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ORIGINAL ARTICLE

Assessing "4 per 1000" soil organic carbon storage rates under Mediterranean climate: a comprehensive data analysis

Rosa Francaviglia[1] · **Claudia Di Bene**[1] · **Roberta Farina**[1] · **Luca Salvati**[2] ·
José Luis Vicente-Vicente[3]

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Abstract

Soil Organic Carbon (SOC) is considered a proxy of soil health, contributing to food production, mitigation, and adaptation to climate change and other ecosystem services. Implementing Recommended Management Practices (RMPs) may increase SOC stocks, contributing to achieve the United Nations Framework Convention on Climate Change 21st Conference of the Parties agreements reached in Paris, France. In this framework, the "4 per 1000" initiative invites partners implementing practical actions to reach a SOC stock annual growth of 4‰. For the first time, we assessed the achievement of 4‰ objective in Mediterranean agricultural soils, aiming at (i) analyzing a representative data collection assessing edaphoclimatic variables and SOC stocks from field experiments under different managements in arable and woody crops, (ii) providing evidence on SOC storage potential, (iii) identifying the biophysical and management variables associated with SOC storage, and (iv) recommending a set of mitigation strategies for global change. Average storage rates amounted to 15 and 80 Mg C ha^{-1} $year^{-1}$ × 1000 in arable and woody crops, respectively. Results show that application of organic amendments led to significantly higher SOC storage rates than conventional management, with average values about 1.5 times higher in woody than in arable crops (93 vs. 63 Mg C ha^{-1} $year^{-1}$ × 1000). Results were influenced by the initial SOC content, experiment duration, soil texture, and climate regime. The relatively lower levels of SOC in Mediterranean soils, and the high surface covered by woody crops, may reflect the high potential of these regions to achieving significant increases in SOC storage at the global scale.

Keywords 4 per 1000 initiative · Carbon sequestration · Carbon storage · Climate change mitigation · Cropping systems · Mediterranean climate

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✉ Rosa Francaviglia
rosa.francaviglia@crea.gov.it

1 Introduction

Carbon (C) sequestration is the fixation and storage of carbon dioxide (CO_2) from the atmosphere to a soil unit in the form of biotic (e.g., plants and plant residues) and Soil Organic Carbon (SOC) pools (Olson et al. 2014; Chenu et al. 2018). C storage is the rate of SOC stocks increase over time, and in some cases does not imply a removal of CO_2 from the atmosphere but rather a transfer of C from one pool to another in the biosphere, as in the case of manure and other exogenous organic material addition (Powlson et al. 2011; Corbeels et al. 2018). Anyhow, the two terms are often used as synonymous (Chenu et al. 2018).

C storage in agricultural soils can potentially contribute to climate change mitigation, provided that global measures to limit the increasing atmospheric CO_2 concentrations deriving from fossil fuel consumption and land use change are implemented (FAO 2017a, b). Moreover, it is widely accepted that a sound management of agricultural soils through improved crop rotations, managing crop residues, application of organic amendments, and reduced or no-tillage practices leads to multiple benefits on SOC storage, crop yields, runoff, water erosion, water quality, biodiversity, and mitigating the effects of extreme climatic events (Lal 2010; Stout et al. 2016).

Earlier studies estimate SOC stock as about 1550 Gt C (1 Gt = 10^{15} g) to 1-m depth in natural soils (Lal 2008), in comparison with 4130 Gt C in fossil fuels, 560 Gt C in vegetation, and 760 Gt of CO_2-C in atmosphere. Therefore, changes in SOC stock can have profound implications for climate change (Smith et al. 2008).

The Intergovernmental Panel on Climate Change (IPCC) has provided the guidelines for measuring and reporting national SOC stock and greenhouse gas (GHG) inventories (IPCC 2006). Calculation approaches for reporting SOC changes are increasingly more accurate and complex: Tier 1, the simplest to be used, based on equations and default parameter values to calculate the changes in SOC stocks over a finite period of time (commonly 20 years); Tier 2, similar to Tier 1 but based on country- or region-specific data; Tier 3 based on higher order methods and resolutions, that include models and inventory measurement systems, repeated over time, possibly disaggregated at the sub-national level.

Recently, the Food and Agriculture Organization of the United Nations (FAO) organized the Global Symposium on Soil Organic Carbon (GSOC17), held at FAO headquarters in Rome (Italy), and attended by representatives of FAO member states, organizing institutions, the private sector and civil society, as well as scientists and practitioners. Participants worked together for the common goal of appropriate SOC management as part of overall sustainable soil management within the climate change mitigation and adaptation, sustainable development, Land Degradation Neutrality (LDN), and food security agendas (FAO 2017c). The final recommendations aimed at supporting the development of policies and actions to encourage the implementation of soil and land management strategies that foster the protection, sequestration, measurement, mapping, monitoring, and reporting of SOC. Although IPCC Tier 1 reference values are still used in many countries, it was recommended to develop national reference SOC stock values to move to Tier 2. Anyhow, many countries will need capacity development and training to support such activities, as well as adequate data management capacities and facilities.

However, monitoring or mapping SOC can be challenging, due to the complexity of the SOC dynamics. In fact, SOC stocks decrease significantly (and often rapidly) in response to (i) changes in land cover and land use (e.g., deforestation, intensification of farmland systems, conversion of permanent crops and pasture to arable crops, urban expansion) and (ii) unsustainable agricultural practices, such as deep tillage, excessive use of agrochemicals, reduced addition of external organic C, and removal of crop residues (Chenu et al. 2018). Even soil carbon pools in deep soil layers, previously considered resilient to degradation, have demonstrated to be highly vulnerable to environmental or anthropogenic changes, contributing to net CO_2 land-atmosphere exchange. Mathieu et al. (2015) and Bernal et al. (2016) have documented the role of temperature, climate aridity, soil properties, and cultivation patterns in shaping rates of organic matter turnover in topsoil, while deep soil carbon was more affected by soil type than by climate regime.

SOC stocks may also be positively affected by afforestation, retention of crop residues, direct addition of external organic C, other land management activities (e.g., minimum or zero tillage), and land uses (e.g., perennial pastures, natural revegetation of abandoned agricultural land) that decrease the breakdown of soil organic matter (Minasny et al. 2017). The incorporation of crop residues, such as cereal straw or cover crops, is an important measure to maintain or increase SOC stocks, especially in rainfed cropping systems (Lugato et al. 2014). Similarly to crop residues, external organic C applied to soils (e.g., organic manure, compost, digestate, black carbon, or biochar) will be subjected both to degradation, with CO_2 release by heterotrophic respiration, and humification processes (Kuzyakov et al. 2000; Diacono and Montemurro 2010).

Climate change is expected to have relevant impacts on SOC dynamics. Rising atmospheric CO_2 concentration could increase biomass production and crop residues returned to soils. However, increasing temperatures could reduce SOC by accelerating microbial decomposition. In this regard, the 4 per 1000 initiative “Soils for Food Security and Climate” launched by French Government in 2015 during the United Nations Framework Convention on Climate Change 21st Conference of the Parties in Paris (http://4p1000.org/) is a voluntary action plan aimed at supporting states and non-governmental stakeholders in their efforts towards a better management of SOC in agricultural soils, and to reach a 4‰ annual growth rate of SOC stocks in the top 40 cm of soils (0.4% per year) as a compensation for the global emissions of greenhouse gases (GHGs) by anthropogenic sources and limiting global warming to 2 °C (Minasny et al. 2017; Baveye et al. 2018). With this aim, considering that the annual GHG emissions from fossil fuel combustion for 2004–2013 are 8.9 Gt C (Le Quéré et al. 2015) and with a global estimate of soil C stock to 2 m of soil depth of 2400 Gt (Batjes 2014), the ratio between emission target and SOC stock (8.9/2400) would be 0.4% or 4‰ (4 per 1000).

The initiative aims to demonstrate that agriculture can provide opportunities for climate change mitigation, while ensuring food security with farming methods that match local conditions (e.g., agroecology, agroforestry, conservation agriculture). The initiative is part of the framework of the Lima-Paris Action Agenda (LPAA) and is linked with multiple Sustainable Development Goals (SDGs) adopted by the United Nations in 2015, particularly with Target 2.4 (improving land and soil quality), Target 15.3 (achieving a land degradation neutral world), and Goal 13 “Climate action” to combat climate change and its impacts, providing C storage and GHG regulation (Lal 2016) and soil functioning as C pool (European Commission 2006).

Mediterranean climate occurs in five regions of the world: the Mediterranean Basin, the Cape Region of South Africa, Southwestern and South Australia, California, and Central Chile, mainly at latitudes between 35° and 42°. The climate is mild or moderately cold, with humid winters and warm dry summers (Cowling et al. 2005); thus, average soil temperatures are higher than in colder climates, with an expected negative impact on SOC content. A relatively vast set of empirical studies across the world assessed SOC storage rates, but evidence for the Mediterranean climate is quite limited. Recommended Management Practices (RMPs) for increasing SOC in Mediterranean cropping systems were widely studied by Aguilera et al. (2013), and particularly in woody crops by Vicente-Vicente et al. (2016, 2017). The effect of soil tillage on SOC storage was studied with a meta-analysis on global data by Luo et al. (2010), as a function of carbon inputs from crops by Virto et al. (2012), and with a data mining approach by Francaviglia et al. (2017) addressing specific issues relative to the Mediterranean basin. Arable and permanent crops, grasslands, pasture, and forests were studied at national level in France (Arrouays et al. 2002; Chenu et al. 2014; Chen et al. 2018b), and arable crops under conservation agriculture in Spain under maritime and continental climates (González-Sánchez et al. 2012). General reviews on different factors affecting SOC storage rates include tillage and crop rotations (West and Post 2002), crop rotation diversification (McDaniel et al. 2014), and cover crops (Poeplau and Don 2015).

Thus, the combined effects of land use and soil/crop management on SOC storage are a research priority, and the choice of improved agricultural practices should be supported by field research demonstrating the contribution of different management systems to increase soil SOC stock across regions and cropping systems.

To our knowledge, the number of comparisons and studies of the present review (235 from 72 references) is higher than other similar studies in Mediterranean conditions, such as Aguilera et al. (2013) with 174 comparisons from 79 references in both arable and woody crops and Vicente-Vicente et al. (2016) with 144 comparisons from 51 references in woody crops. Based on this perspective, this is indeed the first study assessing the achievement of 4 per 1000 objective in agricultural soils under Mediterranean conditions, and the aims were as follows: (i) analyzing a representative collection of earlier studies measuring environmental/ soil variables and SOC stocks from field experiments in Mediterranean regions under different land use and land management systems, (ii) to provide evidence on SOC storage potential to achieve the 4‰ objective in the Mediterranean climate, (iii) to identify the biophysical and management variables most associated with SOC storage in Mediterranean conditions, and (iv) to recommend a set of most promising mitigation strategies for global change.

2 Materials and methods

2.1 Literature review and data selection criteria

We collected and analyzed empirical studies in arable and woody crops, carried out in countries under Mediterranean climate and published until February 2017 (S1). Experiments performed in controlled environments (greenhouse or laboratory) were excluded. The selected studies considered pairwise comparisons between RMPs and conventional management. To be included in the database, studies had to have a duration of at least 3 years. For studies that included more than one treatment, all the treatments were included in the database. The literature survey was conducted using SCOPUS database, searching two fields in the title, abstract, or keywords of the article: “Mediterranean” AND “soil organic carbon” OR “soil organic matter.” Literature cited in the selected articles was further examined for collecting more studies only if they met the adopted criteria.

A total of 235 comparisons from 72 references and 76 sites were available from field experiments carried out in France (2), Greece (2), Italy (28), Morocco (1), Portugal (2), South Africa (2), Spain (36), Syria (1), Turkey (1), and the USA (1).

Sites were located between 32° 64′ and 45° 38′ latitude N, 31° 35′ and 33° 50′ latitude S, altitude − 2–990 m a.s.l., with mean annual temperature (MAT) and rainfall (MAP) in the range 10.9–19.9 °C and 139–1178 mm, respectively (S2, S3). According to the aridity index given by $AI = P/T + 10$ (De Martonne 1926), sites presented the following climate regimes: strongly arid (1), arid (7), semiarid (23), sub-humid (34), and humid (15). Data were organized in a dataset containing basic environmental variables (elevation, temperature, rainfall), soil variables (pH, particle size distribution, and texture group), soil sampling depth (up to 40 cm in arable crops and 60–70 cm in woody crops), length of the field experiment (years), and initial and final soil organic carbon stocks (SOCi and SOCf).

Our analysis was restricted to croplands ($n = 235$), excluding permanent grassland and forests. Arable crops ($n = 120$) and woody crops ($n = 115$) were both examined. Arable crops included in this study were alfalfa (*Medicago sativa* L.), barley (*Hordeum vulgare* L.), corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), durum wheat (*Triticum durum* Desf.), forages, globe artichoke (*Cynara cardunculus* L. var. *scolymus*), legumes, horticultural crops, oilseed rape (*Brassica napus* L.), sunflower (*Helianthus annuus* L.), soybean (*Glycine max* L.), sugar beet (*Beta vulgaris* L.), tomato (*Solanum lycopersicum* L.), and winter wheat (*Triticum aestivum* L.). Woody crops considered were restricted to almond (*Prunus dulcis* Mill.), apricot (*Prunus armeniaca* L.), kiwifruit (*Actinidia chinensis* Planch.), olive grove (*Olea europea* L.), orange (*Citrus sinensis* L.), peach (*Prunus persica* L. Batsch), and vineyard (*Vitis vinifera* L.).

Information on soil management (minimum tillage, no tillage, tillage), rotation types in arable crops (monoculture, 2 years, ≥ 3 years), fertilization management (detailed type of input), and fertilization group (mineral, mixed, none, organic) for the two land uses are shown in Table 1.

Carbon storage rate (CSR) in Mg C ha^{-1} $year^{-1}$ was derived for the soil depth reported in each experiment by the equation:

$$\mathrm{CSR} = (\mathrm{SOCf}\text{–}\mathrm{SOCi})/\mathrm{years}$$

and CSR in Mg C ha^{-1} $year^{-1}$ × 1000 was calculated with the equation:

$$\mathrm{CSR}\ (\mathrm{per}\ 1000) = [(\mathrm{SOCf}\text{–}\mathrm{SOCi})/\mathrm{years}]/\mathrm{SOCi} \times 1000$$

where SOCf and SOCi are final and initial SOC stocks (Mg C ha^{-1}) and years is experiment's length.

Many studies did not report the bulk density (BD in Mg m^{-3}) required to calculate SOC stocks, and missing values were calculated from SOC (g C kg^{-1}) with the equation proposed by Aguilera et al. (2013) for Mediterranean soils:

$$\mathrm{BD} = 1.84\text{–}0.443 \log 10(\mathrm{SOC})$$

No-tillage soil management was the most represented category in woody crops (74 comparisons) and tillage in arable crops (67 comparisons). Rotation types in arable crops were almost equally represented (41 to 43 comparisons each). Organic type of input was predominant in woody crops (79 comparisons), while mineral and mixed types of input were mostly used in arable crops (48 and 53 comparisons, respectively). Mineral and mixed mineral/crop residue inputs were the most represented categories in arable crops (48 and 33 comparisons,

Table 1 Management information and number of comparisons of field experiments

Management information	Arable ($n = 120$)	Woody crops ($n = 115$)
Soil management		
Minimum tillage	22	19
No tillage	31	74
Tillage	67	22
Rotation		
Monoculture	41	–
2 years	43	–
≥ 3 years	43	–
Fertilization management		
Compost	2	4
Cover crop	6	37
Cover crop + manure	–	8
Cover crop + residues	–	4
Manure	6	1
Mineral	48	6
Mineral + compost	4	2
Mineral + cover crop	9	22
Mineral + manure + residues	1	–
Mineral + residues	33	2
Mineral + residues + compost	1	3
Mineral + residues + cover crop	4	–
Mineral + sludge	–	1
Mineral + slurry	1	–
Mixed solid waste	–	2
Municipal organic waste	–	1
Olive mill waste	–	15
Olive mill waste + cover crop	–	1
Organic fertilizer	–	3
Residues	1	3
Sewage sludge	3	–
Slurry	2	–
Fertilization group		
Mineral	48	6
Mixed	53	30
Organic	19	79

respectively); cover crop, mineral + cover crop, and olive mill waste were predominant in woody crops (36, 22, and 15 comparisons, respectively).

2.2 Statistical analyses

A first data analysis was run with the aim to evaluate the impact of selected contextual variables on per 1000 C storage rate using Kruskal-Wallis non-parametric inference (e.g., Salvati 2013; Pili et al. 2017). Results were analyzed by soil attribute, environmental variable, and agricultural management type according to Table 1, and represented by Box-Whisker plots (mean ± standard error). Correlation statistics were based on a non-parametric Spearman rank analysis (Duvernoy et al. 2018), where the p level associated to each correlation coefficient was corrected for multiple comparisons according to Bonferroni's adjustment (Ceccarelli et al. 2014). The sample size included 17 quantitative variables measured in arable crops and 13 variables in woody crops (Table 2). Statistical analyses were performed using Statistica 7.0 (Statsoft, Tulsa, USA).

Table 2 Environmental, crop management, and soil variables considered in the statistical analysis of the data sets

Variable	Unit	Arable crops	Woody crops
Environment			
Elevation	m	X	X
Rainfall	mm	X	X
Temperature	°C	X	X
Management			
Tillage	Yes/no (1/0; tillage, 1; other, 0)	X	X
No-tillage	Yes/no (1/0; no-tillage, 1; other, 0)	X	
Monoculture	Yes/no (1/0; monoculture, 1; other, 0)	X	–
Rotation ≥ 3 years	Yes/no (1/0; ≥ 3 years, 1; other, 0)	X	–
Mineral fertilization	Yes/no (1/0; mineral, 1; other, 0)	X	–
Organic fertilization	Yes/no (1/0; organic, 1; other, 0)	X	X
Irrigation	Yes/no (1/0)	X	–
Duration	Years	X	X
Olive groves	Yes/no (1/0; olive groves, 1; other, 0)	–	X
Vineyards	Yes/no (1/0; vineyards, 1; other, 0)	–	X
Soil			
Sampling depth	cm	X	X
Sand	%	X	–
Clay	%	X	–
pH	0–14	X	–
Coarse texture	Yes/no (1/0; coarse, 1; other, 0)	–	X
Fine texture	Yes/no (1/0; fine; other, 0)	–	X
Initial SOC content	Mg C ha^{-1}	X	X
CSR per 1000	Mg C ha^{-1} $year^{-1}$ × 1000	X	X

CSR carbon storage rate

3 Results

3.1 Arable crops

Per 1000 C storage rate (Mg ha^{-1} $year^{-1}$ × 1000) was significantly different ($p = 0.0382$) in the different climate aridity regimes (Fig. 1), ranking from sub-humid (34.69, $n = 31$) to semiarid

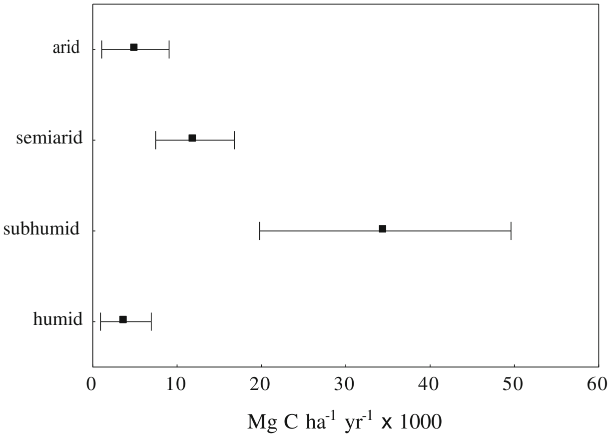

Fig. 1 Per 1000 C storage rate based on the aridity index for arable crops ($p = 0.0382$): arid ($n = 3$), semiarid ($n = 46$), sub-humid ($n = 31$), and humid ($n = 40$). Box-Whisker plots represent central point means ± standard error

(12.13, $n = 46$), arid (5.06, $n = 3$), and humid (3.94, $n = 40$). Soil management effect on per 1000 C storage rate (Fig. 2) was significantly different ($p = 0.0421$) and followed the ranking minimum tillage (22.28, $n = 22$) > tillage (14.42, $n = 67$) > no tillage (11.28, $n = 31$). The effect of fertilization group on per 1000 C storage rate (Fig. 3) was highly significant ($p = 0.000$), and the ranking was organic (63.24, $n = 19$) > mixed (10.30, $n = 53$) > mineral (1.22, $n = 48$).

Per 1000 C storage rate in relation to the type of fertilization management (Fig. 4) was largely positive in the following categories: compost (334.02), sewage sludge (101.58), and mineral + residues + compost (75.69), but these categories were the less represented ($n = 1$ to 3). The effect of cover crops on per 1000 C storage rate differed among the different categories: cover crop (24.30, $n = 5$) > mineral + residues + cover crop (11.94, $n = 4$) > mineral + cover crop (6.01, $n = 9$). The effect of manure on per 1000 C storage rate was 18.70 ($n = 6$), for slurry − 0.07 ($n = 2$). The most negative effect on per 1000 C storage rate was evidenced for the categories mineral + slurry (− 7.02) and mineral + manure + residues (− 6.22).

The effect of the experiment duration on per 1000 C storage rate (Fig. 5) was highly significant ($p = 0.000$) and followed the ranking ≤ 5 years (59.89, $n = 23$), 6–10 years (15.86, $n = 9$), > 10 years

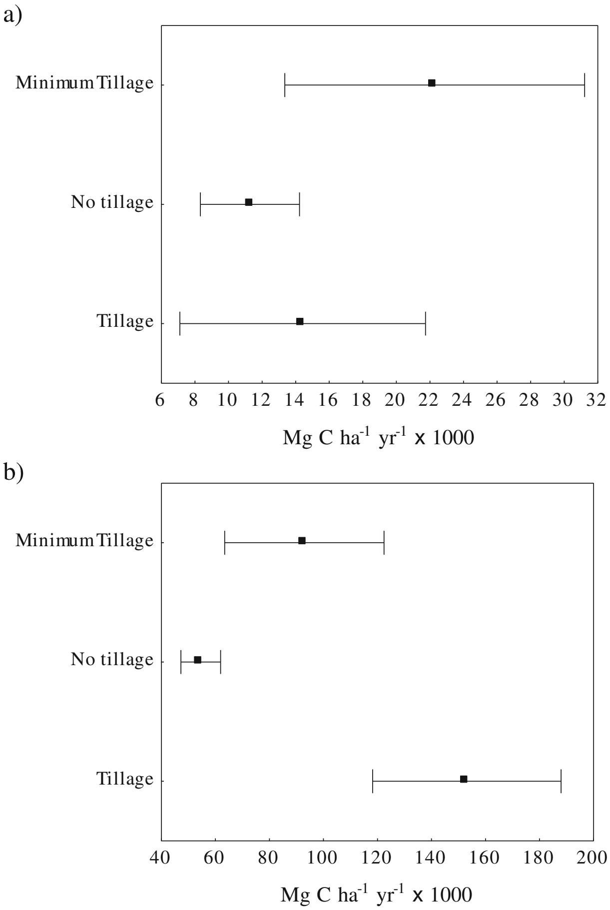

Fig. 2 Per 1000 C storage rate based on soil tillage management for **a** arable crops ($p = 0.0421$) and **b** woody crops ($p = 0.0767$). Number of comparison for each category is reported in Table 1. Box-Whisker plots represent central point means ± standard error

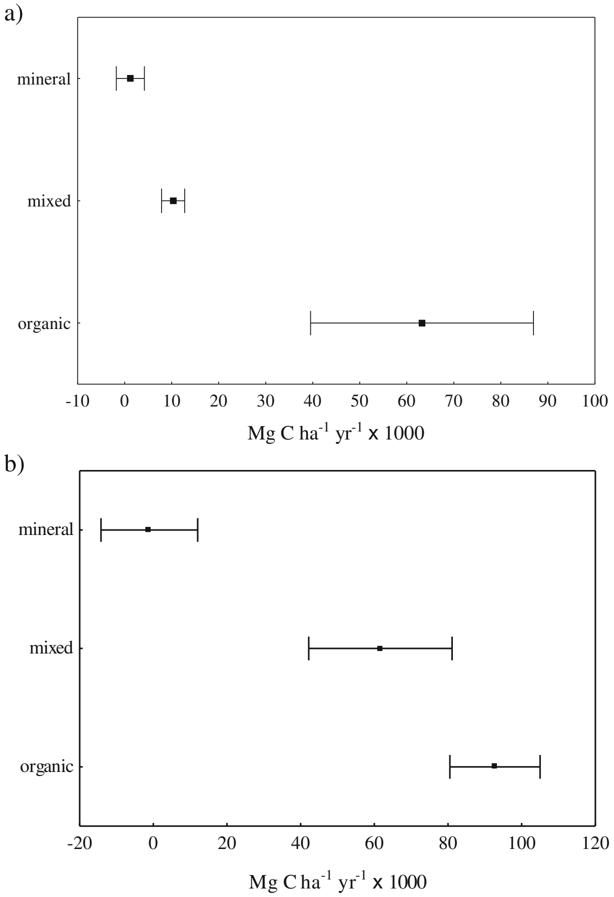

Fig. 3 Per 1000 C storage rate based on fertilization group for **a** arable crops ($p = 0.000$) and **b** woody crops ($p = 0.0004$). Mixed fertilization includes the following categories: mineral/compost, mineral/cover crop, mineral/residues, mineral/residues/cover crop in arable crops, mineral/residues/compost in woody crops, mineral/slurry in arable crops, and mineral/sludge in woody crops. Number of comparison for each category is reported in Table 1. Box-Whisker plots represent central point means ± standard error

(3.25, $n = 88$). Among soil variables, texture group (Fig. 6) was weakly significant ($p = 0.0765$), and the ranking was fine (34.62, $n = 27$), medium (10.71, $n = 66$), and coarse (6.09, $n = 27$).

Spearman rank correlation analysis among per 1000 C storage rate (Mg C ha^{-1} year^{-1} × 1000) and selected independent variables are illustrated in Fig. 7. Significant negative coefficients were reported for soil organic C stocks at the beginning of the study period (SOCi), number of survey years, mineral fertilization, depth of sampling, and tillage (conventional). C storage rate increased significantly with temperature and in sites where organic fertilization and no tillage were adopted.

3.2 Woody crops

The effect of fertilization group on per 1000 C storage rate (Fig. 3) was highly significant ($p = 0.0004$), and the ranking was organic (92.77, $n = 79$) > mixed (61.66, $n = 30$) > mineral (11.81, $n = 5$) > none (− 65.48, $n = 1$).

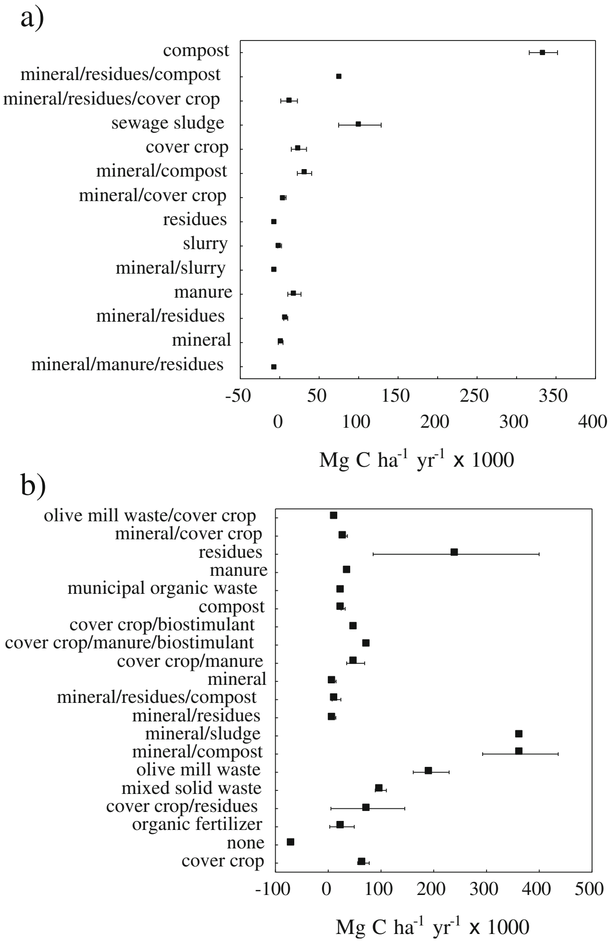

Fig. 4 Per 1000 C storage rate based on the type of fertilization management for **a** arable crops ($p = 0.000$) and **b** woody crops ($p = 0.0002$). Number of comparison for each category is reported in Table 1. Box-Whisker plots represent central point means ± standard error

Per 1000 C storage rate (Fig. 4) was largely positive (> 100) in the categories mineral + compost and mineral + sludge (364.36, $n = 3$), residues (242.56, $n = 3$), and olive mill waste (195.36, $n = 15$); intermediate (50–100) in the categories mixed solid waste (99.77, $n = 2$), cover crop + residues (75.19, $n = 4$), and cover crop (66.43, $n = 37$); low (0–50) ranging from manure (38.52, $n = 1$) to mineral + residues (9.43, $n = 2$); and negative with no fertilization (−65.48, $n = 1$).

The effect of the experiment duration in years on per 1000 C storage rate (Fig. 5) was highly significant ($p = 0.0023$) and higher in the category ≤ 5 years (112.15, $n = 56$), almost equal in 6–10 years (48.91, $n = 37$), and > 10 years (49.17, $n = 22$). These values are higher than those obtained for arable crops (1.87, 3.08, and 15.13 times for ≤ 5, 6–10, and > 10 years, respectively).

Spearman rank correlation coefficients among per 1000 C storage rate (Mg C ha^{-1} year^{-1} × 1000) and selected independent variables are illustrated in Fig. 7. Significant negative coefficients were reported for soil organic C stock at the beginning of the study period (SOCi),

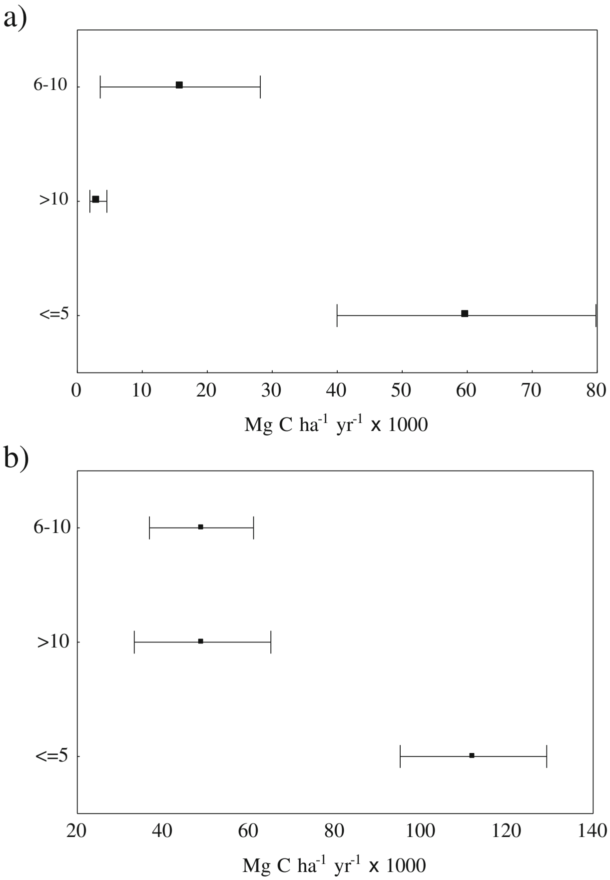

Fig. 5 Per 1000 C storage rate based on the duration of the experiment in years for **a** arable crops ($p = 0.000$) and **b** woody crops ($p = 0.0023$). Number of comparison for each category is reported in Table 1. Box-Whisker plots represent central point means ± standard error

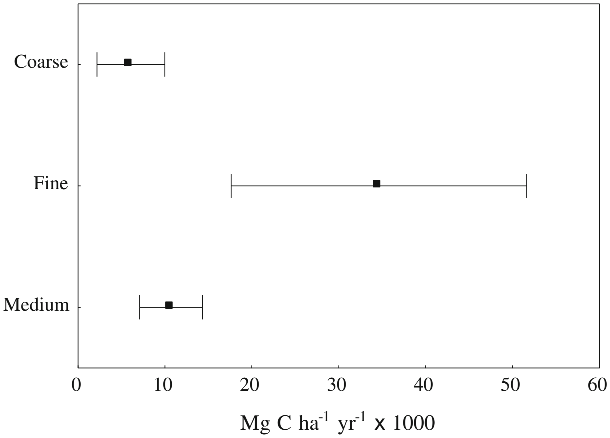

Fig. 6 Per 1000 C storage rate based on texture group for arable crops ($p = 0.0765$). Number of comparison for each category is reported in Table 1. Box-Whisker plots represent central point means ± standard error

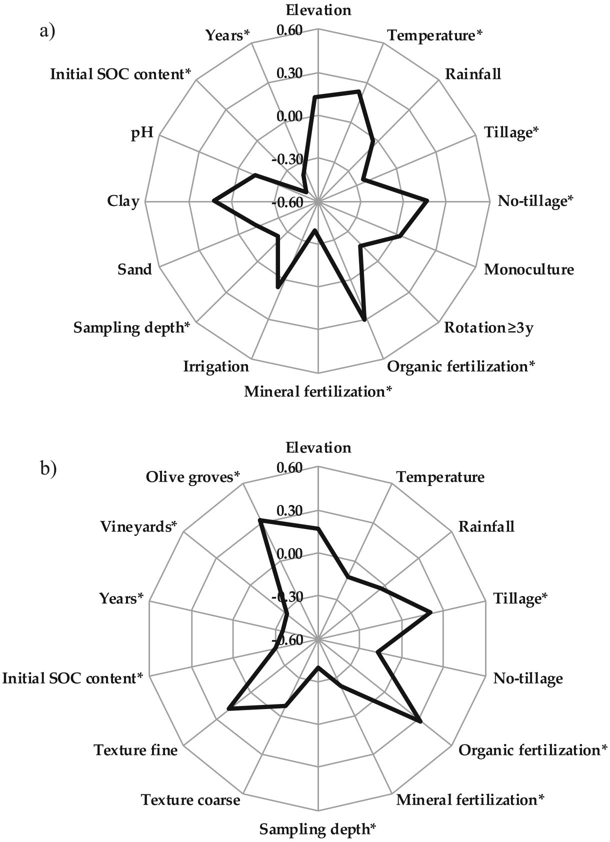

Fig. 7 Spearman rank correlation coefficients (rs) between C storage rate and the remaining variables for **a** arable crops and **b** woody crops. The asterisks indicate both positive and negative correlations (significant coefficients at $p < 0.05$ are above rs = |0.15|)

number of survey years, mineral fertilization, depth of sampling, and vineyard land use. C storage rate increased significantly in sites where organic fertilization and tillage (conventional) were adopted and under olive land use.

3.3 Comparison of arable and woody crops

Average C storage rates were 15.3 and 80.0 Mg C ha^{-1} year^{-1} × 1000 in arable and woody crops, respectively, and the lower and upper bound of means (95%) were 6.6–24.0 Mg C ha^{-1} year^{-1} × 1000 in arable crops and 60.5–99.5 Mg C ha^{-1} year^{-1} × 1000 in woody crops. In both arable and woody crops (Fig. 8), more than 50% of the observations were higher than the objective of 4 per 1000 (59 and 76%, respectively), with ranges − 50 to + 352 and − 65 to + 540 Mg C ha^{-1} year^{-1} × 1000, respectively. In addition, for arable crops, a higher proportion of the observations (36%) showed negative per 1000 C storage rates compared to woody crops (7%).

In the case of woody crops, more positive extreme values were found. This was due to the high values found under tillage management, whereas for arable crops, the dispersion of the data was much lower, and the extreme values were found in the minimum tillage management category (Fig. 2a, b). Positive extreme values were found with the application of organic fertilization in both arable and woody crops (Fig. 3a, b), and in both cases, no negative extreme values were found.

4 Discussion

4.1 Influence of the different variables on 4‰ achievement

4.1.1 Tillage and fertilization

Organic fertilization appears to be one of the main drivers increasing the C storage rate in Mediterranean agriculture. Indeed, according to Vicente-Vicente et al. (2016), assessing the influence of some abiotic variables (e.g., temperature and precipitations) is made difficult in soils amended with compost, manure, or other organic fertilizers due to the strong influence of this management which could mask their effect. The high variability observed in our study is supported by Freibauer et al. (2004), who showed that C storage efficiency is affected by different variables, e.g., climate, composition of the added organic materials, amount of SOC, and soil properties. In our analysis, data derive from a wide variety of pedoclimatic and topographic conditions, resulting in a relatively high spatiotemporal variability.

The results for organic fertilization in arable crops are consistent with those found in a meta-analysis of Mediterranean crops by Aguilera et al. (2013), showing carbon increases by 23.5% in soils amended with organic fertilizers compared with soils under conventional management with mineral fertilization. The same authors reported a significant higher C storage rate in those managements applying compost or manure and concluded that the C

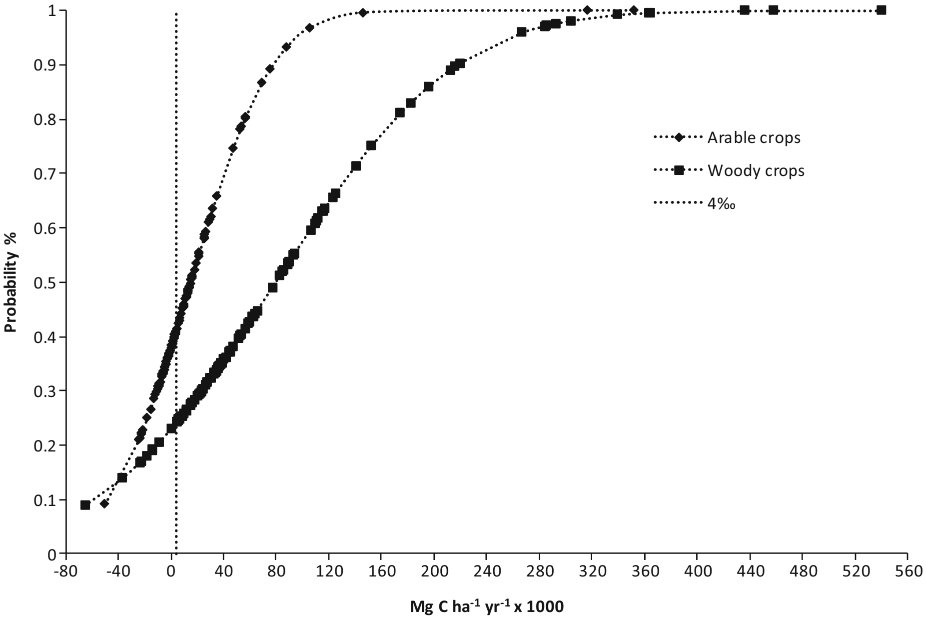

Fig. 8 Cumulative distribution functions of C storage rates in arable and in woody crops

storage rate will depend mainly on the amount of the organic amendment which is incorporated into the soil. However, the use of some exogenous organic C inputs is strictly linked to the local availability, influenced in turn by the specific socioeconomic features of each area. Thus, for example, some by-products of the industry could be combined with cover crops and crop residue addition (e.g., olive mill waste, wine waste, sewage sludge, municipal wastes, compost). However, location of these industries plays a key role in order to avoid long-distance transportations; thus, the trade-off between the possible C storage increase from using these by-products and indirect CO_2 emissions for transportation should be assessed.

With regard to the C storage rate obtainable by cover crop management, it will depend on the Net Primary Production (NPP), which at the same time has an annual variability depending on pedoclimatic conditions. In this respect, Vicente-Vicente et al. (2017) found a great spatial variability of aboveground biomass production and carbon inputs from the spontaneous vegetation cover, within the same year, in olive orchards in Southern Spain. According to Peregrina et al. (2014b) carbon inputs from cover crops also differ between cereal and legume plant covers, being often lower in cereal plant covers due to the lower production of biomass. Therefore, soil properties and climatic conditions will affect especially those managements implementing cover crops (Vicente-Vicente et al. 2017).

In Mediterranean woody crops, no-tillage management is associated very often to the use of herbicides without application of organic inputs; conversely, minimum tillage and tillage are adopted when organic fertilizers are applied, with no or lower herbicide application rates. Our results show that a combination of different RMPs in Mediterranean croplands, such as minimum tillage in arable crops and tillage in woody crops, together with the incorporation of organic amendments, would lead to a relatively fast increase in the SOC content. These practices are also cost-effective, since they are relatively easy to be implemented by farmers at low cost. From a cultural and socioeconomic context, the requirement of specific machinery can encourage farmers to associate in cooperatives, particularly if no-tillage is not a traditional practice in the area. Very often in woody crops, no-tillage systems, associated to the excessive application of herbicides, lead to higher erosion rates due to the lack of vegetation cover (Gómez et al. 2009). But this is the worst combination that should be avoided, and mechanical weed mowing would be preferred to decrease soil erosion and depletion of SOC (Soriano et al. 2012). Considering other possible synergies and joint benefits, reduced or no-tillage systems also positively affect soil compaction, ion retention, exchange and buffering capacity, water balance and retention, and aggregate stability (Brevik et al. 2002; Six et al. 2002; Keesstra et al. 2012; Cerdá et al. 2014; García-Díaz et al. 2016). In addition, a reduced tillage intensity following the incorporation of the organic fertilizers usually improves soil biological and biochemical processes, offering a valuable option in soils with very low SOC content (Alguacil et al. 2014; Laudicina et al. 2016).

Per 1000 C storage rates in relation to fertilization management were higher in woody crops compared with arable crops. In particular, we found a C storage rate about 1.5 times higher in woody crops than in arable crops when applying organic fertilizers (93 vs. 63 Mg C ha^{-1} $year^{-1}$ × 1000). In addition, we found higher positive extreme values of SOC storage rate in woody crops, very often combined with tillage since in this case, the tillage is used to incorporate the organic inputs to the soil faster than when they are left on the soil surface. Arable crops are mainly based on annual cycles of tillage and sowing, whereas woody crops are perennial and soil disturbance is lower (Vicente-Vicente et al. 2016). Moreover, the wider inter-row area of the woody crops can be occupied by cover crops, thus allowing the growth of a green manure which is incorporated into the soil when harvesting, and also contributes to increase the organic C through rhizodeposition (Kuzyakov and Domanski 2000; Ludwig et al. 2007). As a result, woody crops showed an average C storage rate about five times higher than that obtained for arable crops (15 vs. 80 Mg C ha^{-1} $year^{-1}$ × 1000).

4.1.2 Climate regimes

The significant effect of climate regimes was also highlighted by Vicente-Vicente et al. (2016) and Francaviglia et al. (2017), who found a lower C storage rate under arid Mediterranean climate regimes compared to semiarid and sub-humid conditions. In these soils, water scarcity in rainfed agriculture and soil fertility limitations may decrease C storage potential (Post et al. 1996). Furthermore, the low water availability for plants does not allow the optimal growth of cover crops in woody crops, thus reducing the differences in SOC storage rate between conventional and cover crop managements (Vicente-Vicente et al. 2016).

4.1.3 Duration of the experiment

The effect of the duration of the experiment on per 1000 C storage rate is not surprising, since changes in SOC are expected to be stronger immediately after changing the management, and thereafter ramp down until a new equilibrium is reached (Six et al. 2002; Smith 2005; Johnston et al. 2009; Powlson et al. 2012). In this line, in a meta-analysis considering Mediterranean woody crops, Vicente-Vicente et al. (2016) found that the C storage rate was 1.7 times higher in the first 5 years of the experiments than in the following years and would be higher than that of arable crops for most of the sustainable management practices. Poulton et al. (2018) indicated that SOC accumulation can be represented by an asymptotic curve and reported a decrease in per mille storage rate in several long-term field experiments at Rothamsted Research (UK). In particular, Broadbalk experiment was started in 1843 with winter wheat, and results following the application of farmyard manure indicated a fast initial SOC accumulation rate of 43‰ in the first 20 years of the experiment, an annual rate still above 4‰ from 20 to 60 years followed by a decline towards a new equilibrium. Other studies support this finding (e.g., West and Post 2002; Rui and Zhang 2010; Poeplau and Don 2015), but SOC increases can be reversed if the land management practice (e.g., reduced tillage, organic fertilization) is not maintained (Freibauer et al. 2004; Powlson et al. 2011). In ley-arable rotations often adopted in cold temperate climates of Europe, part of the SOC accumulated during the ley period is lost with soil tillage and further decomposes during the arable phase, though with an overall SOC increase in the long term compared with continuous arable cropping (Johnston et al. 2009). In semiarid conditions typical of the warm temperate climates of the Mediterranean basin, a plot experiment on no-tillage and pig slurry application during a wheat-barley rotation included in the present analysis (Álvaro-Fuentes et al. 2014) indicated a decreasing trend of per mille SOC storage rate, equal to 54, 29, 18, and 12‰, respectively, after 1, 4, 11, and 20 years following the conversion from conventional tillage.

4.1.4 Soil variables

Among soil variables, the results for texture in arable crops fit with the widely accepted theory that the SOC content depends on the amount of silt and clay particles (Hassink 1997) due to the chemical protection which is mainly a consequence of the chemical interactions between clay minerals and the organic matter (Six et al. 2002).

The initial SOC content (SOCi) was significantly negatively correlated with C storage rate. This might be due to the lower capacity of the soil to accumulate C as “protected organic C” in some SOC fractions (e.g., physically and chemically protected pool, Six et al. 2002; Vicente-Vicente et al. 2017) as the SOC content of these fractions increases. Chen et al. (2018a) reported that SOC sequestration potential increases with an increase in fine fraction content and was highest for croplands. Therefore, considering the C saturation deficit, i.e., the difference between the theoretical maximum capacity of the soil to accumulate C as protected SOC and the current level (Six et al. 2002), achieving the 4‰ target would play an important role, to be addressed mainly in arable crops that are more SOC depleted due to frequent tillage operations and in coarse textured soils.

4.2 Implications of findings to the Mediterranean agriculture, the 4‰ achievement, and future researches

The incorporation of organic amendments (compost, green manure, residues, etc.) led to significantly higher values of per 1000 C storage rate compared with the conventional management or the use of mineral fertilizers, both in arable and woody crops. However, Mediterranean woody crops have demonstrated to be more sensitive to changes in land management than arable crops, although pedoclimatic conditions may strongly affect C storage dynamics.

Our results shed further light on a particularly relevant issue for Mediterranean and dryland ecosystems, where inputs of organic matter in soils are low and mostly rely on crop residues, while losses are high due to climatic and anthropogenic factors such as intensive and non-conservative farming practices (Farina et al. 2011). In addition, due to SOC depletion, Mediterranean soils are more prone to land degradation, which is often coupled with intense soil erosion (Muñoz-Rojas et al. 2015) arising from extensive land use changes in the last decades (Anaya-Romero et al. 2011).

Future research should help policy makers in Mediterranean areas to assess the extent of cultivated land area offering the best potential to meet the 4‰ target, considering the more favorable soil and climate conditions and the opportunities offered by the local availability of organic fertilizers such as manure or by-products of the agroindustry sector (e.g., olive or wine mill wastes).

Scientific research can additionally help to fill in some gaps existing in basic knowledge, mainly related to the lack of specific field experiments monitoring the long-term effectiveness of different management strategies on both SOC changes and greenhouse gas emissions (CO_2, CH_4, and N_2O). In this regard, future researches should be focused on assessing the 4 per 1000 target together with nitrous oxide (N_2O) emissions, since some previous works have suggested an increase in N_2O emissions while increasing SOC stocks (e.g., van Groenigen et al. 2017; Lugato et al. 2018). For instance, no-tillage management enhances SOC storage due to the combined effect of crop residue retention on the surface and the lower SOC decomposition, but the increased soil moisture content due to the lower crop evapotranspiration reduces soil aeration, and can enhance the denitrification process particularly in fine-textured soils, resulting in higher N_2O emissions compared to conventional tillage (Rochette et al. 2008). Given the close association between N inputs and N_2O emissions, the best practices suitable for C storage can be combined with soil management strategies to reduce N_2O emissions, such as improving N use efficiency by reducing inputs or by better matching applications (timing and amount) to plant demand (Snyder et al. 2014). While the main feedback of N fertilization is to increase crop yields, SOC storage has positive effects both on soil quality and crop productivity, i.e., management systems with higher C returns provide more C to the soil, supply more nutrients back to the crop, and increase crop productivity (Sanderman et al. 2017).

However, most of these studies have not been carried out under Mediterranean conditions. Recently, Cayuela et al. (2017) demonstrated that in Mediterranean conditions, the average N_2O emission factor, i.e., the percentage of N fertilizer applied emitted on site, would be much lower (0.5%) than that proposed by the IPCC (default value of 1%). In detail, N_2O emission factor was lower in rainfed crops (0.27%) than irrigated crops (0.63%), with drip irrigation systems (0.51%) than sprinkler irrigation (0.91%), and under winter cereals (0.26%) than summer crops such as maize (0.83%). Therefore, future studies should assess N_2O emissions in soils under RMPs aimed at achieving 4 per 1000 target, focusing on irrigation and fertilization in summer crops and considering specific Mediterranean pedoclimatic conditions.

Besides enteric fermentation and livestock management, methane (CH_4) emissions from soil management occur under anaerobic conditions from waterlogged soils, i.e., wetlands, peatlands, and rice paddies, that are the largest sources of methane emissions; by contrast, aerobic soils tend to act as sinks for CH_4, and have a positive impact on climate regulation (Le Mer and Roger 2001). Since wetlands are often unmanaged, most mitigation options have been proposed for rice grown under flooded conditions and include draining the fields during the growing season, improved water management in the bare season to avoid waterlogging, selection of cultivars with low exudation rates, fertilization management, and timing and composting of organic residue additions (Smith et al. 2008).

On the other hand, as a next step, the effects of different soil and crop managements on total SOC and SOC fractions at different protective levels—unprotected and physically, chemically, and biochemically protected (Six et al. 2002)—could be further explored with a similar approach.

5 Conclusions

Our literature analysis showed that both arable and woody crops have a large potential to increase SOC storage rates above 4 per 1000 target under Mediterranean climate due to the relatively lower levels of SOC in soils. For arable crops, mitigation strategies should particularly address soils with a coarse texture and adopt minimum or no-tillage soil management, the use of organic fertilizers, and the retention of crop residues in the field. The very high potential of woody crops to increase SOC storage rates, coupled with the high surface of soil covered by these crops, suggests that their potential to achieve the 4 per 1000 may be very important. Mitigation strategies in woody crops should include organic fertilization (e.g., the valorization of olive mill waste, a challenging opportunity for the sustainable and competitive development of olive oil industry in Mediterranean countries), the adoption of cover crops or allowing the growth of a plant cover of weeds in the inter-row area, and minimum tillage with no or lower herbicide application rates. In woody crops under no-tillage management, mitigation strategies should include mechanical weed mowing in sloping lands to decrease soil erosion and SOC depletion. Results also may reflect the high potential of Mediterranean regions across all continents to contribute to a significant increase in SOC storage at the global scale. But SOC storage is non-permanent; thus, to implement a meaningful carbon storage policy on agricultural land, both the land use or land management change must be maintained. In this sense, policymakers should consider the implementation of economic incentives to adopt and maintain RMPs.

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Affiliations

Rosa Francaviglia[1] • Claudia Di Bene[1] • Roberta Farina[1] • Luca Salvati[2] • José Luis Vicente-Vicente[3]

[1] Council for Agricultural Research and Economics, Research Centre for Agriculture and Environment (CREA-AA), Via della Navicella 4, 00184 Rome, Italy

[2] Council for Agricultural Research and Economics, Research Centre for Forestry and Wood (CREA-FL), Viale S. Margherita 80, 52100 Arezzo, Italy

[3] Mercator Research Institute on Global Commons and Climate Change (MCC), Torgauer Straße 12-15, EUREF Campus #19, 10829 Berlin, Germany