climates, but with slightly greater differences in arid conditions (Abdalla et al. 2016).

Concerning data mining, non-parametric correlations between C sequestration rate and selected independent variables were illustrated in Fig. 2. Negative coefficients were reported for soil organic C content at the beginning of the study period (SOCi), number of survey years, mineral fertilization, tillage (CT), production system, and a dummy variable indicating Greek experimental sites. C sequestration rate increased significantly in sites where no tillage (NT) was adopted, and in Spanish sites. The PCA extracted four components explaining 61.8% of total variance (Table 3). Component 1 (22.8%) was negatively associated to soil organic C at the end of the study period and to soil depth, elevation and geographical location of experimental sites in Spain. Positive loadings to component 1 were attributed to mean air temperature, mineral fertilization, irrigation, number of survey years and geographical location in Greece. C sequestration rate received a negative loading to component 2 (14.8%) together with mean air temperature. By contrast, soil organic C at the beginning of the study period received a positive loading to that component. Component 3 (13.2%) was positively associated with annual rainfall, mixed fertilization, soil pH and soil organic C at the end of the study period, showing a negative loading with sandy soils. Component 4 (11.0%) was positively correlated to both conservative production system and CT tillage. Hierarchical clustering (Fig. 3) clearly identified the spatial location of the experimental sites considered in this study on the base of biophysical attributes and selected agronomic practices observed at the local scale. Sites in the same area clustered together. The analysis identified four homogeneous groups of sites with specific biophysical attributes, agronomic practices and responses in terms of C sequestration rate. The first group of comparisons is located in Northern-central Spain (ES: ART, BUR,

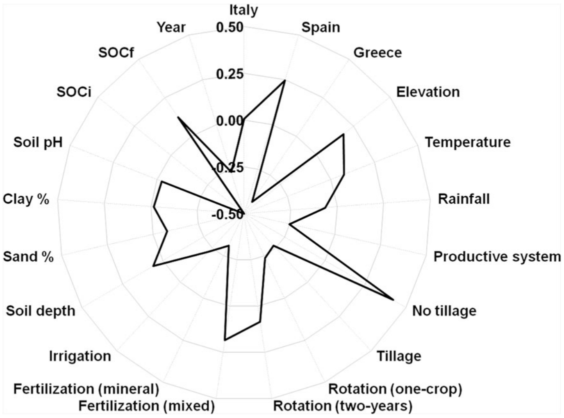


Fig. 2 Spearman pair-wise correlation coefficients (r_s) between C sequestration rate and contextual variables collected in the reviewed study sites (significant coefficients at $p < 0.05$ are above $r_s = |0.25|$)

Table 3 Principal Component Analysis: loadings >|0.5|*

Variable	PC 1	PC 2	PC 3	PC 4
C sequestration rate		−0.74		
Elevation	−0.60			
Temperature	0.56	−0.65		
Rainfall			0.67	
Cropping system				0.81
Tillage_1				−0.62
Tillage_2				0.82
Rotation_1				
Rotation_2				
Fertilization_1			0.60	
Fertilization_2	0.50			
Irrigation	0.58			
Depth	−0.87			
Sand			−0.61	
Clay				
Ph			0.61	
SOC_i		0.76		
SOC_f	−0.64		0.58	
Year	0.57			
Spain	−0.84			
Greece	0.68			
Explained variance %	22.80	14.80	13.20	11.00

* See Table 2

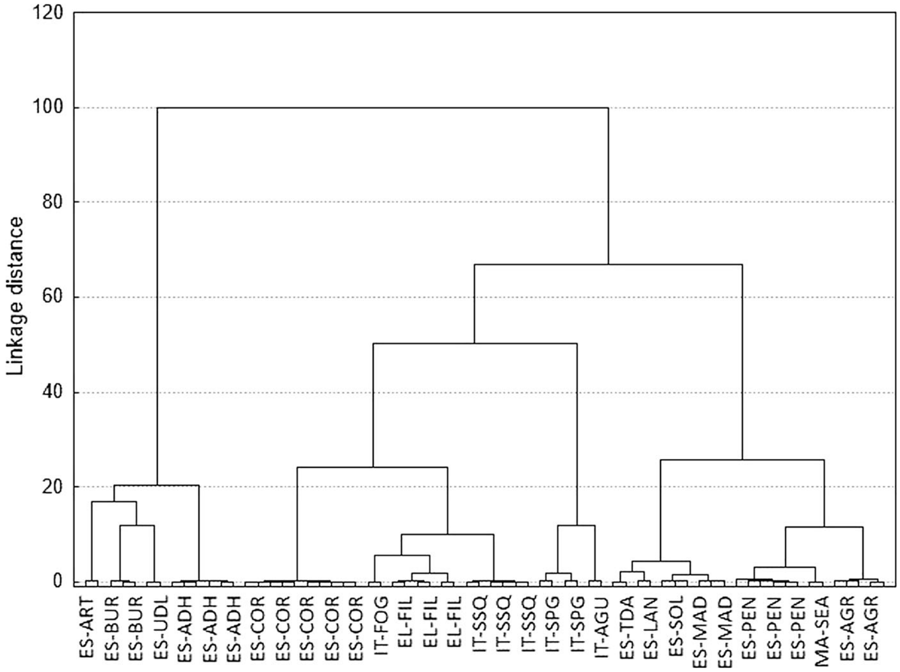


Fig. 3 Hierarchical clustering (Euclidean distances, Ward's method) of the investigated experimental sites

Table 4 Results of stepwise multiple regression (adj-$R^2 = 0.902$, $F_{6,59} = 101.15$, $p < 0.0000$) between C sequestration rate and independent predictors (see list in Table 2)

Variable	B	SE	t_{59}	*p*-level
Intercept	0.00	0.038	0.00	1.000
SOCi	−1.33	0.065	−20.42	0.000
SOCf	0.50	0.065	7.66	0.000
Temperature	−0.21	0.047	−4.44	0.000
pH	0.17	0.043	3.87	0.000
Tillage_1	0.11	0.042	2.58	0.012
Year	0.16	0.049	3.24	0.002

UDL, ADH), the second in the South of Spain, Italy and Greece (ES: COR; IT: FOG, SSQ; EL: FIL), the third uniquely in Central Italy (IT: SPG, AGU), the fourth in Spain and Morocco (ES: TDA, LAN, SOL, MAD, PEN, AGR; MA: SEA).

Results of a step-wise multiple regression with C sequestration rate as the dependent variable and the biophysical/agronomic indicators as predictors are illustrated in Table 4. The best regression model incorporates six predictors (SOCi, SOCf, Temp, pH, Tillage) with adjusted $R^2 = 0.90$ and a significant Fisher–Snedecor F test. The model's outcomes are in agreement with the findings collected from the non-parametric Spearman analysis (see above). C sequestration rate increased especially in sites with colder climate conditions and under no-tillage. Soil pH and experiment's length are additional factors influencing C sequestration rate.

Our evidences are in partial agreement with the scientific literature. Aguilera et al. (2013) compared the RMPs with the conventional management, but did not discriminate between arable and woody crops. In detail, NT ($n = 33$) and reduced tillage ($n = 17$) showed an increase in C sequestration rate of 0.44 and 0.32 Mg C ha^{-1} $year^{-1}$, respectively. González-Sánchez et al. (2012) found increased C sequestration rates of 0.29 Mg C ha^{-1} $year^{-1}$ under NT and 0.43 Mg C ha^{-1} $year^{-1}$ under MT in maritime Mediterranean areas of Spain. Increase of SOC storage induced worldwide by NT implementation was 0.57 ± 0.14 Mg C ha^{-1} $year^{-1}$ (West and Post 2002), and in France 0.20 ± 0.13 Mg C ha^{-1} $year^{-1}$ (Arrouays et al. 2002). The potential rates of SOC sequestration by conservation tillage under European temperate climates were 0.5–1.0 and 0.25–0.5 Mg C ha^{-1} $year^{-1}$ in humid and dry climates respectively (Lal 2008). The application of organic amendments increased C sequestration rate by 1.31 Mg C ha^{-1} $year^{-1}$ and with cover crops by 0.27 Mg C ha^{-1} $year^{-1}$ (Aguilera et al. 2013). Crop rotations and cover crops in temperate Europe showed SOC sequestration rates equal to 0.2–0.5 and 0.1–0.2 Mg C ha^{-1} $year^{-1}$ in humid and dry climates respectively (Lal 2008). In Spain, González-Sánchez et al. (2012) found C sequestration rates of 1.59 Mg C ha^{-1} $year^{-1}$ with the adoption of cover crops, while in Italy Mazzoncini et al. (2011) found an average increase of 0.25 Mg C ha^{-1} $year^{-1}$. In a worldwide meta-analysis, Poeplau and Don (2015) found that cover crops had a significant influence on the SOC stock change with a mean annual C sequestration rate of 0.32 ± 0.08 Mg ha^{-1} $year^{-1}$. Luo et al. (2010) showed that neither mean annual temperature and rainfall nor nitrogen fertilization and duration of adopting NT affected the response of soil C stock after the conversion from CT, but only the C distribution in the soil profile was changed. Virto et al. (2012) found no effect of soil texture, mean annual temperature and rainfall, and aridity index on C sequestration rates, but showed that C input differences can explain 30% of the variability of SOC stocks differences under NT and CT management; they found also a C sequestration rate comparable with the data from West and Post (2002). McDaniel et al. (2014) studied the effect of crop rotations and cover crops on soil C concentrations with a worldwide meta-analysis. They found that the number of crops in the rotations increased soil C by 1.9 to 7.5%, and with the inclusion of a cover crop the increase was 7.8%. Both mean annual temperature and rainfall were positively correlated with soil C at $p = 0.045$ and $p = 0.008$ respectively. Ogle et al. (2005) studied the change in SOC storage in terms of response ratios (RR; given by the ratio of SOC in MT or NT relative to CT). Grouping the studies by climate regime (temperate moist, temperate dry, tropical moist, and tropical dry), they found RR values of 1.09, 1.03, 1.16 and 1.10 respectively in MT treatments, 1.16, 1.10, 1.23 and 1.17 respectively in NT treatments, showing that in temperate dry climates the effect of MT and NT on SOC storage is lower.

Conclusions

The assessment framework proposed in the present study was suitable to evaluate the multifaceted characteristics of soils under different environmental conditions and agronomic practices in Mediterranean landscapes. The intimate relationship between topography, climate, soil C and agronomic practices has been explored using a data mining approach integrating different multivariate statistical techniques. Conservation policies of soils with different quality and C sequestration efficiency may benefit from comprehensive metadata analyses. Reduced soil tillage, improved management of crop residues and application of agro-industry by-products, proved to be the most suitable interventions to enhance organic C stocks in Mediterranean agricultural soils. The adoption of the proposed agricultural practices are part of the “4 per 1000” initiative to reach a 4‰ annual growth rate of the soil carbon stock (http://4p1000.org) and must be encouraged by implementing training and outreach programs for farmers and agricultural development advisers, and supported by:

- study of the mechanisms and assessment of the potential for carbon storage in soils across regions and systems;
- evaluation of the performance offered by beneficial farming practices and their consequences for CO_2 sequestration and other regulation and production services;
- facilitating communication between scientists and the stakeholders in agricultural policies and international development.

Future studies are required to better link knowledge from a larger set of contextual variables associated with differential levels of C sequestration efficiency with a comparative analysis of landscapes experiencing anthropogenic and natural disturbances, considering e.g. various processes of land and soil degradation at wide geographical scales.

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