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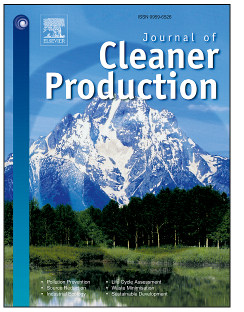

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Soil organic carbon sequestration rates in vineyard agroecosystems under different soil management practices: A meta-analysis

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ABSTRACT

Vineyards are usually cultivated in soils characterised by low soil organic carbon (SOC) content and have high risks of soil erosion and degradation. Increasing SOC stocks in these cropping systems has the potential to contribute to climate change mitigation through SOC sequestration and to enhance soil quality. We conducted a meta-analysis and compared the SOC stock response ratio, the SOC stock rate of change, and the SOC sequestration rate in vineyards under different SOC sequestration (SCS) practices relative to conventional management. SCS practices included organic amendments (OA), biochar amendments (BC), returning pruning residues to the soil (PR), no-tillage (NT), cover cropping (CC), and several combinations of these practices. The average SOC sequestration rate of SCS management was 7.53 Mg CO_2-eq. ha^{-1} yr^{-1} to a 30-cm soil depth. The highest SOC sequestration rate (11.06 Mg CO_2-eq. ha^{-1} yr^{-1}) was achieved under a combination of OA+NT and the lowest (2.82 Mg CO_2-eq. ha^{-1} yr^{-1}) was observed under PR treatments. Field experiments performed in particularly hot and dry bioclimatic zones were associated with lower SOC sequestration rates relative to those performed in more temperate areas. The high SOC sequestration rates obtained for many SCS practices, and the large land area dedicated to viticulture worldwide (7.45 Mha), imply that the adoption of SCS practices in vineyards can contribute to the global efforts to offset atmospheric greenhouse gas concentrations via SOC sequestration to mitigate climate change.

Keywords: climate change; vineyards; soil organic carbon sequestration; soil management practices; soil organic carbon.

1. Introduction

Viticulture represents an economically and culturally important sector of agricultural production in regions of the world with climates compatible with grape (*Vitis vinifera* L.) cultivation (Eldon and Gershenson, 2015). Vineyards constitute one of the most widespread agricultural production systems in several European countries such as Spain, France and Italy (Brunori *et al.*, 2016). In France, viticulture covers 3% of agricultural land, but in 2018 the sector generated 15% of the total agricultural revenue (CNIV, 2019), estimated at €77.5 billion (Insee, 2019), and wine exports achieved €12.2 billion in revenue in the same year (CNIV, 2019). Viticulture is also present outside of Europe and many non-European winegrowing countries (*e.g.*, China, Chile, India) have been expanding their vineyard land areas and increasing their production of grape over the past decade (OIV, 2019).

Vineyards are managed with a broad range of practices, which vary across regions and have a differentiated influence on soil organic carbon (SOC) content (Carlisle *et al.*, 2010). Conventional practices (*e.g.*, maintaining bare soil in the inter-rows through the use of tillage) result in SOC losses in vineyard systems (Eldon and Gershenson, 2015), but alternative viticultural practices (*e.g.*, using cover cropping) may lead to SOC sequestration (Nistor *et al.*, 2018). SOC sequestration corresponds to the process of transferring carbon dioxide (CO_2) from the atmosphere into the soil through plants, plant residues and other organic solids which are stored or retained in the soil as part of the soil organic matter (SOM) (Olson *et al.*, 2014). It assumes a net removal of CO_2 from the atmosphere (Chenu *et al.*, 2019). Understanding SOC dynamics associated with different soil management practices in vineyards is crucial in identifying the most effective practices for SOC sequestration in viticultural soils.

The contribution of viticultural agroecosystems to SOC sequestration at the global scale is gaining increasing attention. Studies (*e.g.*, Brunori *et al.*, 2016; Scandellari *et al.*, 2016) show that properly managed vineyards could act as carbon (C) sinks via SOC sequestration. Vines have specific structural features that allow them to potentially sequester higher quantities of organic carbon (OC) than annual crops (Smaje, 2015). Due to their naturally long life cycle, vines accumulate OC in their woody biomass (Williams *et al.*, 2011), including in their complex root systems (Agnelli *et al.*, 2014), and in the soil (*e.g.*, through rhizodeposition) (Brunori *et al.*, 2016). Their extensive and deep-root systems (reaching down 2 to 5 m on average) also allow for direct transfer of OC into the subsoil (Agnelli *et al.*, 2014), which reduces risks of SOC mineralisation by physically isolating the OC from the activity of soil microorganisms (Ledo *et al.*, 2020).

The global viticultural land area was 7.45 Mha in 2018 (OIV, 2019). Although only a fraction of the global arable land area, round 1.39 Gha in 2017 (FAO, 2019), it may contribute to SOC sequestration in countries with large winegrowing regions. French vineyards have been identified as offering substantial sequestration potential as part of the ‘4 per 1000’ initiative[1] (Minasny *et al.*, 2017). The interest in viticulture and SOC sequestration is supported by broader studies seeking a better understanding of the effects of perennial crop systems on SOC stocks and greenhouse gas (GHG) emissions, and how these effects vary depending on management practices (*e.g.*, Pergola *et al.*, 2017; Ledo *et al.*, 2019; Ledo *et al.*, 2020).

[1] The ‘4 per 1000’ is an international initiative gathering public and private stakeholders under the Lima-Paris Action Plan framework. It aims to achieve an annual growth rate of 0.4% in the global SOC stocks (to a depth of 40 cm) for food security and climate.

There is a substantial body of research considering potential SOC sequestration (SCS) practices in agriculture. Several meta-analyses and reviews (*e.g.*, Poeplau and Don, 2015; Liu *et al.*, 2016; Sykes *et al.*, 2020) have estimated the effects of single or combined soil management practices on SOC stock change. Relative to arable and pasture systems, SOC sequestration in vineyards has received less attention. Most studies relating to SOC sequestration have not taken vineyard agroecosystems into account (*e.g.*, Poeplau and Don, 2015) or have not differentiated them as separate crop systems in the analysis (*e.g.*, Aguilera *et al.*, 2013). Information on SOC sequestration in vineyards remains fragmented and incomplete. There is currently no published meta-analysis evaluating the global potential of vineyards to enhance SOC sequestration under SCS practices applicable to viticulture. Vicente-Vicente *et al.* (2016) considered field experiments performed in vineyards and analysed the influence of some SCS practices specifically for vineyards as part of their meta-analysis in woody croplands, but their study focused on a limited number of SCS practices (cover cropping, organic amendments and a combination of both) and on specific bioclimatic zones (non-Mediterranean vineyards were excluded from their analysis).

Understanding and quantifying the mitigation potential of vineyards is important for future policy decisions in the agriculture sector. This paper presents a meta-analysis of the response of SOC stocks in 0-30 cm depth in vineyards to different SCS management practices from a global sample of individual field studies. It also compares the changes in SOC stocks depending on climate and study length. To our knowledge, this is the first meta-analysis dealing with the influence of SCS management on SOC stocks in vineyards at the global level. The novelty of this study is to consider all SCS practices applicable to vineyard agroecosystems and to estimate the SOC sequestration rate associated with their implementation in viticultural soils located under all types of climate. Our study also represents the first attempt to assess, through meta-analysis, the effect of biochar amendments, pruning residue return and no-tillage on SOC stocks in vineyards specifically.

2. Materials and methods

2.1. Data collection

A literature search focusing on publications reporting pairwise comparisons between conventional management and SCS practices in vineyards was conducted in October 2019. The search covered the electronic databases of ISI Web of Knowledge and Scopus, using the keywords “soil organic carbon”, “soil organic matter” or “soil carbon sequestration” and “vineyard” or “*Vitis vinifera*”. Seeking complete coverage, a second search of the same databases used the keywords: “cover crop”, “no-tillage”, “amendment”, “biochar”, “hedge”, “agroforestry”, “pruning”, “soil erosion” or “pH” in combination with “vineyard” or “*Vitis vinifera*”. These keywords correspond to SCS practices applicable to viticultural soils, to soil properties playing a role in SOC sequestration, or to phenomena affecting SOC sequestration.

Selected studies fulfilled the following criteria: (i) they included experiments measuring SOC or SOM levels within existing vineyards or through experimental manipulation of vineyard management practices; (ii) they were performed under field conditions (laboratory studies and pot experiments were excluded) for a minimum period of three years; and (iii) they were published in or after 2000. When several studies contained data from the same field experiment, only the longest study was selected to avoid redundancy in the data.

2.2. Definition of categories

2.2.1. Soil management practices

Five different SCS practices were found during the literature search: organic amendments (OA), biochar amendments (BC), returning pruning residues to the soil (PR), no-tillage (NT) and cover cropping (CC). Other SCS practices applicable to viticulture (*e.g.*, using contour hedges) were not considered by any of the field experiments gathered in the literature search and were, therefore, not included in this study.

- OA included comparisons where organic amendments (*e.g.*, compost, manure, green waste, sludge, etc.) were applied to the vineyard. Biochar amendments and pruning residues were both excluded from this category and constituted a category of their own.
- BC included comparisons where biochar amendments were applied to the vineyard.
- PR included comparisons in which pruning residues were left on the ground or were incorporated into the soil after being crushed.
- NT included comparisons where no-tillage was implemented continuously in the vineyard, meaning that the soil was not disturbed by tillage during the experiment. When used as a single practice, weeds were controlled using pre-emergence herbicides to ensure no other vegetation cover in the inter-rows.
- CC included comparisons in which a cover crop was grown in the inter-rows of the vineyard. Cover crops were either native vegetation growing spontaneously or sown. In the latter case, different varieties of crops were chosen depending on the experiment, such as barley (*Hordeum vulgare*), clover (*Trifolium pratense*), vetch (*Vicia sativa*), etc. The cover crops were permanent or allowed to grow temporarily between early autumn and mid-spring. In all the experiments, the plant residues from

the cover crops were left on the soil surface or incorporated in the soil, which means that the produced organic matter (OM) was not removed from the agroecosystem by the experiment observers. When used as a single practice, the inter-row soil was ploughed at least once a year to control the vegetation, usually during spring.

The comparisons were classified by soil management according to the SCS practices used in the experiment. The comparisons included either a single SCS practice (*i.e.* OA, BC, PR, NT or CC) or a combination of two or three SCS practices (*e.g.*, OA+NT or PR+NT+CC); a category was created for each combination of practices. Conventional management was used as a control group and was characterised by the use of frequent tillage and, in most cases, the application of mineral fertilisers. All SCS treatments were cultivated under conventional management before the start of the experiments. The control groups showed no or a negligible change in SOC stocks throughout the duration of the experiments, suggesting that the soil of control and SCS treatments was in equilibrium before the introduction of SCS management.

2.2.2. Climate classification

Comparisons between SCS and conventional management in field experiments were also classified depending on their sub-climate using the Köppen-Geiger classification (Peel *et al.*, 2007). The classification differentiates 30 sub-climate types gathered in 5 broader categories (Table 1). Vineyards are commonly found under B-, C- and D-type climates. Grape is also grown in tropical regions (A-type climates), though to a lesser extent. Viticulture is, however, not conducted in polar regions.

2.2.3. Duration of the experiments

Each pairwise comparison was, in addition, classified according to the duration of the experiment. Three categories were created: short-term studies (*i.e.* < 6 years), medium-term studies (*i.e.* between 6 and 10 years) and long-term studies (*i.e.* > 10 years).

2.3. Data management and estimation methods

Data on SOC stocks (in Mg C ha^{-1}) at the beginning and the end of the experiment were collected for all the treatments included in the selected studies (Appendix B). In cases where the initial SOC stock values for SCS treatments were unavailable or could not be calculated, initial SOC stocks from conventional treatments were used instead, assuming that both the control and experimental plots had similar initial SOC stocks considering that they were established on the same soil and under similar pedoclimatic conditions. Only a limited number of studies provided values of SOC stocks; in most cases, SOC was given as a concentration. SOC stocks were, thus, derived from the concentration using Equation (1), in which *SOC stock* represents the SOC stock (in Mg C ha^{-1}), d_i the soil depth (in m), ρ_i the bulk density (in Mg m^{-3}) and $[SOC]_i$ the SOC concentration (in g C kg^{-1} of soil) for all the different soil layers included in each field experiment (*i.e.* from *i* to *n* soil layers).

$$SOC\ stock = \sum_{i=1}^{n} \frac{d_i \rho_i [SOC]_i}{10} \quad (1)$$

Whenever the bulk density was not provided by the studies, values were estimated using the pedotransfer function in Howard *et al.* (1995) for vineyards located under non-Mediterranean climates (Equation (2)) and, for vineyards located under Mediterranean climates, the same function but re-parametrised by Aguilera *et al.* (2013) with data from Mediterranean soils

(Equation (3)), in which *ρ* represents the bulk density (in g cm^{-3}) and *[SOC]* the SOC concentration (in g C kg^{-1} of soil). When SOC concentrations were not determined by the study, they were derived from the SOM concentrations using the relationship developed by Pribyl (2010): [SOC] = [SOM] x 0.5.

$$\rho = 1.3 - 0.275\ log10([SOC]) \quad (2)$$

$$\rho = 1.84 - 0.443\ log10([SOC]) \quad (3)$$

Since studies reported SOC stocks (and SOC or SOM concentrations) for different soil depths, a quadratic density function, based on (Smith *et al.*, 2000a) and used by Abdalla *et al.* (2018), was used to derive a scaling cumulative distribution function (cdf) for soil density as a function of soil depth up to 1 m. This allowed measured or calculated SOC stocks (Mg C ha^{-1}) at the beginning and the end of each experiment at a given depth *d* (in m) to be scaled to the equivalent values at 0.3 m following Equations (4) and (5). A depth of 0.3 m was chosen, since the great majority of the change in SOC occurs in the top 0.3 m of soil, even though some changes may also occur below 0.3 m (Smith *et al.*, 2000b). Besides, scaling all studies to a depth of 0.3 m provided a standardised analysis compatible with the Tier 1 methods of the IPCC (2006) guidelines.

$$cdf(d) = (22.1 - \frac{33.3d^2}{2} + \frac{14.9d^3}{3})/10.41667 \quad (4)$$

$$SOC\ stock\ (0.3\ m) = SOC\ stock\ (d)\ \times\ cdf\ (0.3)/cdf\ (d) \quad (5)$$

2.4. Statistical analyses

The collected data harmonised to a depth of 0.3 m was used to calculate three effect sizes for SOC stock comparisons: (i) the SOC stock response ratio (RR), to estimate the change in SOC stocks under SCS practices relative to conventional management, (ii) the SOC stock rate of change (R), as a measure of the annual growth rate in SOC stocks under SCS management relative to conventional management, and (iii) the raw difference in means of SOC stocks for SOC sequestration rate comparisons. Statistical analyses were performed in the R environment software (R Core Team, 2019). When several treatments with similar management shared the same control, one composite effect size was computed for these treatments to ensure that all the comparisons in the meta-analysis were independent. The composite effect size was calculated by averaging the effect sizes of the non-independent treatments. When these treatments had different sample sizes, a weighted mean was used to give more importance to the treatments with a higher sample size (Borenstein *et al.*, 2009).

RR was defined by the methods of Hedges *et al.* (1999) as the natural logarithm of the ratio of the SOC stock at the end of the experiment under SCS management ($(SOC\ stock)_f$ in Mg C ha^{-1}) to the SOC stock at the beginning of the experiment ($(SOC\ stock)_i$), according to Equation (6). The use of the natural logarithm allowed for a linearization of the metric, leading to a more normal sampling distribution (Hedges *et al.*, 1999). The SOC stock was preferentially chosen for RR calculation over the SOC concentration to reduce the impact of the differences in soil depth and bulk density between studies. Data on the absolute amount of SOC change is also required to assess the contribution of SOC sequestration to climate change mitigation.

$$RR = \ln\left((SOC\ stock)_f\right) - \ln((SOC\ stock)_i) \quad (6)$$

R, expressed in yr^{-1}, was computed following Equation (7), according to the methods used by Abdalla *et al.* (2018). *t* stands for the duration of the experiment (in years).

$$R = RR/t \quad (7)$$

The SOC sequestration rate (expressed in Mg C ha^{-1} yr^{-1}) corresponds to the change in the SOC stock per hectare and per year for a 0.3 m depth under SCS management relative to conventional management. It was calculated following Equation (8), in which $(SOC\ stock)_f$ stands for the SOC stock (in Mg C ha^{-1}) at the end of the experiment, $(SOC\ stock)_i$ for the SOC stock at the beginning of the experiment and *t* for the duration of the experiment (in years). The unit of the SOC sequestration rate was converted into CO_2 equivalent (CO_2-eq. ha^{-1} yr^{-1}) by multiplying the results by the ratio of the molecular weight of CO_2 to the molecular weight of carbon (44/12).

$$SOC\ sequestration\ rate = \frac{(SOC\ stock)_f - (SOC\ stock)_i}{t} \quad (8)$$

Weighted mean effect sizes of each category of SCS practices, bioclimatic zones and study length were calculated. The studies were weighted by sample size (Adams *et al.*, 1997) according to Equation (9), where w_i refers to the weight of a given comparison *i*, and N_i^{SCS} and N_i^{CON} refer to the sample sizes of the SCS treatment and the control treatment in the comparison, respectively. In meta-analyses, studies are usually weighted by the inverse of their variance (Borenstein *et al.*, 2009); however, the variance was not provided in many of the studies. Sample size, on the contrary, was available in all references. Its use allowed for the inclusion of all the studies gathered during the literature search, while maintaining the reasoning of the meta-analysis, which relies on attributing more weight to larger studies in effect sizes.

$$w_i = \frac{N_i^{SCS} N_i^{CON}}{N_i^{SCS} + N_i^{CON}} \quad (9)$$

Bias-corrected 95% confidence intervals were generated for each weighted mean effect size by bootstrapping procedure with 10,000 iterations (Adams *et al.*, 1997), using the R package 'boot' (Canty and Ripley, 2019).

3. Results

3.1.General findings

A total of 50 studies were compiled, providing 146 independent comparisons between SCS and conventional management practices. An overview of the studies can be found in Appendix A. Almost all studies were peer-reviewed articles published in scientific journals (n = 46); only a few were conference papers (n = 2) or book chapters (n = 2). Most of the studies were published over the last ten years. Overall, the initial SOC stock was reported in 70% of the studies selected and the bulk density in 30%. The mean experiment duration was 8.5 years (StDev = 5.8), with most comparisons being in the medium term (n = 70), slightly fewer in the short term (n = 57), and a fewer again in the long term (n = 19); the longest field experiments (n = 5) had a duration of 28 years. The mean soil depth was 0.31 m (StDev = 0.18), with values ranging from 0.05 to 1 m.

The SCS management practices were very diverse, with a mix of single and combined practices. A combination of two SCS practices was used in the majority of the comparisons (n = 83). The most prominent combination was NT+CC (n = 70), followed by OA+NT (n = 6), OA+BC (n = 3), PR+CC (n = 3) and PR+NT (n = 1). The number of comparisons associated with the use of a single SCS practice was lower (n = 52). OA was the most commonly used single SCS practice, with 27 comparisons, followed by CC (n = 9), NT (n = 7), PR (n = 5) and BC (n = 4). The number of comparisons dealing with a combination of three SCS practices was substantially lower, with only 11 comparisons: OA+NT+CC (n = 7), PR+NT+CC (n = 3) and OA+PR+NT (n = 1).

The majority of studies (39 out of 50) were conducted in countries of the European Union (Fig. 1). The largest number of studies was from Spain (n = 17), followed by Italy (n = 11), France (n = 10), the USA (n = 5), South Africa (n = 4), and Australia (n = 1), Germany (n = 1) and Turkey (n = 1). The sub-climate Cfb, which corresponds to a temperate oceanic climate, was the most represented in the meta-analysis with 38 comparisons, followed by Csa (n = 25), Csb (n = 24), BSk (n = 17), BWh (n = 17), Cfa (n = 17), Csc (n = 5) and Dfa (n = 3). The majority of comparisons (n = 105) were conducted under a Mediterranean climate (which includes the sub-climates BSk, BWh, Cfa, Csa, Csb and Csc), while fewer comparisons (n = 41) were undertaken under a non-Mediterranean climate (which includes the sub-climates Cfb and Dfa).

3.2. Impacts of soil management, climate and study length on the SOC stock response ratio (RR)

The RR was significantly higher than 0 for all SCS practices (Fig. 2). This implies that all SCS practices analysed in this study were, on average, associated with an increase in SOC stocks in vineyards relative to conventional management. The average RR for all SCS practices was 0.40, which corresponded to an average increase in SOC stocks by +40% under SCS management relative to conventional management. The lowest RR (0.09) was observed in vineyards in which OA+BC had been used, whereas the highest RR (0.60) was found in vineyards in which a combination of OA+NT had been put in place.

Changes in SOC stocks under SCS management differed between Köppen-Geiger sub-climates (Fig. 3). The RR was significantly higher than 0 for all sub-climates, ranging from 0.13 (obtained under Csc, a cold-summer Mediterranean climate) to 0.71 (obtained under BSk, a cold semi-arid climate). This means that the use of SCS practices was associated with an increase in SOC stocks under all sub-climates, but to a lesser extent under certain sub-climates (*e.g.*, Cfa, a humid subtropical climate, and Csc) than under others (*e.g.*, BSk and Csa, a hot-summer Mediterranean climate).

Management duration also had an effect on the change in SOC stocks under SCS management relative to conventional management (Fig. 4). The RR was significantly lower for short-term experiments (0.27) than for medium- (0.58) and long-term ones (0.53).

3.3. Effects of soil management, climate and study length on the SOC stock rate of change (R)

All SCS management practices were associated with a positive SOC stock change rate relative to conventional management (Fig. 5). The R averaged 0.058 yr^{-1} for all SCS practices. This corresponded to an annual SOC stock growth rate of +5.8% yr^{-1} under SCS management. The R ranged from 0.019 to 0.074 yr^{-1} and was significantly higher than 0 for all SCS management practices. The lowest R (+1.9% yr^{-1}) was found under PR, while the highest value (+7.4% yr^{-1}) was observed under OA+NT+CC.

The R varied significantly depending on the sub-climate of the field experiment (Fig. 6). The BSk sub-climate was associated with the highest R (0.095 yr^{-1}). On the contrary, the Csc sub-climate was associated with the lowest R (0.021 yr^{-1}).

The SOC stock change rate differed significantly according to the study length (Fig. 7). Short-term comparisons were associated with the highest R (0.064 yr^{-1}), followed closely by medium-term comparisons (0.059 yr^{-1}). Inversely, the R of long-term comparisons (*i.e.* between 10 and 28 years) was low (0.025 yr^{-1}): it was 2.6 and 2.4 times lower than that of short- and medium-term studies, respectively.

3.4. Influence of soil management, climate and study length on the SOC sequestration rate

Annual SOC sequestration rates averaged 7.53 Mg CO_2-eq. ha^{-1} yr^{-1} for all SCS management practices, ranging from 2.82 to 11.06 Mg CO_2-eq. ha^{-1} yr^{-1} (Fig. 8). The highest value was found under OA+NT. It was 3.9 times higher than the lowest value observed under PR treatments. Across all comparisons, only 3 out of 146 had a negative annual SOC sequestration rate (observed under NT, CC and PR+CC); the annual SOC sequestration rate of all the other comparisons was positive.

The SOC sequestration rate varied significantly according to the sub-climates under which field experiments were undertaken (Fig. 9). The highest SOC sequestration rate was found under the BSk sub-climate (11.40 Mg CO_2-eq. ha^{-1} yr^{-1}), while the lowest rate was found under the BWh sub-climate (0.79 Mg CO_2-eq. ha^{-1} yr^{-1}), which corresponded to a hot desert climate with low mean annual precipitation.

The SOC sequestration rate significantly differed depending on the experiment duration, with long-term comparisons being associated with lower SOC sequestration rates than medium- or short-term comparisons (Fig. 10). The SOC sequestration rate averaged 8.66 Mg CO_2-eq. ha^{-1} yr^{-1} for short-term studies, 6.95 Mg CO_2-eq. ha^{-1} yr^{-1} for medium-term studies and 3.99 Mg CO_2-eq. ha^{-1} yr^{-1} for long-term studies. It was 25% and 117% higher for short-term studies than for medium- and long-term experiments, respectively.

4. Discussion

4.1. Effects of soil management, climate and study length on the change in SOC stocks

4.1.1. SCS management practices

SCS management aims to increase SOC stocks in different ways: by increasing OC inputs to the cropping system, by reducing OC losses from the cropping system, or both (Sykes *et al.*, 2020). The type of SCS practices adopted decides which of these options is realised in a given cropping system. The adoption of OA and that of BC lead to increased OC inputs to the cropping system by increasing the primary productivity of the crop and adding OC produced outside the cropping system to the soil (Sykes *et al.*, 2020). Implementing CC also increases OC inputs to the cropping system through the integration of additional biomass producers within the system. PR and NT both intend to reduce OC losses from the cropping system, the former by minimising the deliberate removal of OC from the system, the latter by reducing soil disturbance, which lessens the atmospheric release of CO_2 from microbial mineralisation (Sykes *et al.*, 2020). OA and CC may also reduce OC losses by minimising the lateral transport of SOC via erosion processes.

The use of OA had a positive effect on the SOC stock to 30-cm depth, which increased by +44%, with an average SOC sequestration rate of 7.89 Mg CO_2-eq. ha^{-1} yr^{-1}. Vicente-Vicente *et al.* (2016) also found a positive effect of OA on SOC stocks in vineyards. The value they estimated for the SOC sequestration rate of this practice (2.38 Mg CO_2-eq. ha^{-1} yr^{-1}) was 3.3 times lower than that found in our meta-analysis, which could be due to the small number of comparisons for OA treatments gathered by Vicente-Vicente *et al.* (2016) in their meta-analysis (n = 8) and to the exclusion of vineyards located in non-Mediterranean regions from their analysis. Mohamad *et al.* (2016) found a similar SOC sequestration rate to that of our meta-analysis (7.33 Mg CO_2-eq. ha^{-1} yr^{-1}) for the use of OA in olive (*Olea europea* L.) orchards located in southern Italy. Baldi *et al.* (2018) estimated a slightly higher average SOC sequestration rate in a nectarine (*Prunus persica* L.) orchard under compost amendment in Italy (9.35 Mg CO_2-eq. ha^{-1} yr^{-1}). This shows that the application of OA may have a similar effect on SOC stocks in vineyard systems as in other woody crop systems (such as olive and citrus orchards). However, a net reduction in atmospheric CO_2 using this practice in vineyards would happen only if the added organic amendments were developed specifically for vineyard agroecosystems and were not displaced from another area where they would have otherwise been applied to the soil or if they were diverted from an alternative use that would cause the OC in the amendments to be rapidly lost to the atmosphere, *e.g.*, through burning (Powlson *et al.*, 2011).

The long-term impact of BC on SOC stocks has been proven to be positive in agricultural soils (*e.g.*, Liu *et al.*, 2016; Bai *et al.*, 2019), though neutral or negative effects have also been observed (*e.g.*, Majumder *et al.*, 2019). The effects of BC on SOC stocks are BC-, climate- and soil-specific, which makes the application of this practice in agricultural soils at the global level context-dependent. Our meta-analysis showed that the application of BC in vineyards led to an increase in SOC stocks by +18%, with a SOC sequestration rate of 8.96 Mg CO_2-eq. ha^{-1} yr^{-1}. These values were higher than those found by Safaei Khorram *et al.* (2019) in an apple (*Malus domestica* Borkh.) orchard in Iran, where the use of BC increased SOC stocks by +8% and was associated with a SOC sequestration rate of 4.48 Mg CO_2-eq. ha^{-1} yr^{-1}. Results from our meta-analysis suggest that BC can be used in vineyards as a way to enhance SOC sequestration. The use of BC in viticultural soils may also lead to increased vineyard productivity with no negative impact on grape quality as observed by Genesio *et al.* (2015), though more comprehensive and long-term evidence is required. However, all the field experiments included in the BC category in our meta-analysis had a short duration (≤ 5 years); further studies with long-term experiments are, thus, needed to improve knowledge on the effect of BC on SOC stocks in vineyards in the long term.

The SOC sequestration rate obtained under PR (2.82 Mg CO_2-eq. ha^{-1} yr^{-1}) was the smallest among all SCS practices. Though small, it was nevertheless significantly positive, suggesting that the practice led to an accumulation of SOC relative to conventional management. The use of PR is particularly relevant in winegrowing regions where the removal of pruning residues for burning is quite common and results in residue-removal-induced SOC losses, *e.g.*, in Burgundy and Beaujolais in France (Agreste, 2017). In these winegrowing regions, incorporating the pruning residues into the soil is likely to increase SOC stocks (Wang *et al.*, 2015), since crop residues are precursors for SOM, which constitutes the main store of OC in the soil (Smith *et al.*, 2008). The use of this practice may also be associated with an increase in crop yield (García-Orenes *et al.*, 2016) while maintaining wine quality (Morlat and Chaussod, 2008).

The introduction of NT practices in agricultural systems may have many benefits for sustainable soil management, including reducing soil erosion, improving soil structure and enhancing soil moisture (Derpsch *et al.*, 2010). Adopting NT management may also increase SOC stocks (Ogle *et al.*, 2019), as NT helps to preserve soil aggregates, physically protecting SOC from mineralisation (Merante *et al.*, 2017). Nevertheless, the adoption of NT is not universally applicable for increasing SOC stocks; its effects on SOC stocks are context-specific and depend on climate and soil characteristics (Ogle *et al.*, 2019). Our meta-analysis indicated that, in the case of viticultural soils, the use of NT led to an average positive change in SOC stocks by +20%, resulting in a SOC sequestration rate of 3.50 Mg CO_2-eq. ha^{-1} yr^{-1}. In comparison, Morugán-Coronado *et al.* (2020) reported a higher SOC sequestration rate (5.13 Mg CO_2-eq. ha^{-1} yr^{-1}) under NT management in Mediterranean fruit orchards (including vineyards and almond, olive and citrus orchards). This confirms the positive effect of NT on SOC stocks in vineyards as well as in other woody crop systems. Our results, which were based on field experiments with varying climates and different soil types, helped to reduce the large uncertainties associated with the use of NT in agricultural soils (Ogle *et al.*, 2019).

The use of CC in viticultural soils resulted in an increase in SOC stocks by +22%, with a SOC sequestration rate of 4.45 Mg CO_2-eq. ha^{-1} yr^{-1}. Comparatively, Vicente-Vicente *et al.* (2016) calculated a SOC sequestration rate of 2.86 Mg CO_2-eq. ha^{-1} yr^{-1} in Mediterranean vineyards under CC. Winter *et al.* (2018) also reported a positive change in SOC stocks in viticultural soils under CC relative to conventional management. Our results confirm the positive effect of CC on SOC stocks in viticultural soils observed by previous studies. In addition, Pardo *et al.* (2017) reported that the use of CC in orchards located in Spanish Mediterranean coastal areas (including citrus trees, fruit trees, olive groves and vineyards) resulted in a SOC sequestration rate of 1.61 Mg CO_2-eq. ha^{-1} yr^{-1}. Morugán-Coronado *et al.* (2020) found a SOC sequestration rate of 2.64 Mg CO_2-eq. ha^{-1} yr^{-1} in Mediterranean fruit orchards under CC. Vicente-Vicente *et al.* (2016) estimated that CC in Mediterranean olive and almond orchards were associated with a SOC sequestration rate of 4.03 and 7.48 Mg CO_2-eq. ha^{-1} yr^{-1}, respectively. The SOC sequestration rate found in our study aligns with the broad range of values reported by the literature on woody crop systems. These variations in SOC sequestration rates could be due to the differences in area covered by the CC, which may lead to differing amounts of aboveground and belowground biomass between woody crop systems.

Combinations of SCS practices increased SOC stocks relative to conventional management and were associated with higher SOC sequestration rates than single SCS practices. The combination of SCS practices with the strongest change in SOC stocks (+60%) was OA+NT, with a SOC sequestration rate of 11.06 Mg CO_2-eq. ha^{-1} yr^{-1}, which was 1.4 and 3.2 times higher than that of OA and NT used as single practices, respectively. A slightly lower change in SOC stocks was found under OA+NT+CC (by +41%, for a SOC sequestration rate of 10.51 Mg CO_2-eq. ha^{-1} yr^{-1}). These values were higher than those observed in fruit tree orchards put under similar combined management practices. In a peach (*Prunus persica* L.) orchard under a Mediterranean climate, the use of OA+NT+CC increased SOC stocks by +19% and was associated with a SOC sequestration rate of 3.15 Mg CO_2-eq. ha^{-1} yr^{-1} (Montanaro *et al.*, 2017), which was more than 3 times lower than that observed in vineyards in our study. This suggests that OA+NT+CC is a recommended SCS management option in viticultural agroecosystems, where it may have the potential to increase SOC stocks even more than in other woody cropping systems (*e.g.*, peach orchards).

Combined SCS practices without the use of external organic amendments had a lower positive impact on SOC stocks than OA+NT and OA+NT+CC (+48% for NT+CC and +23% for PR+NT+CC) and were associated with lower SOC sequestration rates (7.63 Mg CO_2-eq. ha^{-1} yr^{-1} for NT+CC and 6.35 Mg CO_2-eq. ha^{-1} yr^{-1} for PR+NT+CC). Though lower, the SOC sequestration rates of these combined practices rely only on carbon inputs produced within the vineyard system and are not subject to the availability of organic fertilisers. Moreover, in the case of NT+CC, the SOC sequestration rate was 1.7 times higher than that of CC used with conventional tillage. This shows the importance of tillage with regards to OC accumulation in the soil: under a combination of NT+CC, the cover crop residues are left onto the soil surface, which leads to slower incorporation and decomposition of OM than when the residues are mechanically incorporated to the soil by tillage and to an overall higher accumulation of SOC in the upper soil layers (Reicosky *et al.*, 1995). In contrast, however, conversion from conventional tillage to NT may result in a decline in SOC stocks at deeper depths and modify the distribution of SOC in the soil profile (Luo *et al.*, 2010).

4.1.2. Köppen-Geiger sub-climates

The comparison of SOC stock responses to SCS management under different climates showed that the BWh sub-climate was associated with the lowest SOC sequestration rate (averaging 0.79 Mg CO_2-eq. ha^{-1} yr^{-1}) among all sub-climates. Vicente-Vicente *et al.* (2016) also observed, in their meta-analysis, that the SOC sequestration rate of CC treatments in woody croplands (including vineyards and olive and almond orchards) under the BWh sub-climate was lower than those under temperate climates, with values averaging 1.43 Mg CO_2-eq. ha^{-1} yr^{-1} for BWh, while Cfb, Csb and Csa were associated with SOC sequestration rates of 4.33, 4.47 and 4.66 Mg CO_2-eq. ha^{-1} yr^{-1}, respectively. The authors attributed the lower SOC sequestration rate measured under the BWh sub-climate to the low net primary crop productivity found in hot and dry locations due to water limitations and physical and chemical constraints to carbon accumulation present under such climate (Post *et al.*, 1996). Water limitations may explain the differences in SOC stock change observed between BSk and BWh treatments, with the SOC sequestration rate of BWh, a hot desert climate with low mean annual precipitation, being significantly lower than that of BSk, a cold semi-arid climate which is wetter than BWh.

Results suggested that SCS management was particularly effective at sequestering OC in vineyards located in cold semi-arid winegrowing regions (*e.g.*, in the Western Cape Province in South Africa), where it was associated with a SOC sequestration rate of 11.40 Mg CO_2-eq. ha^{-1} yr^{-1}. In comparison, the effects of SCS management on SOC stocks were lower in vineyards located in temperate winegrowing regions without a dry season in summer (Cf-type sub-climates, found for instance in the French Loire Valley or Mosel, Germany) and with a dry season in summer (Cs-type sub-climates, found for example in Sicily, Italy or Setúbal, Portugal), where SOC sequestration rates averaged 7.98 (n = 58) and 7.22 (n = 54) Mg CO_2-

eq. ha^{-1} yr^{-1}, respectively. These findings could serve to inform policy making relating to the adoption of SCS management practices in vineyards based on bioclimatic zones.

4.1.3. Study length

The analysis of the impacts of study length on SOC stock change showed that short-term experiments were associated with a SOC sequestration rate 1.2 and 2.2 times higher than that of medium- and long-term experiments, respectively. The same trend was observed for the SOC stock rate of change, whose value for short-term studies was 1.1 and 2.6 times higher than that for medium- and long-term ones, respectively. Plotting the SOC sequestration rate (a) and the SOC stock rate of change (b) against the study length highlighted a negative correlation between the variables, with the SOC sequestration rate and the SOC stock rate of change decreasing as the study length increases (Fig. 11). It aligns with the observations of Francaviglia *et al.* (2019), who also found a negative correlation between the SOC stock rate of change and the duration of SOC sequestration in woody perennial crops under Mediterranean climates. This negative relationship can be due to the specific pattern that the change in SOC stocks follows after the implementation of an SCS practice: the SOC stock, if in equilibrium, increases quickly after new soil management is implemented and progressively declines thereafter until a new equilibrium in the soil is reached (Smith, 2014). According to the IPCC (2006) guidelines, it is considered that most of the change in SOC stocks happens over the 20 years following the adoption of new soil management, though soil equilibrium may take a century to reach (Poeplau and Don, 2015). Thus, studies taking place in the short term only capture the early stage of the SOC response to a change in soil management, *i.e.* when the SOC stock increases rapidly, which leads to overly high SOC sequestration rates calculated. The studies gathered in this paper mainly had a short- (< 6 years) or medium-term (between 6 and 10 years) experiment length (n = 127) and were not long enough to approach SOC stock equilibrium. Results found in this meta-analysis are valid for a period of 10 years following the adoption of SCS management and, to avoid overestimating SOC sequestration rates in the viticulture sector, should not be generalised to the long term.

In addition, changes in SOC stocks must be observed over large temporal scales, since the inter-annual variability of climatic factors (*e.g.*, inter-annual or seasonal temperature and precipitation patterns) have large effects on C cycling (Chou *et al.*, 2008). Long-term studies are more reliable than short- or medium-term studies to estimate SOC stock change but they are rarer in the case of vineyards. Despite the growing number of field experiments in vineyards published over the past two decades, most studies with an experiment length of 10 years or longer were published before 2012. This highlights the need for more long-term experiments in vineyards to be undertaken and published. However, because SOC sequestration has a finite potential and is non-permanent, it is a riskier long-term strategy for climate change mitigation than direct GHG emission reduction (Smith, 2004). Actions to reduce GHG emissions in the wine sector must, therefore, accompany efforts to increase SOC sequestration in viticultural soils.

4.2. Implications of findings regarding the carbon footprint of viticulture and the ‘4 per 1000’ initiative

Overall, the SOC sequestration rates estimated in our meta-analysis averaged 7.53 Mg CO_2-eq. ha^{-1} yr^{-1} for all SCS practices. This suggests that the use of SCS management is an effective way to sequester OC in viticultural soils, particularly for a crop that is commonly cultivated under low input conditions. This value can be compared to area-based life-cycle

GHG emissions in vineyard systems: Aguilera *et al.* (2015) estimated that 0.96 Mg CO_2-eq. ha^{-1} yr^{-1} was emitted in conventional vineyards in Spain (including direct emissions and inputs production); Ponstein *et al.* (2019) estimated GHG emissions from conventional wine grape production in Germany to reach, on average, 1.70 Mg CO_2-eq. ha^{-1} yr^{-1} (including direct emissions and inputs production); Litskas *et al.* (2017) estimated emissions from conventional vineyards in Cyprus to be of 3.37 Mg CO_2-eq. ha^{-1} yr^{-1} (taking into account different types of grapevine variety and their varying input requirements). These values, which are considerably smaller than the average SOC sequestration rate calculated in this study, indicate that the introduction of SCS practices in vineyards could offset GHG emissions from viticultural activities. Assuming that area-based life-cycle GHG emissions from vineyard systems are unchanged under SCS management, the use of SCS management may result in an average GHG emission balance of –6.57 Mg CO_2-eq. ha^{-1} yr^{-1} in Spanish vineyards (ranging from –1.86 under PR to –10.10 Mg CO_2-eq. ha^{-1} yr^{-1} under OA+NT), of –5.83 Mg CO_2-eq. ha^{-1} yr^{-1} in German vineyards (ranging from –1.12 under PR to –9.36 Mg CO_2-eq. ha^{-1} yr^{-1} under OA+NT), and of –4.16 Mg CO_2-eq. ha^{-1} yr^{-1} in Cypriot vineyards (ranging from 0.55 under PR to –7.69 Mg CO_2-eq. ha^{-1} yr^{-1} under OA+NT). This is in line with the results from Bosco *et al.* (2013) and Chiriacò *et al.* (2019), who also estimated a negative GHG emission balance in vineyards under SCS management, though it is considerably higher than the GHG emission balance of –0.03 Mg CO_2-eq. ha^{-1} yr^{-1} estimated by Chiriacò *et al.* (2019) in Italian vineyards under PR+NT+CC.

However, these values do not consider the possible variations in GHG emissions induced by a change in soil management. Previous studies (*e.g.*, Rochette *et al.*, 2008; Lugato *et al.*, 2018) reported increased nitrous oxide (N_2O) emissions associated with positive changes in SOC stocks. The use of NT, for instance, can lead to higher N_2O emissions under SCS management than under conventional management (Rochette *et al.*, 2008), though not always (He *et al.*, 2019). Further research on GHG emissions associated with the use of SCS practices would be necessary to better estimate the GHG emission balance in viticultural soils under SCS management. These values also only take into account GHG emissions from the viticultural phase of wine production, and not that of the whole production of a bottle of wine. The viticultural phase represents about 30% of the product carbon footprint for wine, with values ranging from 19% in Germany (Ponstein *et al.*, 2019) and 25% in Nova Scotia, Canada (Point *et al.*, 2012) to 40% in Italy (Vázquez-Rowe *et al.*, 2013). This suggests that SOC sequestration would not suffice to offset the totality of GHG emissions resulting from wine production. Further actions should, thus, be implemented to reduce GHG emissions in the wine sector, such as switching to light-weighted glass bottles, implementing energy efficiency measures at the vineyard and winery level, and reducing the carbon footprint associated with the transportation of bottled wine (CSWA, 2011).

Furthermore, this study provided the SOC stock rate of change of different SCS management practices in viticultural soils (Fig. 5). The average SOC stock rate of change for all SCS practices was +5.8% yr^{-1} to a 30-cm soil depth, which was much higher than the ‘4 per 1000’ target of increasing SOC stocks by +0.4% annually to a 40-cm soil depth. It suggests that vineyards could play an important role in meeting the annual target of the initiative, especially in countries with a large viticultural land, such as Spain or France. Reaching the ‘4 per 1000’ objective in France would require a SOC sequestration rate of 14.4 Tg C yr^{-1} (*i.e.* 52.8 Tg CO_2-eq. yr^{-1}) in the 0-30 cm soil layer (Minasny *et al.*, 2017). Considering that there are 0.793 Mha dedicated to viticulture in France (OIV, 2019), the use of SCS management in all French vineyards could potentially sequester 5.97 Tg CO_2-eq. yr^{-1} on average in the 0-30 cm soil layer (with values ranging from 2.24 under PR to 8.77 Tg CO_2-eq. yr^{-1} under

OA+NT). This means that French viticultural soils may sequester 11% of the total amount of carbon needed to reach the target of the initiative at the national level annually (or between 4 and 17% depending on the SCS practices considered). However, the feasibility of this SOC sequestration in French viticultural soils depends on the initial SOC stocks in vineyards, as soils with an already high SOC stock might not store much more carbon, while it might be hard to increase SOC stocks in soils with low OC due to climatic or management constraints (Minasny *et al.*, 2017).

4.3.Gaps and uncertainty

The high representation of Spain, Italy and France in the studies collected occurred as these countries have a large area dedicated to viticulture: 0.969 Mha for Spain, 0.705 Mha for Italy and 0.793 Mha for France in 2018 (OIV, 2019). Together, these three countries represent 33% of the global land area dedicated to viticulture and are all in the top five countries by viticultural land. However, no experiment taking place in China was found by the literature search, even though China's area dedicated to viticulture is the second biggest in the world with 0.875 Mha in 2018 (OIV, 2019). This could be explained by the fact that grape cultivation has expanded in China only recently, growing from 10,000 ha in the 1960s (FAO, 2019) to 875,000 ha in 2018 (OIV, 2019), and is mainly dedicated to the production of table (84.1%) and dried (5.6%) grapes (OIV, 2019). Turkey, whose area under vines is the fifth in the world with 0.448 Mha in 2018 (OIV, 2019), was also underrepresented in the meta-analysis with a single study taking place in the country. The other countries (the USA, South Africa, Australia and Germany), by comparison, have a smaller land area dedicated to viticulture (< 0.450 Mha), which is coherent with the number of studies found for these countries.

Other gaps have been identified relating to the SCS practices and bioclimatic zones included in the meta-analysis. Though several SCS practices applicable to viticulture were analysed, not all of them were covered in this study (*e.g.*, using contour hedges, optimising soil pH or water management were missing), which underlines the need for further research to be undertaken about SCS practices in viticultural soils. In addition, the sub-climates included in the study were consistent with the climatic distribution of vineyards at the global level: most vineyards producing high-quality wine are located in regions where the average temperature during the growing season (*i.e.* between April and October in the Northern Hemisphere and between October and April in the Southern Hemisphere) is between 13 and 21 °C (Jones, 2006). However, other sub-climates under which viticulture is also found were missing (*e.g.*, BSh in Pantelleria, Italy or Dfb in Styria, Austria).

Some sources of uncertainty in our study were due to the fact that our methodology used an approach based on fixed depth to calculate SOC stocks. Bulk density, which was used with SOC concentration and sampling depth to estimate SOC stocks, was only provided in a few studies (30%). Pedotransfer functions (Equations (2) and (3)) were, thus, used to estimate this parameter from the SOC concentration reported in the studies. However, there is a high uncertainty in the prediction of bulk density using these functions, since specific management practices may affect differently bulk density within a given land use, according to the IPCC (2019) guidelines. Efthimiadou *et al.* (2010) proved that the use of OA generally decreases bulk density, while reducing tillage is usually associated with a positive change in bulk density (Hernanz *et al.*, 2009). The uncertainty related to the effect of bulk density changes on SOC stock estimation may lead to an overestimation or an underestimation of the SOC stock in the experiment (IPCC, 2019). A more accurate way to estimate SOC stocks would be to use a soil-mass equivalent approach instead of a soil-volume equivalent approach, as recommended by the IPCC (2019) guidelines. Unfortunately, most studies gathered in our meta-analysis did not provide the necessary information required to use a soil-mass equivalent approach (*i.e.* dry sample mass, area sampled by the probe or auger, etc.).

In addition, the average sampling depth in field experiments was 0.31 m. This value is in line with the IPCC (2006) guidelines, which recommend the sampling of the top 0.3 m of soil to estimate changes in SOC stocks under new soil management. However, a number of studies included in the meta-analysis showed that changes in SOC stocks occurred deeper than 30 cm (*e.g.*, Peregrina *et al.*, 2014) and, in some cases, deeper than 60 cm (*e.g.*, Agnelli *et al.*, 2014). Field experiments reporting shallower depths (< 30 cm) tended to underestimate the SOC sequestration potential by overlooking changes in SOC stocks in deeper soil layers. Luo *et al.* (2010) also showed that the adoption of NT may provoke a redistribution of SOC in the soil profile, with increases in SOC stocks in surface layers and decreases in SOC stocks in deeper layers. Focusing only on the top 0.3-m soil layer may have led to an overestimation of OC sequestration in viticultural soils under NT, since potential net losses occurring in deeper soil layers were not accounted for in SOC stock change calculations.

5. Conclusions

This research could serve to inform policy making with regards to climate change mitigation in the viticulture sector by estimating potential SOC sequestration rates in 0-30 cm depth that could be obtained in viticultural soils following the adoption of SCS practices. Our findings indicated that the use of SCS practices may increase SOC stocks in viticultural soils, with an average SOC sequestration rate of 7.53 Mg CO_2-eq. ha^{-1} yr^{-1} to 30-cm depth for all SCS practices relative to conventional management. The increase in SOC stocks was the highest under a combination of OA+NT, which was associated with a SOC sequestration rate of 11.06 Mg CO_2-eq. ha^{-1} yr^{-1}. This combination of SCS practices may, therefore, be a suitable management option for increasing SOC sequestration in vineyards. The lowest SOC sequestration rate for 0-30 cm depth was found under PR (2.82 Mg CO_2-eq. ha^{-1} yr^{-1}). However, even though the change in SOC stock associated with this practice was low, it was positive and non-negligible. This suggests that, even though their global land area is not as extensive as grasslands' or annual croplands', vineyards can play a crucial role in the global efforts to enhance SOC sequestration in agricultural land to mitigate climate change.

Our study also showed that the adoption of SCS practices in vineyards may offset GHG emissions from viticultural activities and contribute to reducing the carbon footprint of the wine sector at the global level. Findings from this study indicated that the use of SCS practices in vineyard agroecosystems may help to achieve the targets of the '4 per 1000' initiative, particularly in regions with a large viticultural land, as SCS management may be associated with an increase of +5.8% yr^{-1} in SOC stocks in viticultural soils to a 30-cm soil depth. More exhaustive field experiments providing measurements of all necessary data to calculate changes in SOC stocks in vineyards under SCS management compared to those under conventional management and of GHG fluxes are needed, however, to improve the accuracy of our findings. Further research is also needed to quantify the change in SOC stocks in vineyards under SCS management using modelling approaches to complement the findings from our meta-analysis. Modelling could also be conducted at the regional level to investigate the variations of SOC stock response under SCS management according to the differences in climate, soil texture, initial SOC stocks, etc. between and within winegrowing regions.

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Competing interests

Declarations of interest: none.

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Table 1. Defining criteria of the Köppen-Geiger classification and climate symbols (Peel *et al.*, 2007).

1st	2nd	3rd	Description	Criteria
A			Tropical	$T_{cold} \geq 18$ °C
	f		- Rainforest	$P_{dry} \geq 60$ mm
	m		- Monsoon	Not (Af) & $P_{dry} \geq (100 – MAP/25)$
	w		- Savannah	Not (Af) & $P_{dry} < (100 – MAP/25)$
B			Arid	$MAP < 10 \times P_{threshold}$
	W		- Desert	$MAP < 5 \times P_{threshold}$
	S		- Steppe	$MAP \geq 5 \times P_{threshold}$
		h	- Hot	$MAT \geq 18$ °C
		k	- Cold	$MAT < 18$ °C
C			Temperate	$T_{hot} > 10$ °C & 0 °C $< T_{cold} < 18$ °C
	s		- Dry summer	$P_{sdry} < 40$ mm & $P_{sdry} < P_{wwet}/3$
	w		- Dry winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Cs) or (Cw)
		a	- Hot summer	$T_{hot} \geq 22$ °C
		b	- Warm summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold summer	Not (a or b) & $1 \leq T_{mon10} < 4$
D			Cold	$T_{hot} > 10$ °C & $T_{cold} \leq 0$ °C
	s		- Dry summer	$P_{sdry} < 40$ mm & $P_{sdry} < P_{wwet}/3$
	w		- Dry winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Ds) or (Dw)
		a	- Hot summer	$T_{hot} \geq 22$ °C
		b	- Warm summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold summer	Not (a, b or d)
		d	- Very cold winter	Not (a or b) & $T_{cold} < –38$ °C
E			Polar	$T_{hot} < 10$ °C
	T		- Tundra	$T_{hot} > 0$ °C
	F		- Frost	$T_{hot} \leq 0$ °C

MAP = mean annual precipitation, MAT = mean annual temperature, T_{hot} = temperature of the hottest month, T_{cold} = temperature of the coldest month, T_{mon10} = number of months where the temperature is above 10 °C, P_{dry} = precipitation of the driest month, P_{sdry} = precipitation of the driest month in summer, P_{wdry} = precipitation of the driest month in winter, P_{swet} = precipitation of the wettest month in summer, P_{wwet} = precipitation of the wettest month in winter. If 70% of MAP occurs in winter, then $P_{threshold}$ = 2 x MAT; if 70% of MAP occurs in summer, then $P_{threshold}$ = 2 x MAT + 28; otherwise, $P_{threshold}$ = 2 x MAT + 14.

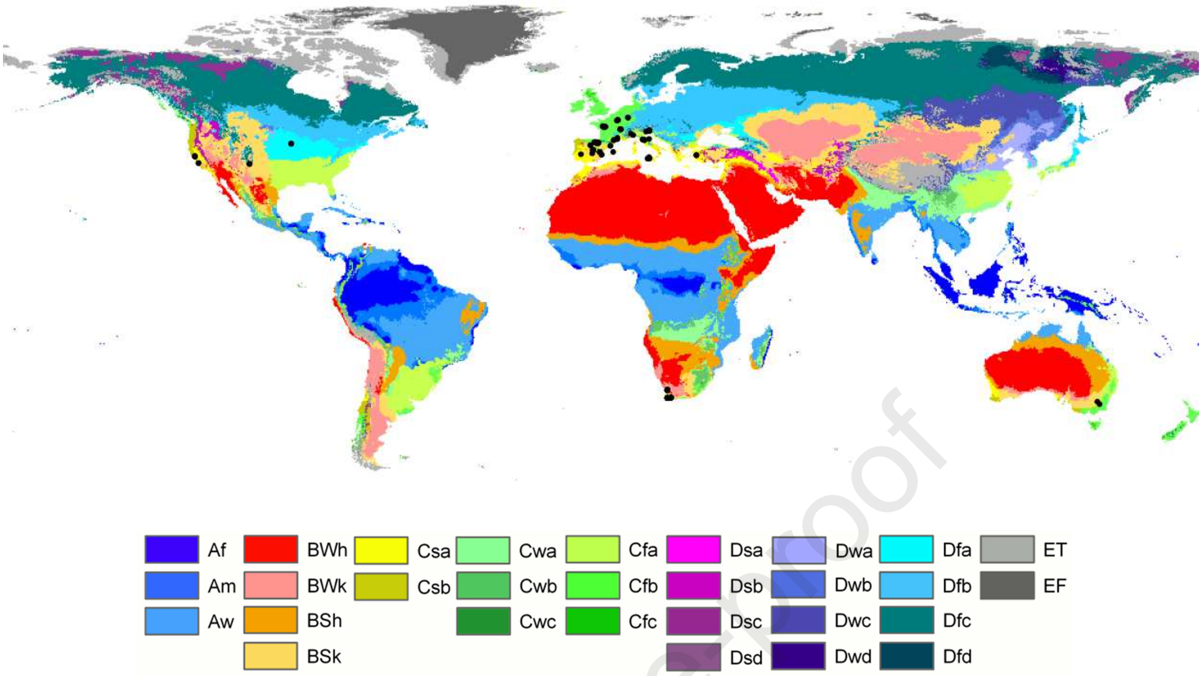


Figure 1. Map of the present Köppen-Geiger classification (Beck *et al.*, 2018) with the locations of the experimental vineyards considered in this meta-analysis.

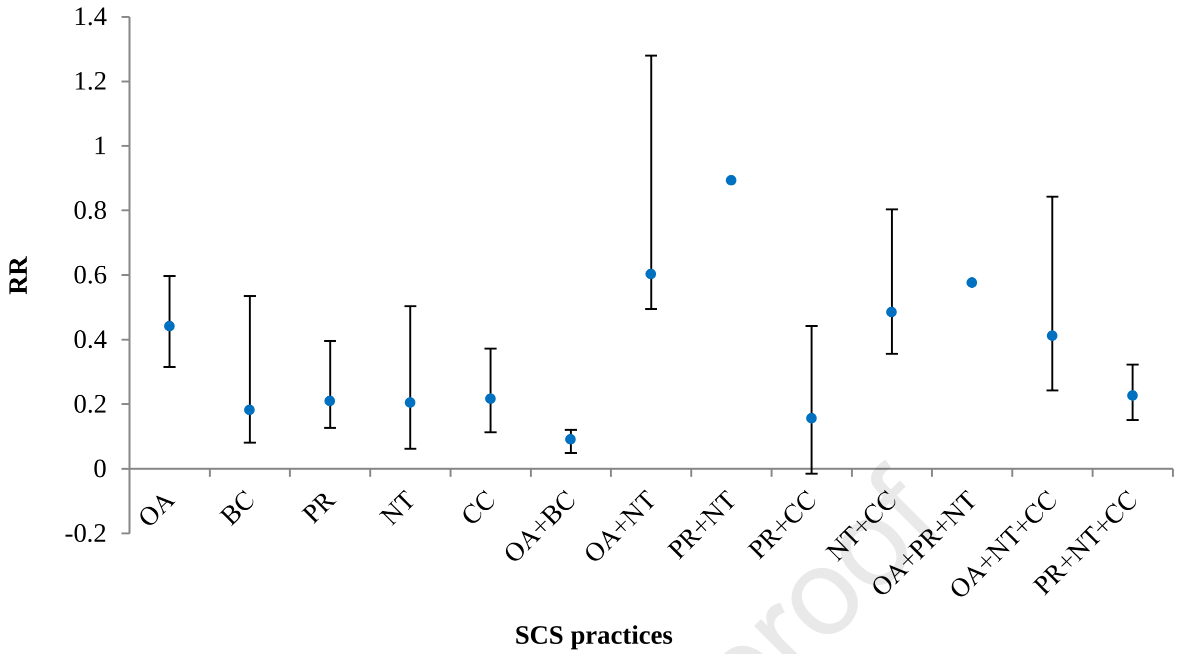


Figure 2. Influence of SCS practices (OA, organic amendments; BC, biochar; PR, pruning residues; NT, no-tillage; and CC, cover crop) on the SOC stock response ratio (RR). PR+NT and OA+PR+NT were not included in the analysis, since only one comparison was observed for these categories. Points represent weighted average values, whereas error bars correspond to the 95% confidence intervals.

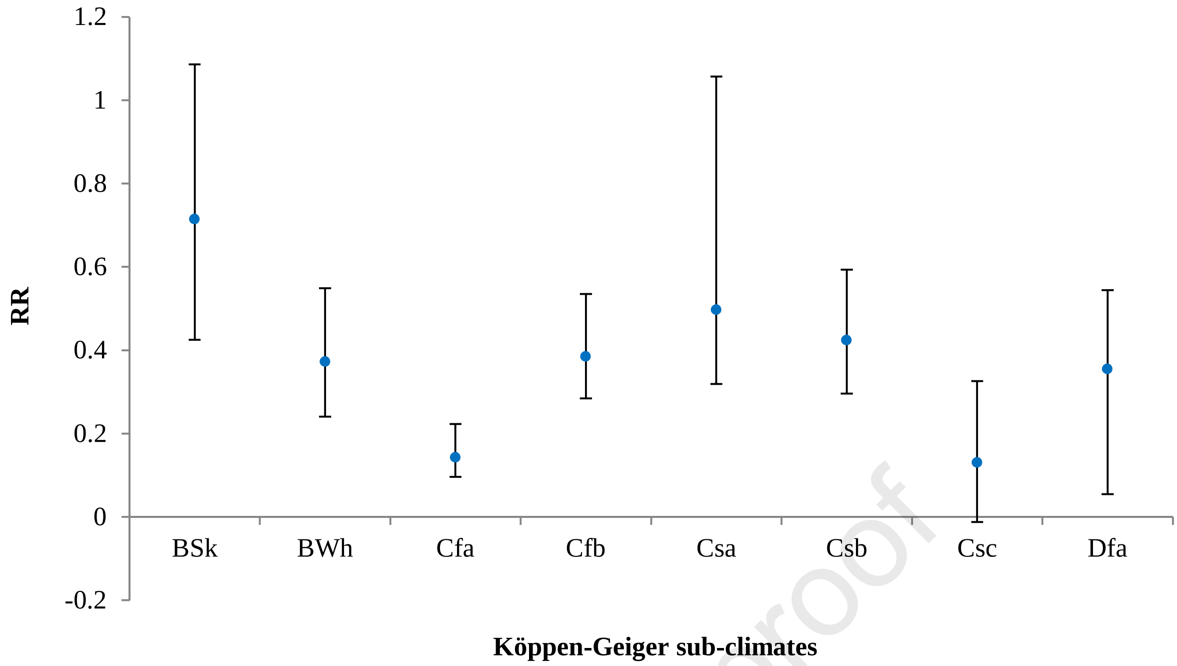


Figure 3. SOC stock response ratio (RR) per Köppen-Geiger sub-climate (BSk, cold semi-arid climate; BWh, hot desert climate; Cfa, humid sub-tropical climate; Cfb, temperate oceanic climate; Csa, hot-summer Mediterranean climate; Csb, warm-summer Mediterranean climate; Csc, cold-summer Mediterranean climate; Dfa, hot-summer humid continental climate). Points represent weighted average values, whereas error bars correspond to the 95% confidence intervals.

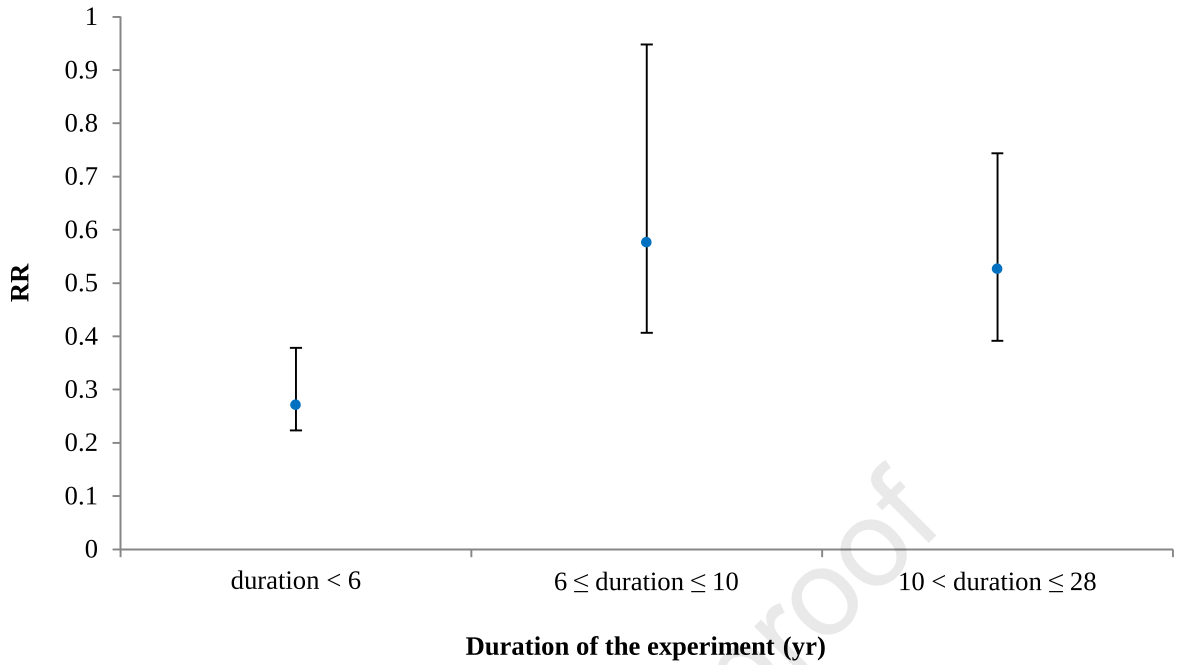


Figure 4. Influence of management duration on the SOC stock response ratio (RR). Points represent weighted average values, whereas error bars correspond to the 95% confidence intervals.

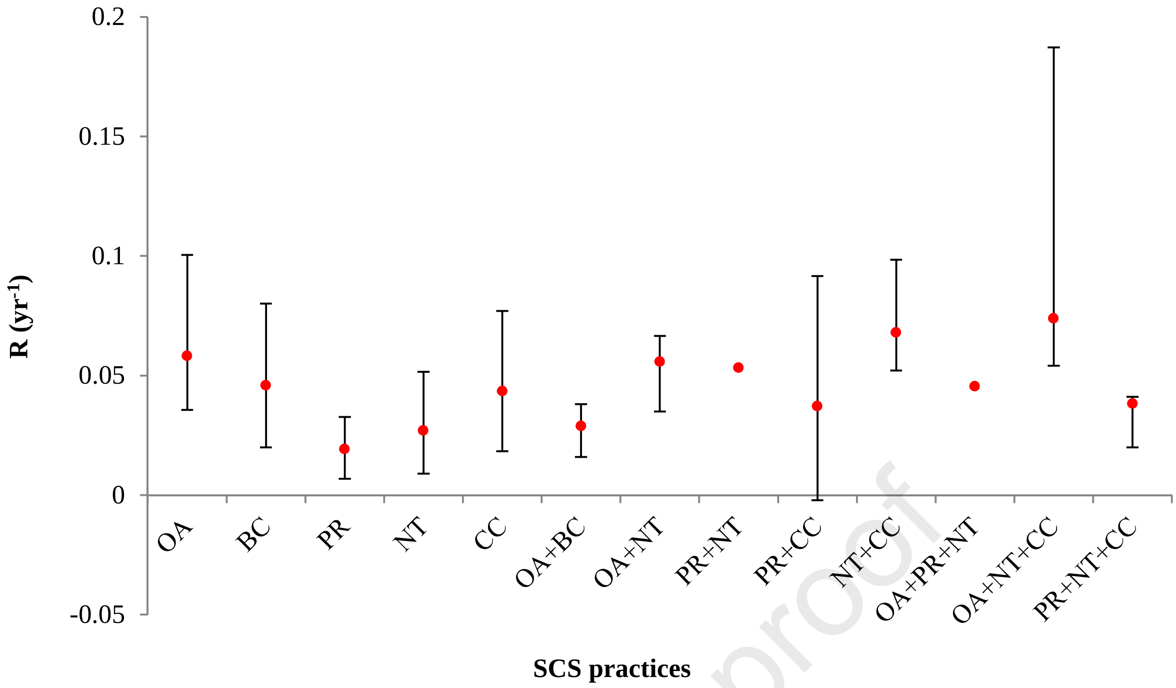


Figure 5. Effects of SCS practices (OA, organic amendments; BC, biochar; PR, pruning residues; NT, no-tillage; and CC, cover crop) on the SOC stock rate of change (R). PR+NT and OA+PR+NT were not included in the analysis, since only one comparison was observed for these categories. Points represent weighted average values, whereas error bars correspond to the 95% confidence intervals.

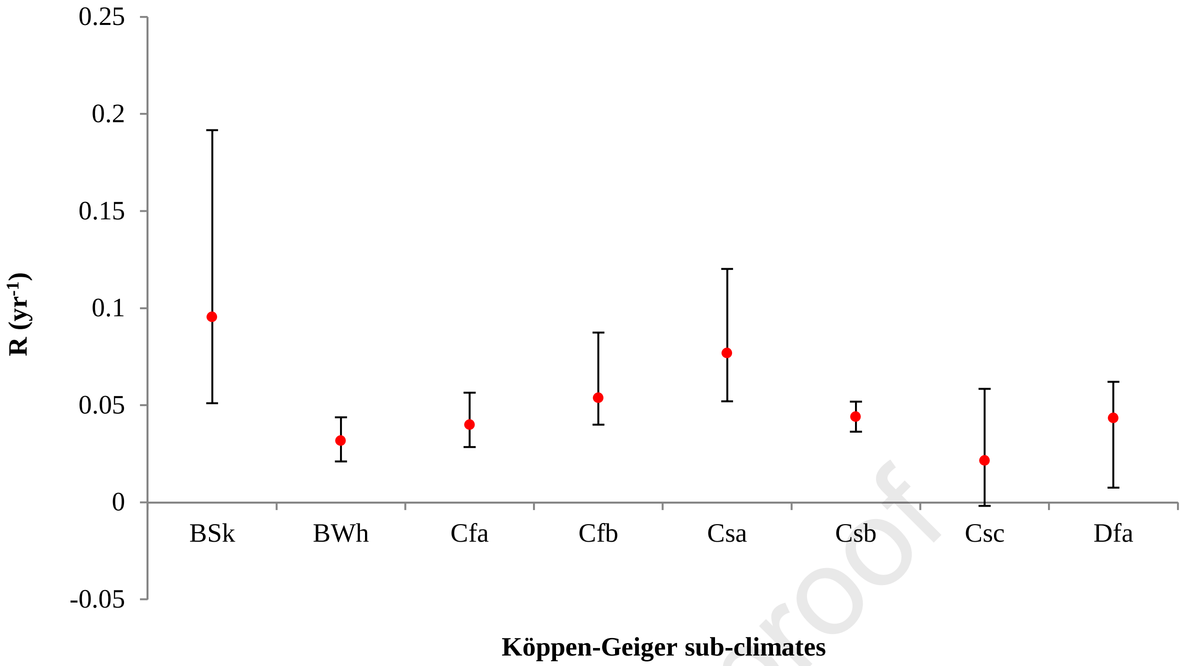


Figure 6. SOC stock rate of change (R) per Köppen-Geiger sub-climate (BSk, cold semi-arid climate; BWh, hot desert climate; Cfa, humid sub-tropical climate; Cfb, temperate oceanic climate; Csa, hot-summer Mediterranean climate; Csb, warm-summer Mediterranean climate; Csc, cold-summer Mediterranean climate; Dfa, hot-summer humid continental climate). Points represent weighted average values, whereas error bars correspond to the 95% confidence intervals.

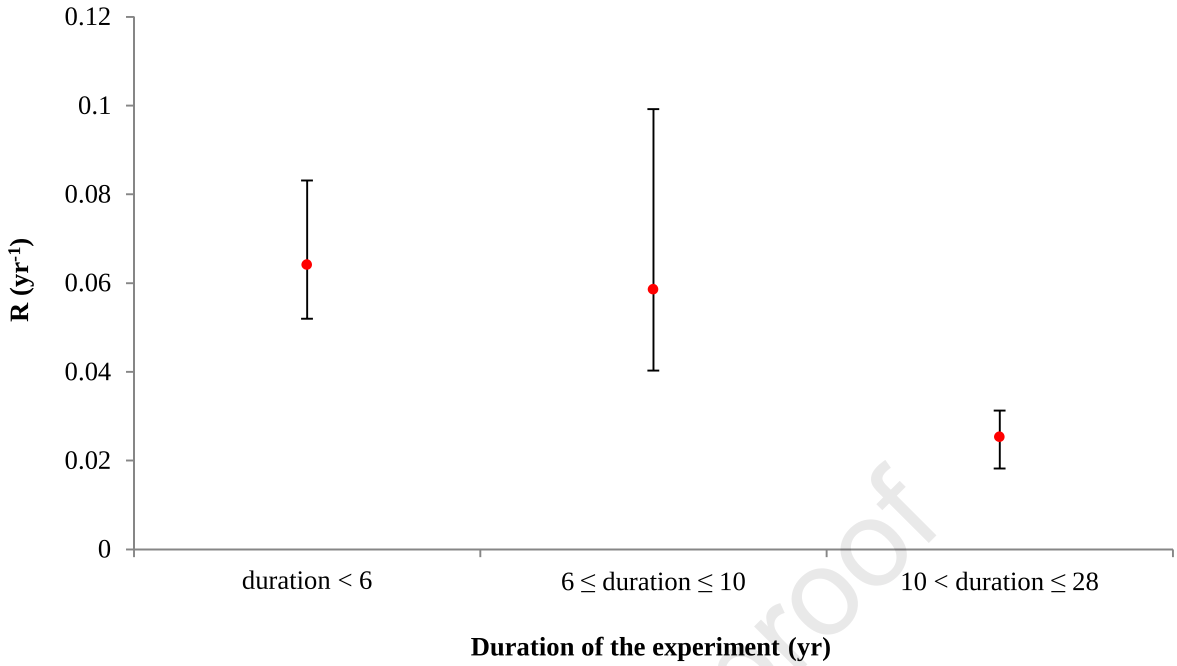


Figure 7. Effects of management duration on the SOC stock rate of change (R). Points represent weighted average values, whereas error bars correspond to the 95% confidence intervals.

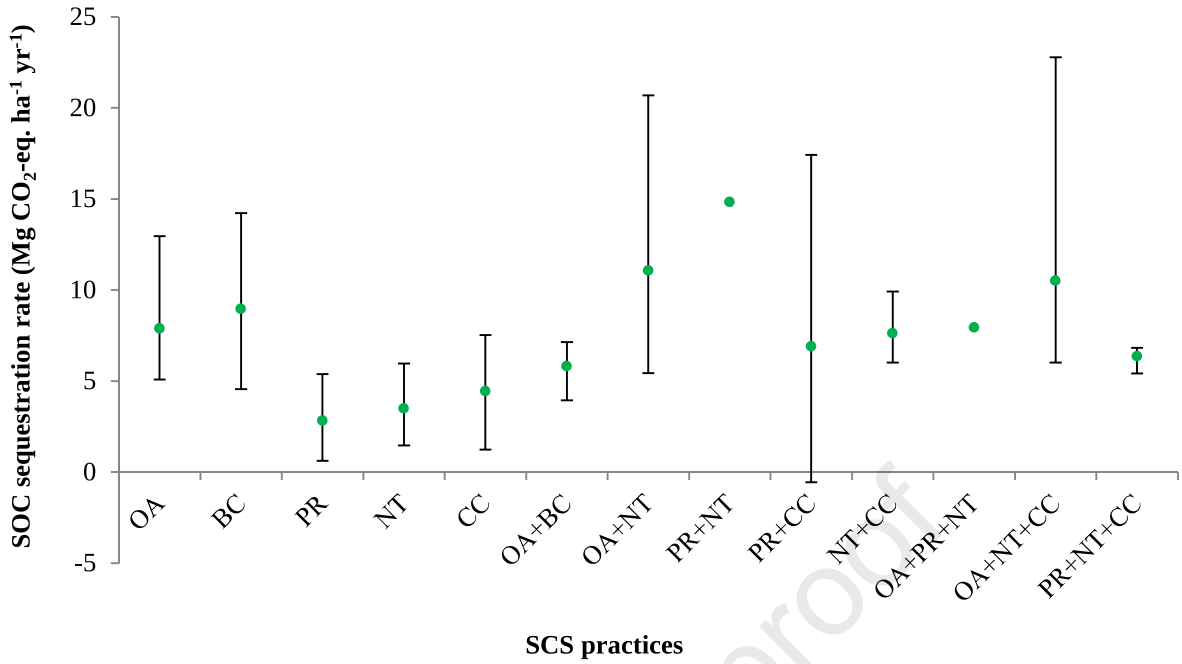


Figure 8. Impacts of SCS practices (OA, organic amendments; BC, biochar; PR, pruning residues; NT, no-tillage; and CC, cover crop) on the SOC sequestration rate. PR+NT and OA+PR+NT were not included in the analysis, since only one comparison was observed for these categories. Points represent weighted average values, whereas error bars correspond to the 95% confidence intervals.

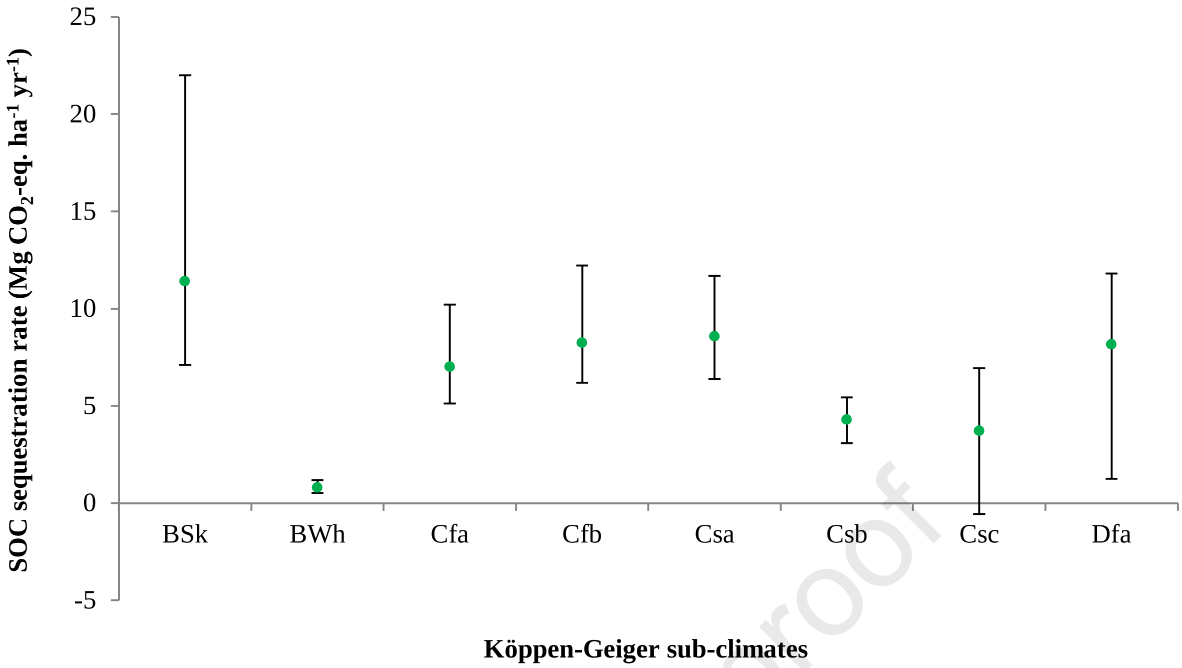


Figure 9. SOC sequestration rate per Köppen-Geiger sub-climate (BSk, cold semi-arid climate; BWh, hot desert climate; Cfa, humid sub-tropical climate; Cfb, temperate oceanic climate; Csa, hot-summer Mediterranean climate; Csb, warm-summer Mediterranean climate; Csc, cold-summer Mediterranean climate; Dfa, hot-summer humid continental climate). Points represent weighted average values, whereas error bars correspond to the 95% confidence intervals.

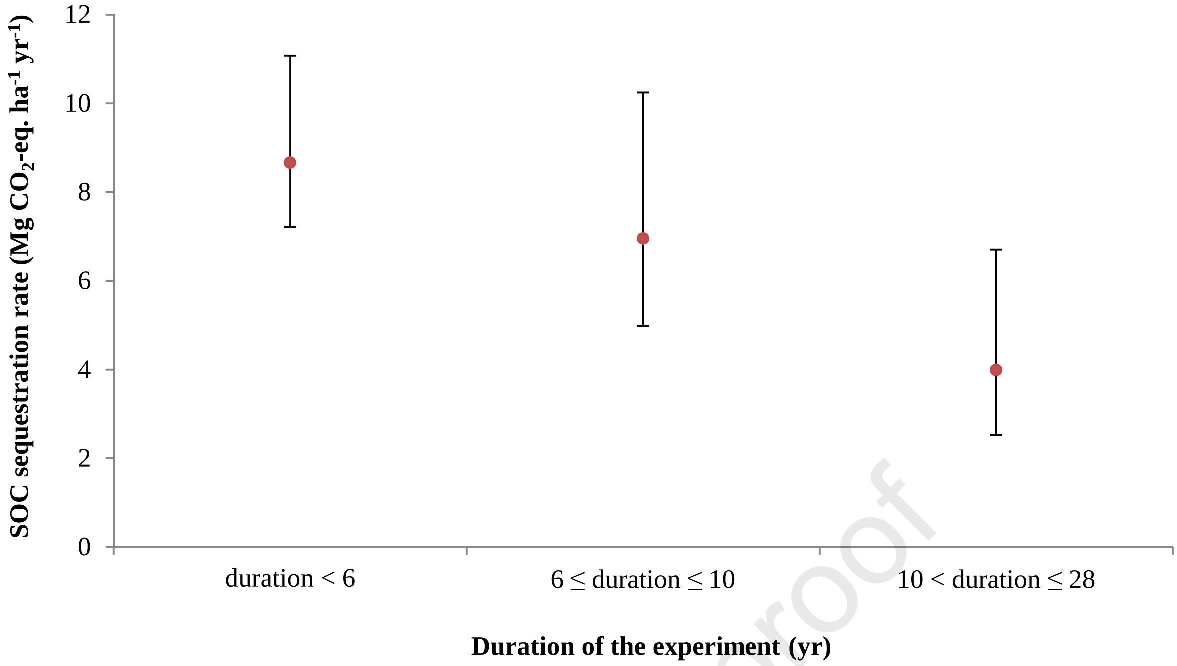
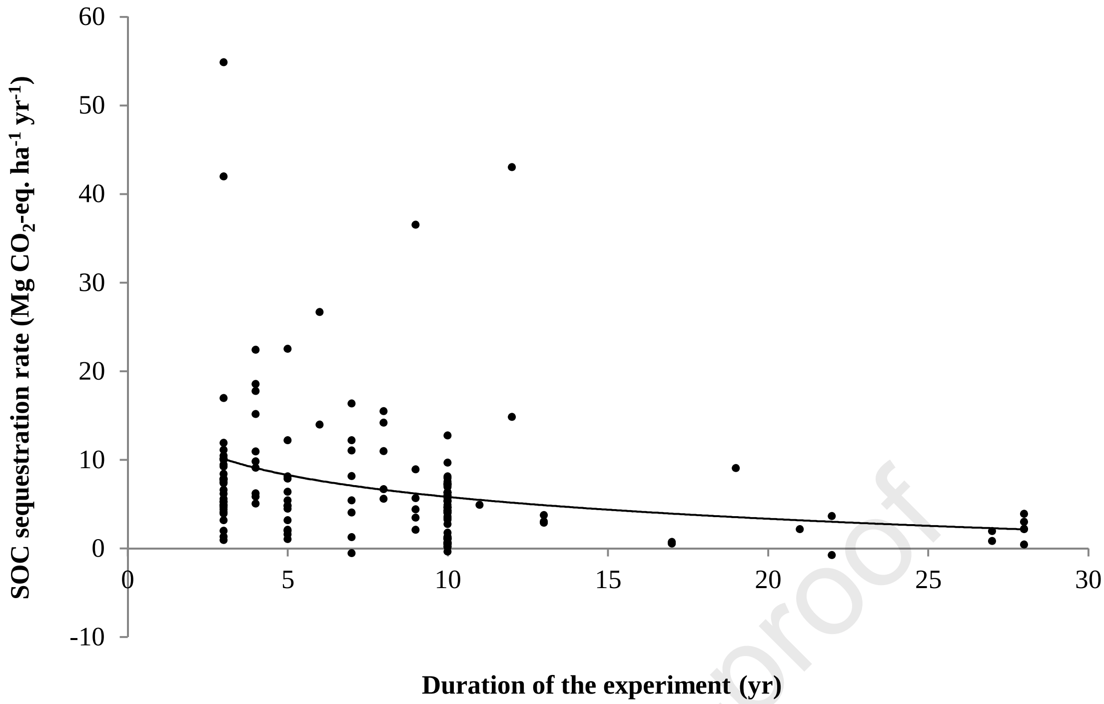
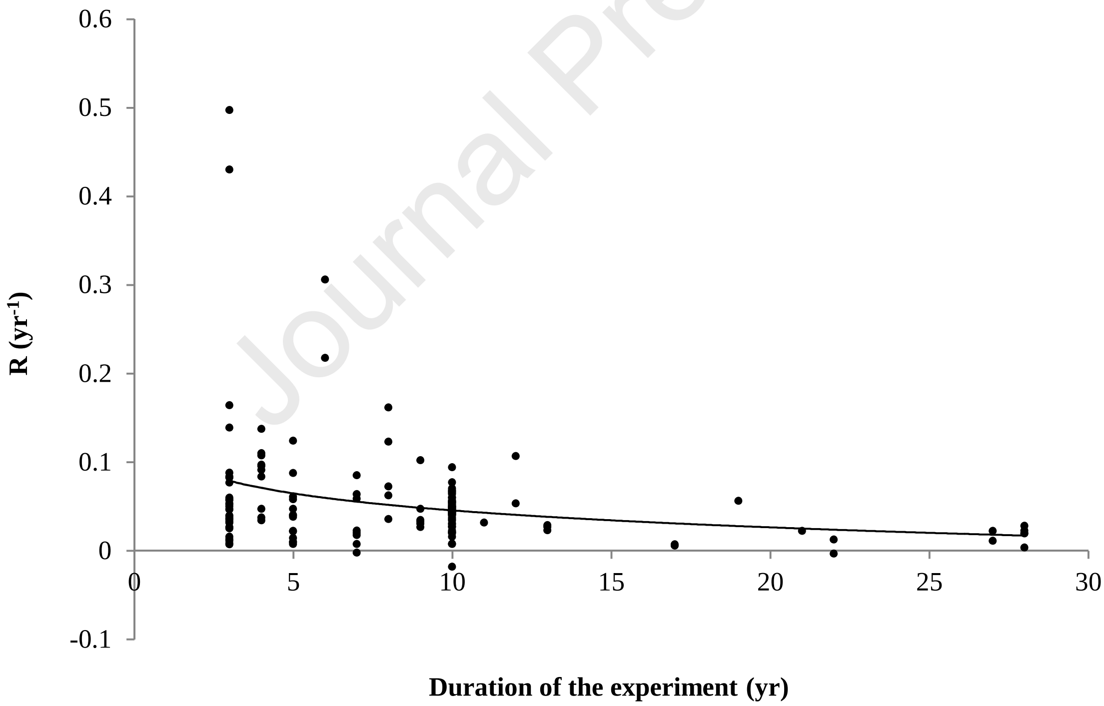


Figure 10. Impacts of management duration on the SOC sequestration rate. Points represent weighted average values, whereas error bars correspond to the 95% confidence intervals.



(a)



(b)

Figure 11. Variation of the SOC sequestration rate (a) and R (b) according to the duration of the experiment.

Highlights

- Effects of soil carbon sequestration (SCS) practices were assessed in vineyards using a meta-analysis.
- All SCS practices led to soil organic carbon (SOC) accumulation in viticultural soils.
- The average SOC sequestration rate was 7.53 Mg CO_2-eq. ha^{-1} yr^{-1}.
- The impact of SCS management on SOC stocks was climate-dependent.

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: