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Effect of green covers and organic amendments on soil organic carbon stock in Mediterranean vineyards: A meta-analysis

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ABSTRACT

Since the start of agriculture, soils in the Mediterranean have been losing carbon (C) to the atmosphere due to land conversion and inadequate agricultural practices, which undermine soil functions, such as nutrient cycling and water retention, and contribute to global warming through CO_2 emissions. Among Mediterranean crops, vineyards exhibit the highest rates of soil loss, leading to shallower soils with lower soil organic carbon (SOC) content. A change to recommended management practices (RMPs) may increase soil carbon content and enhance net carbon sequestration. In this meta-analysis, we assess the potential of RMPs by comparing SOC stock in vineyards under conventional management with those managed using different RMPs, specifically green covers (GC) and organic amendments (OA). The publications were sourced from the Web of Science database and the bibliography of previous meta-analyses. Publications that reported content of organic carbon or organic matter in control and RMP Mediterranean vineyards were included. Egger's regression tests and funnel plots were generated to diagnose publication bias. The carbon stock standardised mean difference (CS_{SMD}) was calculated as the effect size. A total of 47 studies and 173 comparisons were included in the meta-analysis: 38 studies and 124 comparisons examined GC, 15 studies and 53 comparisons focused on OA, and 12 comparisons from 5 studies applied GC and OA in the same field. Results indicate that Mediterranean vineyards managed with GC and/or OA have higher SOC stock than conventionally managed vineyards, particularly in the top 30 cm layer. On average, GC and OA increase SOC by 1.32 Mg C ha^{-1} and 2.22 Mg C ha^{-1}, respectively. These practices are more effective in colder climates, and GC efficiency also increases in more humid climates. On average, OA-driven SOC stock improvement peaks after four years of application, while GC is more effective in enhancing SOC stocks in sloped vineyards. Lack of information on environmental variables, soil stone content, bulk density and initial SOC stock are important limitations for this meta-analysis, and longer studies are required to observe more stable changes in SOC.

KEYWORDS: SOC, regenerative viticulture, carbon sequestration, global warming

INTRODUCTION

Soils provide essential ecosystem services and functions we rely upon, such as crop production, carbon sequestration, water retention, and nutrient cycling (Wagg *et al.*, 2014; Wall *et al.*, 2010), while also hosting a significant portion of global biodiversity (Anthony *et al.*, 2023).

The biggest carbon (C) pool is the dissolved inorganic C in the ocean (37000 Gt). However, soils represent the greatest terrestrial C pool, with an estimated global content of 1700 Gt, approximately four times larger than the terrestrial aboveground carbon pool (Friedlingstein *et al.*, 2023). However, soil also emits 60 Gt of CO_2 annually, ten times more than fossil fuels (Tang *et al.*, 2022). A significant portion of this efflux is driven by land conversion to agriculture and agricultural practices, such as tillage (Zhang *et al.*, 2012).

Sanderman *et al.* (2017) calculated, using a model, that 133 Gt C have been lost in the top 2 m of soil worldwide since the beginning of agriculture 12,000 years ago. Since then, carbon inputs to the atmosphere have continued to increase due to fossil CO_2 emissions and land-use changes. Friedlingstein *et al.* (2023) estimated total anthropogenic emissions to be 11.1 Gt C yr^{-1} in 2022. Current agricultural practices contribute to 10–12 % of total human-induced greenhouse gas emissions (Smith *et al.*, 2014) and are also responsible for increased soil degradation (Wood *et al.*, 2000), which undermines ecosystem services (Foley *et al.*, 2005).

Soil organic carbon (SOC) and ecosystem services losses can be minimised through the so-called recommended management practices (RMPs), which promote closed nutrient cycles and may lead to an increase in soil carbon concentration and net carbon sequestration (Jarecki & Lal, 2003). With the global adaptation of these practices, SOC levels could increase at a rate of 0.9–1.85 Gt C yr^{-1} (Zomer *et al.*, 2017). However, there is some controversy over whether this increase is globally achievable due to cultural and economic barriers, as well as whether it would be sufficient to significantly alleviate the carbon dioxide imbalance (Amundson & Biardeau, 2018). On a local scale, however, SOC increases can enhance agricultural outcomes due to its central role in soil ecosystem services. SOC contributes to improved soil structure (micro- and macro-aggregates), enhances soil water storage and nutrient retention, prevents topsoil erosion, and supports biodiversity (Montanaro *et al.*, 2017). Conversely, SOC is also highly sensitive to soil degradation (Costantini *et al.*, 2018) and therefore considered a major indicator of soil quality (Zornoza *et al.*, 2015). This is why SOC loss itself is often considered a degradation process, alongside erosion, salinisation, and compaction (Lal, 2015).

In the future, climate change is expected to accelerate SOC decomposition rates and reduce SOC accumulation, potentially resulting in significant losses of C stored in agricultural soils (Davidson & Janssens, 2006; Zhang *et al.*, 2024). However, authors such as Almagro *et al.* (2017) have observed that CO_2 flux is more sensitive to temperature increments under conventional tillage than under reduced tillage, the latter also associated with higher SOC stocks. This indicates that management practices are a significant factor in the vulnerability of organic carbon mineralisation in the context of global warming. Novara *et al.* (2020) reports CO_2 emissions from SOC dynamics in conventional vineyards of 0.30 Mg ha^{-1} yr^{-1}, while vineyards with green covers can achieve negative emissions (–0.04 Mg ha^{-1} yr^{-1}). This and other studies highlight the importance of SOC to build resistance to climate change (Lal *et al.*, 2011) and also mitigate global warming through carbon sequestration, especially in the Mediterranean (Aguilera *et al.*, 2013).

Vineyards show the highest rate of soil loss of all Mediterranean agriculture (Kosmas *et al.*, 1997), leading to shallower soils and lower SOC content. However, Mediterranean woody crops, such as grapevines, have significant potential to enhance agricultural sustainability because of their resilience and their capacity to sustain perennial biomass. They can coexist with green covers and other crops, while their soil can be managed under various practices to improve environmental sustainability. Additionally, rainfed crops usually have lower greenhouse gas emissions compared to irrigated crops, as the addition of water and fertilisers in irrigated systems favour these emissions (MedECC, 2020). Among the most widely adopted RMPs in vineyards are the use of soil organic amendments and the establishment of green covers. These practices are central to regenerative agriculture, which involves a combination of different practices aimed at improving soil quality and enhancing biodiversity (Schreefel *et al.*, 2020).

Previous meta-analyses on Mediterranean crops (Aguilera *et al.*, 2013), Mediterranean woody crops (Vicente-Vicente *et al.*, 2016), and vineyards worldwide (Payen *et al.*, 2021b) have demonstrated that RMPs significantly promote C sequestration, especially when the practices involve the addition of substantial C inputs to the soil. These studies highlight RMPs as an effective strategy to offset anthropogenic greenhouse gas emissions and mitigate climate change.

Our study aims to review current knowledge and conduct a meta-analysis to compare the efficiency of various soil management practices in C sequestration, which may, in turn, enhance ecosystem services in Mediterranean vineyards. The meta-analysis includes studies comparing different green cover and organic amendment practices with conventional management, while also evaluating the influence of various factors that moderate the effectiveness of these practices. Although previous studies have provided meta-analyses on potential carbon sequestration in vineyards and have studied the effect of climatic factors on the efficiency of green covers and organic amendments, this is the first study assessing the carbon sequestration potential focused on Mediterranean vineyards that explores all these environmental and soil properties variables as moderators of the meta-analyses.

MATERIALS AND METHODS

1. Data collection

The publications were sourced from the Web of Science database, last consulted in December 2023, using a specific query applied to the abstracts of the papers: "carbon stock" OR "carbon sequestration" OR "SOC" OR "C sequestration" OR "SOM" AND "viticulture" OR "grapevine" OR "vineyard" OR "*Vitis vinifera*" AND "soil". We then applied the following exclusion criteria: 1) publications focused on crops other than grapevine; 2) studies conducted in non-Mediterranean climate; 3) research unrelated to the soil management practices of interest; 4) non-empirical studies based on predictive models; 5) studies that did not report standard error or standard deviation; and 6) studies on specific vineyards that are also reported in more recent studies. Additionally, articles cited in the bibliographies of previous meta-analyses that were not included in the initial search were also revised (Payen *et al.*, 2021b; Vicente-Vicente *et al.*, 2016).

If precipitation, temperature, altitude, and slope data were not specified in the paper, the values were obtained from the Worldclim 2 database (Fick & Hijmans, 2017) whenever the coordinates of the experimental site were available. In cases where a study did not specify irrigation, it was assumed that the vineyard was rainfed. Information about climate was extracted from the Köppen–Geiger climate classification (Beck *et al.*, 2020). Additionally, when soil texture was indicated but clay content was not specified, it was approximated using the USDA Soil Texture Calculator (USDA, n.d.) by assigning the midpoint value of the clay range to each texture class.

2. Response calculation and explanatory variables categorisation

Carbon stocks (CS), expressed in kg C m^{-2}, was the primary response variable of interest. When data was only available in graphical form, numeric values were extracted using WebPlotDigitizer software v.5 (Rohatgi, 2024). For studies that reported soil organic matter (SOM) of the fine-earth fraction, SOC was calculated following (Payen *et al.*, 2021b), using the relationship developed by Pribyl (2010): SOC = 0.58 × SOM. Given this, CS was calculated using Equation (1) (Food and Agriculture Organization of the United Nations, 2017):

$$CS = d * BD * SOC * (1\text{-}(\%\ S/100)) \quad \text{(Equation 1)}$$

where *CS* is expressed in kg m^{-2}; d is the depth of the soil layer in m; *BD* is the bulk density in kg m^{-3}; *SOC* is the fine earth fraction (in g g^{-1}) (particles < 2 mm) organic carbon concentration; and *S* represents stoniness, expressed as the percentage of coarse elements (particles > 2 mm).

When BD was not provided in the study, it was estimated using Equation (2), a pedotransfer function re-parametrised for Mediterranean climates by Aguilera *et al.* (2013):

$$BD\ (\text{g cm}^{-3}) = 1.84\text{-}0.443*\log([SOC\ (\text{g kg}^{-1})];10) \quad \text{(Equation 2)}$$

Stone content data were obtained from authors by e-mail when studies did not make it available. It was available from only 11 studies, and, to account for missing values, the mean stoniness percentage from these studies (47.28 %) was used as the estimated stoniness for all studies that did not report this information. This adjustment was necessary, as failing to account for stoniness is a significant source of error in SOC estimations, leading to overestimation (Aguilera *et al.*, 2013).

3. Meta-analysis

A meta-analysis is a statistical technique used to systematically combine and analyse data from multiple independent studies, providing more robust and generalisable conclusions than individual studies alone. We conducted random-effects model meta-analysis using the *rma* function of the metafor R package (R Core Team, 2025; Viechtbauer, 2010). This approach accounts for the heterogeneity arising from differences in study methods and sample characteristics by assuming that variability is not fixed but random.

The management practices assessed in these meta-analyses were (i) the inclusion of green covers (GC) and (ii) the addition of any sort of organic amendment (OA). The control for green covers was either tillage or herbicide use, while for organic amendments, the control was the absence of amendments.

Additionally, the influence of other factors beyond these two management practices was assessed by including them as categorical moderators: green cover family, green cover life cycle, type of organic amendment, depth sampled, time of implementation, mean annual temperature (MAT), mean annual precipitation (MAP), altitude, clay content, slope, Köppen–Geiger climate subcategory, and irrigation. The continuous variables were transformed into categorical variables with different levels, distributing the studies into similar-sized groups for GC and for OA separately. These moderator variables were considered for their potential influence on carbon stocks, in addition to management practices, as they may account for part of the heterogeneity in the true effects. The argument "*mods*" in the *metafor::rma* function was used for this purpose. A summary of these variables is shown in Table 1.

Comparisons of SOC stocks between conventionally managed vineyards and vineyards managed with GC or OA were excluded from the corresponding analysis when information for a given variable was not available.

A separate meta-analysis was conducted for each management practice (GC, OA and GC + OA), along with a global meta-analysis including all studies. The carbon stock standardised mean difference (CS_{SMD}), expressed in Mg ha^{-1}, was used as the effect size in all meta-analyses. This standardised measure, which can be calculated from any number of statistical outputs (Vicente-Vicente *et al.*, 2016), is commonly used in a meta-analysis to facilitate comparison across studies. CS_{SMD} was calculated using Equations (3) and (4) of the *metafor::escalc* function in R.

TABLE 1. Variables and categorical classes used in the meta-analyses assessing the effects of green covers and organic amendments on soil carbon stocks.

Variable	Green covers	Organic amendments
Family of the main plant species	Legumes (Fabaceae)	
	Grasses (Poaceae)	-
	Legumes and grasses	
Life cycle of the main plant species	Annual plants	
	Perennial plants	-
	Annual and perennial plants	
Type of amendment		Pruning residues (PR)
		Biochar (B)
		Organic fertilisers and manure, including poultry and cattle manure (MA)
	-	Spent mushroom substrate (SMS) (MU)
		Compost, including composted spent mushroom substrate (C)
Depth (cm)	0–10 (studies assessing 0–5 cm were considered here)	0–10 (studies assessing 0–5 cm were considered here)
	0–20 (studies assessing 0–15 and 0–22 cm were considered here)	0–20 (studies assessing 0–15 and 0–22 cm were considered here)
	0–30 (studies assessing 0–25, 0–35 and 0–50 cm were considered here)	0–30 (studies assessing 0–25, 0–35 and 0–50 cm were considered here)
	> 30 (studies assessing 25–100, 25–45, 50–100 and 20.6–101.4 were considered here)	> 30 (studies assessing 25–100, 25–45, 50–100 and 20.6–101.4 were considered here)
Koppen–Geiger climate subcategory	Bsk: Arid cold steppe	Bsk: Arid cold steppe
	Cfa: Temperate, hot summer and no dry season	Cfa: Temperate, hot summer and no dry season
	Cfb: Temperate, warm summer and no dry season	Cfb: Temperate, warm summer and no dry season
	Csa: Temperate, dry and hot summer	Csa: Temperate, dry and hot summer
	Csb: Temperate, dry and warm summer	Csb: Temperate, dry and warm summer
Time of implementation (yrs)	0–3	0–3
	4–7	4–7
	8–10	8–10
	> 10	> 10
Mean annual temperature (MAT) (°C)	9–14	9–14
	14.1–23	14.1–18
Mean annual precipitation (MAP) (mm)	350–500	350–500
	501–700	501–700
	701–1250	701–1250
Altitude (masl)	0–200	0–200
	201–400	201–500
	401–700	501–1000
	701–1000	
Clay content (%)	9–24	6–9
	25–40	9.1–24
		25–41.4
Slope (%)	0–5	0–5
	5.1–10	5.1–10
	10.1–35	
Irrigation	Irrigated (Studies with drip irrigation only in case of water stress were included here)	Irrigated (Studies with drip irrigation only in case of water stress were included here)
	Non-irrigated	Non-irrigated

$$CS_{SMD} = \frac{(m1i - m2i)}{sp_i} \quad \text{(Equation 3)}$$

$$sp_i = \sqrt{\frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{(n_1-1)+(n_2-1)}} \quad \text{(Equation 4)}$$

where m_{1i} is the mean CS of the alternative management group, m_{2i} is the mean CS of the control group, sp_i is the pooled standard deviation of the two groups, s_1 and s_2 are the standard deviations of each group, and n_1 and n_2 are the sample sizes of each group.

When studies reported standard errors (SE) instead of standard deviations (SD), the latter were calculated using Equation (5) (Higgins *et al.*, 2024).

$$s = SE \times \sqrt{n} \quad \text{(Equation 5)}$$

Egger's regression tests and funnel plots, which display observed outcomes against standard errors, were generated to diagnose publication bias. Sensitivity analyses were conducted using a fixed-effects model and a leave-one-out approach.

Significant differences between levels of moderator variables were determined by conducting *t*-tests that compared each level to the others. The contribution of each moderator to the total heterogeneity percentage was calculated using Equation (6) (Viechtbauer, 2010):

$$Contribution\ \% = \left(\frac{tau^2_{MA} - tau^2_{MA.mods}}{tau^2_{MA}}\right) * 100 \quad \text{(Equation 6)}$$

where tau^2_{MA} is the estimated total heterogeneity in the meta-analysis without the variable as a moderator, and $tau^2_{MA.mods}$ is the estimated residual heterogeneity in the meta-analysis when the variable is included as a moderator.

C sequestration rates (CSR) per year were estimated using Equation (7) (Intergovernmental Panel on Climate Change, 2019).

$$CSR = \frac{CS_i - CS_f}{t} \quad \text{(Equation 7)}$$

where CS_i is the initial soil organic carbon, CS_f is the final soil organic carbon in the alternative management, and t is the duration of the experiment in years.

When the initial carbon stock data for the alternative management practice were not available, CS of the control treatment was used instead, under the assumption that there was no net carbon flow in conventional management.

RESULTS

1. Effect of management practices

A total of 47 studies and 173 comparisons were included in the primary dataset for the meta-analyses (Figure 1), as some studies reported multiple control-treatment comparisons. Of these, 38 studies and 124 comparisons examined green covers (GC), while 15 studies and 53 comparisons focused on organic amendments (OA). Additionally, 12 comparisons from 5 studies evaluated the combined effect of GC and OA in the same field (GC + OA) (Table S1). This small number of comparisons in GC + OA resulted in unreliable results in the moderator analyses, as some categories were represented by a single comparison (Table S1).

Meta-analyses performed using the CS_{SMD} as the effect size indicated that Mediterranean vineyard soils managed with GC significantly stored more carbon than conventionally tilled vineyards, as shown by an SMD of 1.32 Mg C ha^{-1} (95 % CI [1.00, 1.64], $z = 8.0533$, $p < 0.001$) (Figure S1, Table S2). Similarly, vineyards managed with OA significantly stored more carbon than those without amendments, with an SMD of 2.22 Mg C ha^{-1} (95 % CI [1.65, 2.79], $z = 7.6519$, $p < 0.001$) (Figure S2, Table S2).

Funnel plot analyses validate the meta-analysis's acceptance. They show few outliers, with most studies clustered at the top (*i.e.*, smaller standard errors). However, studies appear asymmetrically scattered around the overall effect size line, suggesting some degree of publication bias in both meta-analyses. This bias likely arises from the tendency for studies reporting positive outcomes for alternative management practices to be more likely to be published (Figures S3 and S4). Both meta-analyses also revealed a high percentage of variation due to heterogeneity among studies (GC $I^2 > 85.35$ %, $Q = 441.6210$, $p < 0.001$; OA $I^2 = 79.03$ %, $Q = 201.6357$, $p < 0.001$) (Table S2). This indicates that studies differ considerably in ways that could influence their findings, and that while there is a consistent positive effect, the magnitude of this effect may vary depending on the context in which each study was conducted. To address this heterogeneity, various factors were examined by including the previously listed moderators in the meta-analyses. The analysis revealed that the climate subcategory where the vineyards are located accounted for 24.71 % and 43.69 % of the heterogeneity in the GC and OA meta-analyses, respectively. Additionally, the sampling depth contributed 39.22 % of the heterogeneity in the OA meta-analysis, but only 3.16 % in the GC meta-analysis (Table 2).

The additional meta-analysis conducted to determine the effect of the combined application of GC and OA in the same field had a significant positive effect on carbon stocks built (0.94 Mg ha^{-1}, 95 % CI [0.38, 1.51], $z = 3.2785$, $p < 0.001$) (Table S2), although to a lower extent compared to the application of GC or OA alone, with the CS_{SMD} for OA alone being higher than for GC alone or GC combined with OA (Figure 2a). In contrast to the other meta-analyses, this meta-analysis showed low heterogeneity ($I^2 = 15.37$ %; $Q = 13.7584$, $p = 0.2467$) (Table S2).

Fixed-effects models also report positive estimates (Table S3), confirming that the meta-analysis consistently indicates that RMPs store more C in soils than conventional management. The difference between the fixed-effects (0.8 Mg ha^{-1}, 95 % CI [0.7, 1.9]) and random-effects estimates (1.7 Mg ha^{-1}, 95 % CI [1.4, 2.0]) when including

all studies further confirms the high heterogeneity between studies. The leave-one-out analysis (Table S3) determined that individual studies have a similar influence on the overall result, supporting the robustness of the findings.

The main plant families used as green covers in the studies were Poaceae and Fabaceae (46 and 44 comparisons, respectively). There were 21 comparisons in which both families were used as the main plant species, and 13 comparisons from studies that did not specify the green cover species. No differences in the CS_{SMD} were observed between the different families (data not shown).

Regarding the life cycle of the main plant species of green covers, there were 81 comparisons with annual plants, 19 with perennial plants, and 5 with both annual and perennial plants. Additionally, 19 comparisons did not report this data. Perennial green covers showed a tendency for higher CS_{SMD} than annual covers, with values of 1.72 Mg C ha^{-1} and 1.25 Mg C ha^{-1}, respectively (Figure 3a), although this difference was not statistically significant ($p = 0.34$).

Organic amendments were categorised into subgroups regarding the nature of the amendment: pruning residues, biochar, manure (including poultry, cattle and farmyard manure), spent mushroom substrate (SMS), and compost (including composted SMS. Biochar and manure (3.45 Mg C ha^{-1} and 3.09 Mg C ha^{-1}, respectively) showed higher CS_{SMD} than compost (1.46 Mg C ha^{-1}). No significant differences were found between spent mushroom substrate and pruning residues (Figure 3b).

There were no significant differences in CS_{SMD} between irrigated and non-irrigated vineyards.

2. Variation with depth

CS_{SMD} in topsoil was higher than in subsoil (> 30 cm) in the meta-analysis including both GC and OA (Figure 2b). The same tendency is observed in OA meta-analysis and GC meta-analysis, but in GC, subsoil is only significantly different from topsoil sampled to a depth of 10 cm (Figure 4).

3. Role of time

In the OA meta-analysis, when considering the time since practice implementation as a discrete moderator (Table 3), CS_{SMD} is higher when the OA has been applied for 4 years or more, compared to when it is applied for 3 years or less. In contrast, in the GC meta-analysis, the CS_{SMD} remains steadier over the years, indicating a consistent effect size that does not change significantly with the duration of green cover implementation. Conversely, in the GC + OA meta-analysis, CS_{SMD} becomes negative when the study duration exceeds 10 years.

Using the CSR as the effect size for the meta-analysis, averages of 0.72 Mg C ha^{-1} yr^{-1} (95 % CI [0.31, 1.13], $z = 3.4766$, $p < 0.001$) in GC (Figure S6) and 1.2 Mg C ha^{-1} yr^{-1} (95 % CI [0.66, 3.17], $z = 2.9968$, $p = 0.0027$) in OA were obtained (Figure S7). The CSR of biochar (7.57 Mg C ha^{-1} yr^{-1}) is significantly higher than the rest of the OA types (Figure S8).

4. Impact of climatic variables and altitude

In colder Mediterranean areas, where the mean annual temperature (MAT) ranges between 9 and 14 ºC, CS_{SMD} is higher than in warmer locations with an MAT of 14–23 ºC (Table 3). There is also a tendency for higher CS_{SMD} in locations with mean annual precipitation (MAP) greater than 700 mm, but only in the GC meta-analysis (Table 3). Using the Köppen–Geiger climate classification as a moderator for GC, we found that more humid climates (Cfa and Cfb) generally exhibited significantly higher CS_{SMD} than drier climates (Csa, Csb and Bsk). For the OA meta-analysis, the results of this moderator are not aligned with humidity or temperature, as the highest CS_{SMD} are found in Bsk (colder and drier) and Cfa (hotter and more humid) (Table 3).

CS_{SMD} were significantly higher in vineyards with OA located at lower altitudes (0–200 masl) than those located at higher altitudes (400–701 masl). GC did not show differences between altitude categories, but the combination of GC + OA in the same vineyard showed higher CS_{SMD} in higher altitudes (401–700 masl) (Table 3).

5. Contribution of clay content and slope

In vineyards managed with organic amendments, there is a trend suggesting lower CS_{SMD} with lower soil clay content (6–9 %), although this difference is not statistically significant, likely due to the high variability within the dataset. Meanwhile, the CS_{SMD} for green-cover vineyards was similar across clay content categories (Table 3).

Regarding the effect of topography, vineyards with green covers on medium (5–10 %) and high (10.1–35 %) slopes exhibit significantly higher CS_{SMD} compared to those on low slopes. No effect of slope on CS_{SMD} was observed for the organic amendment practices (Table 3).

DISCUSSION

1. Green covers

Our estimated C sequestration rate for GC is comparable to the rate reported for Mediterranean vineyards in the meta-analysis performed by Vicente-Vicente *et al.* (2016), at 0.72 Mg C ha^{-1} yr^{-1} in our study and 0.78 Mg C ha^{-1} yr^{-1} in theirs. However, other meta-analyses performed on a global climate scale found higher sequestration rates; Payen *et al.* (2021b) reported a rate of 1.23 Mg C ha^{-1} yr^{-1} for vineyards, while Hu *et al.* (2022) estimated a rate of 2 Mg C ha^{-1} yr^{-1} for woody crops. Conversely, a meta-analysis on Mediterranean croplands by Aguilera *et al.* (2013) found a lower sequestration rate of 0.27 Mg C ha^{-1} yr^{-1}, probably due to the inclusion of other non-woody crops. These differences suggest that green covers in the Mediterranean climate achieve less C sequestration when compared to global climate, and that this practice might be more effective in perennial woody systems.

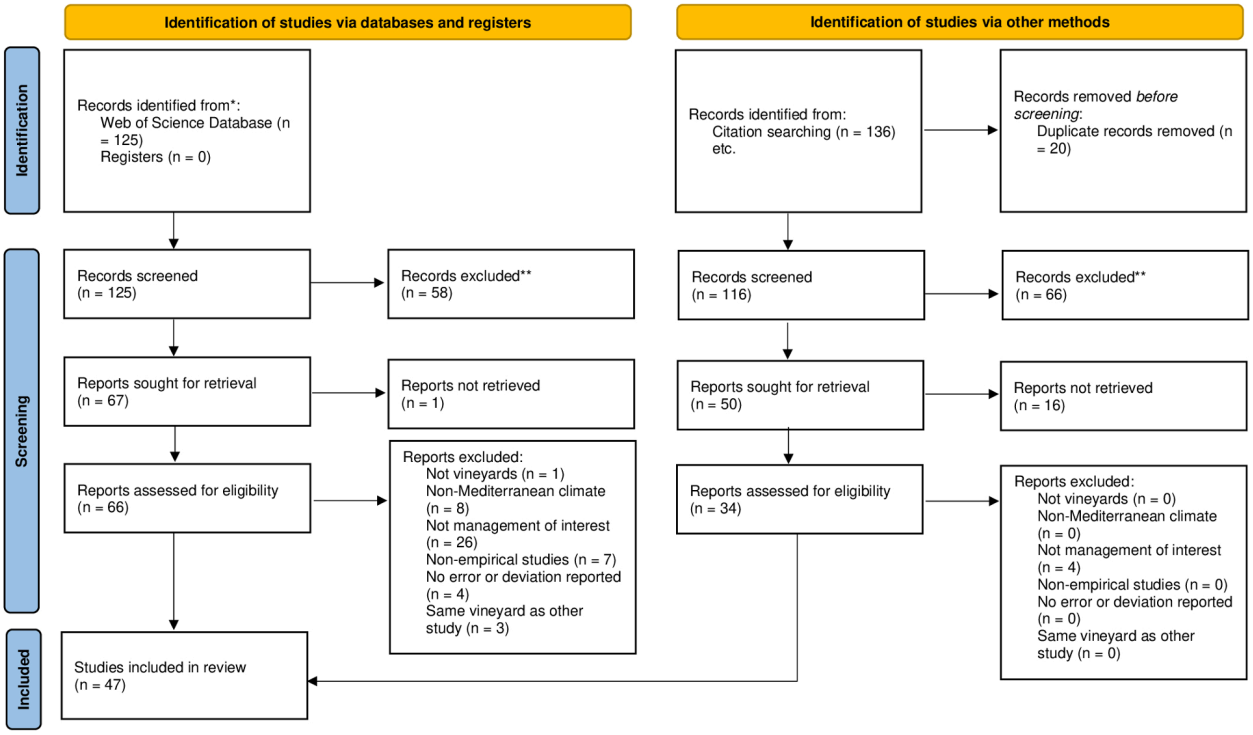


FIGURE 1. PRISMA flow diagram showing the process of identification, screening, eligibility, and inclusion of studies in the meta-analysis. Adapted from Page *et al.* (2021).

TABLE 2. Contribution of each moderator to total heterogeneity percentage in carbon stocks standardised mean differences (CS_{SMD}).

Variable	% Contribution of each moderator to total heterogeneity in GC	% Contribution of each moderator to total heterogeneity in OA
Green cover family	7.64	-
Green cover life cycle	No contribution (–19.47)	-
Type of organic amendment	-	12.05
Depth sampled	3.16	39.22
Time of implementation	12.72	12.51
Mean annual temperature	No contribution (–14.65)	No contribution (–4.45)
Mean annual precipitation	No contribution (–5.85)	6.78
Köppen–Geiger subcategory	24.71	43.69
Altitude	No contribution (–16.7)	No contribution (–2.51)
Clay content	No contribution (–84.66)	No contribution (–1.33)
Slope	No contribution (–35.99)	No contribution (–10.27)
Irrigation	No contribution (–2.22)	0.69

Moderators with negative values are considered to not have any contribution to total heterogeneity. Missing values correspond to moderators that did not exist in the specific meta-analysis of GC or OA.

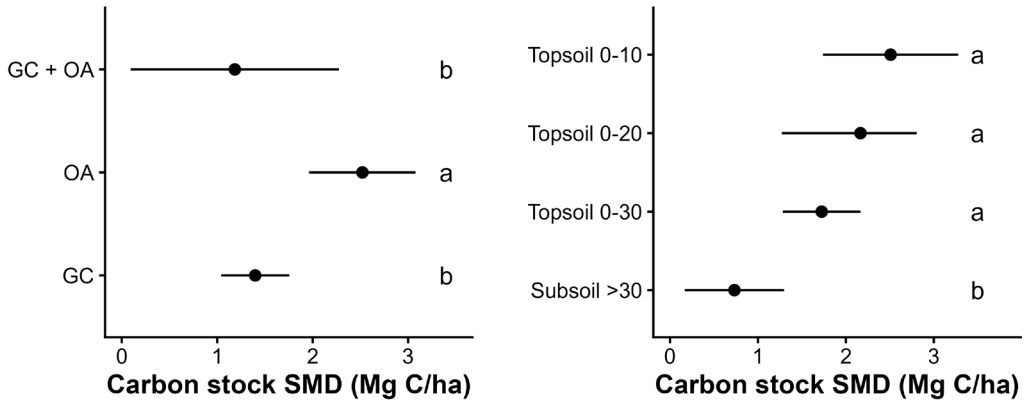


FIGURE 2. Carbon stocks standardised mean differences (CS_{SMD}) and confidence intervals for (a) each management practice, and (b) each sampling depth. Letters indicate statistically significant differences between modalities (*t*-test, $p < 0.05$).

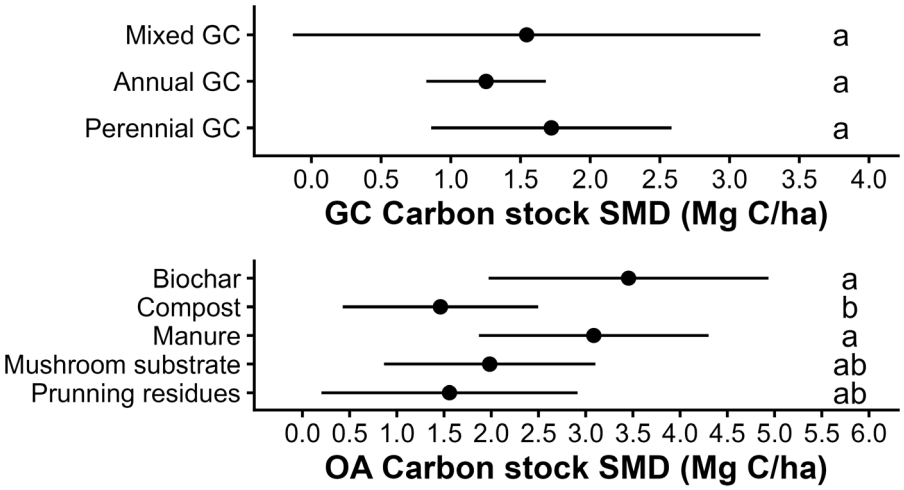


FIGURE 3. Carbon stocks standardised mean differences (CS_{SMD}) and confidence intervals for each category of (a) green covers (GC) and (b) organic amendments (OA). Letters indicate statistically significant differences between modalities (*t*-test, $p < 0.05$).

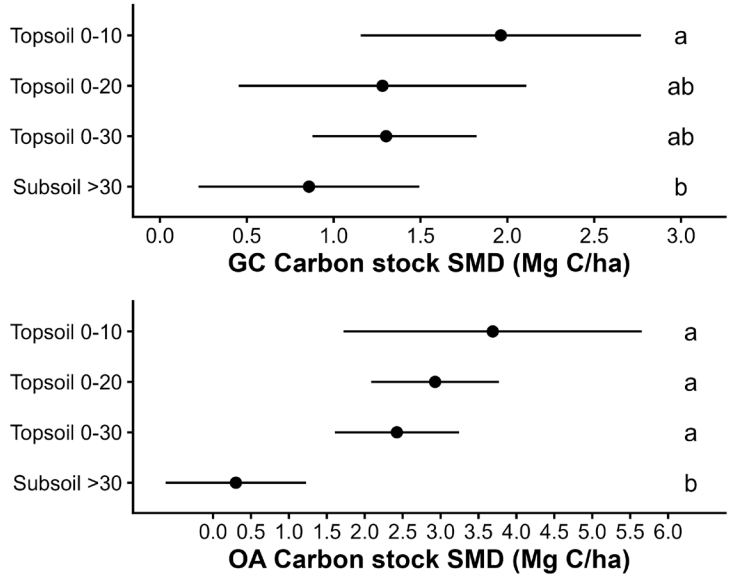


FIGURE 4. Carbon stocks standardised mean differences (CS_{SMD}) and confidence intervals for each sampling depth as affected by (a) green covers (GC) and (b) organic amendments (OA). Letters indicate significant differences between subgroups within management practice (*t*-test, $p < 0.05$).

TABLE 3. Effect sizes (CS_{SMD}) of green covers (GC), organic amendments (OA), and their combined use on soil organic carbon stocks across different climatic, soil, and management conditions. Values in brackets represent the 95 % confidence intervals of CS_{SMD}. Different letters indicate significant differences among categories within each variable (*t*-test, $p < 0.05$).

Variable		CS_{SMD} GC		CS_{SMD} OA		CS_{SMD} GC + OA
Time	0–3 years	1.48 (0.79, 2.18) ab	0–3 years	1.15 (0.33, 1.98) b	0–3 years	1.51 (0.76, 2.27) a
	4–7 years	0.65 (–0.03, 1.32) b	4–10 years	4.89 (2.61, 5.17) a	> 10 years	0.37 (–0.35, 1.09) b
	8–10 years	1.62 (1.12, 2.12) a	> 10 years	2.50 (1.66, 3.33) a		
	> 10 years	1.23 (0.45, 2.01) ab				
MAT	9-14 °C	1.98 (1.20, 2.76) a	9–14 °C	2.82 (1.84, 3.80) a	9–14 °C	2.00 (0.86, 3.20) a
	14.1–23 °C	1.05 (0.63, 1.48) b	14.1–18 °C	1.52 (0.67, 2.38) b	14.1–23 °C	0.35 (–0.48, 1.18) b
MAP	350–500 mm	1.34 (0.89, 1.78) ab	350–500 mm	3.04 (0.31, 5.76) a	350–500 mm	1.42 (0.15, 2.69) ab
	501–700 mm	0.67 (–0.01, 1.36) b	501–700 mm	1.30 (0.42, 2.17) a	501–700 mm	–
	701–1250 mm	2.10 (1.11, 3.09) a	701–1250 mm	2.50 (1.66, 3.34) a	701–1250 mm	1.50 (0.76, 2.25) a
Koppen–Geiger classification	Bsk	0.18 (–0.48, 0.84) c	Bsk	3.58 (1.95, 5.22) ab	Bsk	1.42 (0.15, 2.69) ab
	Csa	0.82 (0.34, 1.30) c	Csa	2.03 (1.02, 3.03) b	Csa	0.42 (–0.22, 1.06) b
	Csb	1.84 (1.36, 2.33) b	Csb	0.45 (–0.43, 1.33) c	Cfb	1.97 (0.85, 3.08) a
	Cfa	2.84 (0.85, 4.83) ab	Cfa	6.42 (3.60, 9.24) a		
	Cfb	3.20 (2.01, 4.40) a	Cfb	2.64 (1.91, 3.37) b		
Altitude	0–200	1.51 (1.00, 2.02) a	0–200	2.94 (1.91, 3.98) a	200–400	–0.09 (–0.93, 0.75) b
	201–400	1.06 (0.36, 1.76) a	201–400	2.57 (0.81, 4.33) ab	401–700	1.73 (0.89, 2.57) a
	401–700	2.42 (1.15, 3.68) a	401–1000	1.34 (0.45, 2.23) b		
	701–1000	0.79 (–0.57, 2.15) a				
Clay	9–24 %	1.03 (0.25, 1.80) a	6–9 %	2.29 (1.06, 3.51) a	6–9 %	0.00 (–1.70, 1.70) a
	25–40 %	1.78 (1.09, 2.47) a	9.1–24 %	3.28 (2.26, 4.29) a	9.1–24 %	0.72 (0.06, 1.38) a
			25–41.4 %	3.92 (2.15, 5.70) a		
Slope	0–5 %	0.41 (–0.31, 1.14) b	0–5 %	2.02 (1.25, 2.80) a		
	5.1–10 %	3.26 (1.57, 4.95) a	5.1–10 %	2.82 (1.26, 4.37) a		
	10.1–35 %	2.29 (1.23, 3.35) a				
Irrigation	Non-irrigated	1.25 (0.77, 1.72) a	Non-irrigated	2.39 (1.76, 3.03) a	Non-irrigated	1.42 (–0.10, 2.95) a
	Irrigated	1.38 (0.94, 1.82) a	Irrigated	1.48 (0.18, 2.79) a	Irrigated	0.88 (0.25, 1.50) a

This meta-analysis shows that vineyards managed with green covers sequester more carbon in soil than those under conventional management. Perennial green covers tend to sequester more carbon than annual green covers, although this trend was not statistically significant. Similarly, a study on crop rotation by King and Blesh (2018) reported increased SOC in perennial GC due to higher root C inputs, including root biomass and root exudates, despite having lower shoot C inputs compared to annual crops. Eagle and Olander (2012) also observed higher C sequestration potential by replacing annuals with perennials in rotations and, in the same line, Sprunger *et al.* (2020) concluded that perennial polycultures (prairies, forest and early successional systems) could be the best strategy for stabilising soil C.

SOC stock differences were more pronounced in the top 10 cm of soil than in the subsoil. This is because topsoil SOC, which is primarily affected by litter inputs and pedoclimatic conditions, is more strongly influenced by land use and agricultural management than subsoil SOC (Funes *et al.*, 2019; Kunlanit *et al.*, 2019; Vos *et al.*, 2019).

Climatic factors also influence the effectiveness of GC in SOC sequestration, explaining an important part of the heterogeneity (Koppen–Geiger classification explains 24.71 %). Temperature and precipitation are important factors for carbon sequestration, since they affect the SOC decomposition rate. High temperatures promote organic matter mineralisation, which decreases SOC stock, and precipitation is positively correlated with SOC (Lembaid *et al.*, 2022; Liu *et al.*, 2024; Rey *et al.*, 2002). Green covers can increase soil porosity, which enhances the soil thermal insulation, thereby reducing organic matter mineralisation. In summer, GC are usually cut and left on the soil surface as mulch, which protects the soil from high temperatures and retains water from the scarce summer precipitation typical of Mediterranean climates (Fraga & Santos, 2018; Kassam *et al.*, 2012). Our results indicate that wetter and colder climates enhance the sequestration effects of GC, probably because the organic matter provided by GC takes more time to mineralise with colder temperatures, and higher precipitation enhances net primary production of GC, providing more C inputs (Gabarrón-Galeore *et al.*, 2015; Kirschbaum, 1995; Kurganova *et al.*, 2012). These results align with the conclusions of Payen *et al.* (2021a) and Vicente-Vicente *et al.* (2016). According to Hu *et al.* (2022), higher MAP (> 400 mm) was associated with greater SOC accumulation during the first three years of cover cropping. Beyond this period, however, the lowest SOC accumulation rates were found in areas with MAP exceeding 800 mm.

In sloped vineyards, soil erosion accelerates carbon losses, as runoff transports topsoil to lower areas or watercourses. Green covers have a key role in reducing soil erosion in these terrains (Hu *et al.*, 2022). For instance, Pappalardo *et al.* (2019) estimated that in the Prosecco area, conventional vineyard management resulted in a soil erosion rate of 19.5 Mg ha yr^{-1}, which increased to more than 40 Mg ha yr^{-1} on steep slopes. However, inter-row grass cover reduced this rate from 43.7 to 14.6 Mg ha yr^{-1}. The higher impact of GC in steep slopes is evidenced for the first time in a meta-analysis by our results in medium and high sloped vineyards: CS_{SMD} of 3.26 and 2.29 Mg C ha^{-1}, compared to 0.41 Mg C ha^{-1} in plain vineyards. Another study in Italy (Novara *et al.*, 2019) reported similar results, as GC in a sloped area increased SOC by 3 % more than in a flat area.

2. Organic amendments

Our estimated C sequestration rate for organic amendments is similar to the one found by Hu *et al.* (2022) for woody crops (3.17 Mg C ha^{-1} yr^{-1} and 3.73 Mg C ha^{-1} yr^{-1}, respectively). In contrast, the rate for organic amended vineyards reported by Vicente-Vicente *et al.* (2016) is much lower (0.65 Mg C ha^{-1} yr^{-1}). Additionally, we estimated a rate for manure that is comparable to the one found by Aguilera *et al.* (2013) for manure applied with GC (0.61 Mg C ha^{-1} yr^{-1} in our study *vs* 0.62 Mg C ha^{-1} yr^{-1} in theirs), but their CSR for compost is lower than the one we obtained (1.32 Mg C ha^{-1} yr^{-1} and 2.06 Mg C ha^{-1} yr^{-1}, respectively). Our estimated CSR for biochar is notably high (7.57 Mg C ha^{-1} yr^{-1}) and differs from the CSR for biochar estimated by Payen *et al.* (2021b) (2.47 Mg C ha^{-1} yr^{-1}). This unusually high CSR might be caused by a single study that presents much higher SOC values in biochar (60–80 Mg C ha^{-1}) than in conventional management (38 Mg C ha^{-1}) in a short period of time (2 years), and it accounts for nearly half of the total effect within the biochar category. Payen *et al.* (2021b) also found that leaving pruning residues in the soil had the lowest C sequestration rates, which is consistent with our results (0.77 Mg C ha^{-1} yr^{-1} in their meta-analysis *vs* 0.35 Mg C ha^{-1} yr^{-1} in ours).

Organic amendments significantly lead to a greater increase in SOC stock than green covers when compared to their respective conventional controls, primarily because these amendments add organic material directly to the soil. This increase is more pronounced when the carbon in the amendments is more stabilised. While the labile fraction of organic amendments may not significantly contribute to C sequestration, it can indirectly promote sequestration by enhancing the physical protection of SOC, which increases carbon persistence in the soil (Lee *et al.*, 2021; Raya-Moreno *et al.*, 2017). It is also important to take into account that C sequestration efficiency of OA depends on their interaction with the soil microbial community, which can accelerate the decomposition of stable soil endogenous C as a result of co-metabolism, thus inhibiting C sequestration, a process that is known as the priming effect (Blagodatskaya & Kuzyakov, 2008; Kok *et al.*, 2022). However, the positive effect sizes of our results suggest that OA in vineyards have a negative priming effect on the soil microbial community, which has not accelerated the decomposition rate of native C.

The higher CS_{SMD} observed in biochar can therefore be explained by the fact that the carbon contained in it is more stable, due to its richness in aromatic structures, which are difficult for soil microorganisms to degrade (Criscuoli *et al.*, 2021; McBeath *et al.*, 2015; Rudra *et al.*, 2024). Biochar may also induce a negative priming

effect on SOM, decreasing native SOM decomposition rates and further enhancing C sequestration (Wang *et al.*, 2016). However, biochar typically induces positive priming effects in soils with low fertility (Wang *et al.,* 2016), which can partially counteract the increase in SOC stocks by increasing the microbial degradation of native SOC. Nevertheless, even in such cases, the net increase in SOC resulting from biochar addition remains.

In this meta-analysis, similarly to the GC meta-analysis, more differences were observed in topsoil SOC than in subsoil, as the top few centimetres of soil are more influenced by management practices (Funes *et al.*, 2019; Kunlanit *et al.*, 2019; Vos *et al.*, 2019). In this case, sampling depth explained a high percentage of heterogeneity (39.22 %), suggesting that it should be considered when comparing studies.

Climatic factors are important to assess the effectiveness of OA in SOC sequestration (43.69 % of heterogeneity explained with the Koppen–Geiger moderator). Colder climates enhance the effects of OA on SOC sequestration. This may be due to a slower decomposition of the organic matter at low temperatures (Kirschbaum, 1995; Kurganova *et al.*, 2012), which results in a slower loss of carbon compared to that in hotter climates. Similar to the GC meta-analysis, our results align with those of Payen *et al.* (2021a) and Ma *et al.* (2024), who found that organic amendments had more positive effects in areas with an annual mean temperature of 8–15 °C. Hu *et al.* (2022) also found that SOC accumulation is faster in crops with organic amendments in areas with lower MAT.

Moderator analysis indicates that the altitude is an influencing factor on OA effectiveness, with the highest altitudes (0–200 masl) having the lowest CS_{SMD}. In our dataset, the studies in higher altitudes are also studies with less than 3 years of OA application, and this relation can be influencing the result in the altitude moderator analysis, since we have already observed that a longer time of application increases CS_{SMD}.

Clay content plays an important role in explaining the heterogeneity between studies on OA practices, but not for GC studies. This difference might be due to the interaction between clay and organic matter added as organic amendments. For example, a review on biochar's stability by Han *et al.* (2020) evidences that biochar increases the formation of macro-aggregates more strongly in clayey soils. In these soils, biochar is stabilised due to its interaction with reactive minerals such as phyllosilicate (clays) and iron oxides, forming biochar-mineral complexes.

3. Limitations and future work

For a better understanding of the potential that GC and OA have in C sequestration in the long term, it is important to study the dynamics and stabilisation of the C added to the soil and, for this purpose, the measurement of labile SOC and stable SOC rather than total SOC is essential. Regarding organic amendments, nitrogen content would be an interesting variable to consider, since N plays a role in decomposition and the effect of N addition on soil C depends on several factors, such as mineralogy, acidity, microbial physiology, and C:N stoichiometry (Averill & Waring, 2018; Finn *et al.*, 2015; Zhou *et al.*, 2012).

Long-term studies (10 years or more) are required to observe further and more stable changes in SOC stock, because these practices may increase SOC stock gradually, and short-term studies may be influenced by climatic conditions of those short time periods. In this meta-analysis, 73 comparisons from 13 studies lasted 10 years or more, while 66 comparisons from 21 studies lasted 5 years or less.

The lack of information on stone content and bulk density is a very important limitation for the comparison of SOC stock between different types of soil, and our assumptions may introduce bias and uncertainty into the results, especially regarding stone content, which was rarely reported and, unlike BD, cannot be estimated from a pedotransfer function. Moreover, the lack of information about environmental variables is a limitation for the analysis of moderators. Furthermore, most studies did not report initial SOC stock, which is essential for calculating the C sequestration rate.

Livestock grazing to manage green covers while fertilising the soil is also a practice that can increase C sequestration (Lazcano *et al.*, 2022; Meunier *et al.*, 2025), but there are not sufficient studies about it to be included in this meta-analysis.

There are co-benefits and drawbacks associated with these practices that could also be evaluated to achieve a better understanding of RMPs' implications for the wine sector. Green covers and organic amendments can improve biodiversity (Abad *et al.*, 2021; Blaise *et al.*, 2022; Oehl & Koch, 2018) and enhance the abundance of natural enemies (Beaumelle *et al.*, 2021; Sáenz-Romo *et al.*, 2019). They can also improve soil structure (Liebhard *et al.*, 2024; Regus *et al.*, 2024), water retention and infiltration (Abad *et al.*, 2021; Göblyös *et al.*, 2011). Green covers specifically can reduce the use of nitrogen fertilisers if the green cover is composed of leguminous plants (Sharifi *et al.*, 2024; Sulas *et al.*, 2017). On the other hand, green covers can compete with vines for water and nutrients (Celette *et al.*, 2009; Ruiz-Colmenero *et al.*, 2011) and increase the risk of frost (Meier *et al.*, 2018). It is also important to evaluate these practices under different agroclimatic conditions and different climate change scenarios to assess their potential in each case.

CONCLUSIONS

Mediterranean vineyards managed with green covers (GC) and/or organic amendments (OA) significantly increase SOC stocks compared to conventionally managed vineyards, with a greater impact on the top 30 cm of soil.

The effectiveness of these practices is favoured in colder climates, and in the case of GC also in more humid climates. OA performs better when this practice has been applied for more than 4 years, and we evidenced for the first time in a meta-analysis that GC is particularly effective in sloped vineyards.

Biochar and manure are the organic amendments that obtain higher CS_{SMD} values, while compost and pruning residues achieve lower increases.

Further research is needed to assess the stability of the sequestered C that these practices can provide and to understand how environmental variables affect these practices, with the objective of determining the best management strategies for specific climatic and edaphic conditions in future climate change scenarios.

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