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META-ANALYSIS

Cover crops promote regulating and supporting ecosystem services without compromising grape yield in temperate vineyards. A meta-analysis

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Abstract
Vineyards play a crucial role in the economies, landscapes, and ecosystems of temperate regions. Cover cropping is an agroecological practice that enhances ecosystem services delivery while mitigating the negative impacts associated with grapevine cultivation. This meta-analysis assessed for the first time the influence of cover crops through multiple explanatory variables, including edaphic and climatic factors, vineyard and cover crop management on provisioning, regulating, and supporting ecosystem services in temperate vineyards worldwide. We analyzed data from 64 studies (n = 1308 paired comparisons) using the natural logarithm of the response ratio [Ln(RR)] as the effect size, with 95% confidence intervals (95% CI) to evaluate the magnitude and significance of response variables. A random-effects model was used for the overall meta-analysis. Effect sizes for explanatory variables were subsequently compared using subgroup meta-analyses with mixed-effects models. Overall, cover crops had no significant effect on provisioning (−0.056; 95% CI: −0.154 to 0.042; p = 0.263), but significantly improved regulating (0.342; 95% CI: 0.075, 0.610; p = 0.012) and supporting ecosystem services (0.124; 95% CI: 0.008, 0.241; p = 0.036). Regulating ecosystem services were particularly enhanced in semiarid climates, organic systems, irrigated vineyards, under high grapevine density and in-row cover crop management, and where cover cropping had been adopted for a medium to long period. Greater gains were also associated with spontaneous vegetation, mixed or non-traditional cover crop species, and termination via green manuring or mowing. Supporting ecosystem services also benefited where cover cropping had been adopted for a medium to long period, particularly under organic farming, with cover crop mixtures, and when terminated via roller-crimping. Among studies assessing multiple ecosystem services, 28% reported win–win outcomes, 17% showed lose–lose scenarios, 42% exhibited trade-offs, whereas 13% did not affect ecosystem services. These results demonstrate the ecological benefits of cover crops in temperate vineyards, especially for regulating and supporting ecosystem services, without compromising grapevine yield.

Keywords Agroecology · Grasses · Legumes · Service crops · Termination method · Viticulture · Sustainability

1 Introduction

Viticulture, the cultivation of grapevines, holds a prominent position in temperate environments, contributing significantly to socioeconomic structures, cultural landscapes, and ecological processes (Martucci et al. 2019). The global vineyard surface area stood at approximately 7.2 Mha in 2023 (FAOSTAT 1997), predominantly located in temperate climates, typically between 30° and 50° latitude in both hemispheres, where conditions are optimal for grape cultivation. Given this distribution, it can be inferred that the largest global vineyard area, likely over 90%, is situated within these temperate zones.

Vineyards are complex agroecosystems that provide multiple ecosystem services (ESs) essential for sustainable wine production (Brussaard et al. 2007; Van der Heijden et al. 2008; Ochoa-Hueso et al. 2023). These services range from tangible products such as grapes for

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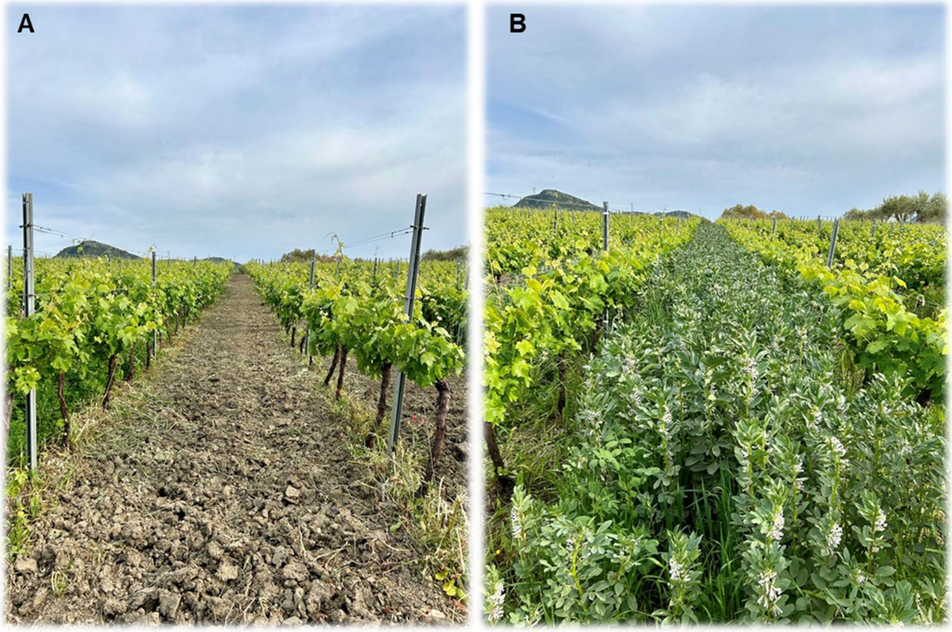

Fig. 1 Vineyard under conventional tillage without cover crops (**A**) and vineyard managed with legume-based cover crop mixtures (**B**). Photos taken from the PhD experimental field trial conducted by Francesca Calderone at the "Tenuta Lacco" farm in Rodi Milici, Messina, Italy (38°06′ N, 15°08′ E; 100 m a.s.l.) (photo credit: Francesca Calderone)

wine, fresh consumption, and juice production to intangible benefits such as soil conservation, carbon sequestration, and the preservation of biodiversity (Capello et al. 2019). These services can be categorized into four main types: cultural, regulating, supporting, and provisioning (MEA 2005). Cultural services include the esthetic value of vineyard landscapes, ecotourism, and the cultural heritage associated with traditional viticulture. Regulating services (RESs) encompass critical ecological functions such as pest control and weed suppression, carbon sequestration, erosion control, and water regulation. Supporting services (SESs) involve processes such as soil formation, soil fertility, and nutrient cycling. Finally, provisioning services (PESs) refer to the direct benefits from grapevine cultivation, including grape yield and wine production (MEA 2005).

Despite their ecological and economic importance, vineyard agroecosystems are increasingly threatened by high-input farming practices, often leading to soil degradation, biodiversity loss, and increased dependency on synthetic inputs (Garcia et al. 2018). To mitigate these challenges, agroecological approaches, such as the integration of cover crops (Fig. 1), have gained attention as a sustainable practice to increase ESs (Duru et al. 2015). Cover crops (CCs), which are non-cash plant species, enhance functional agrobiodiversity across multiple spatial and temporal scales (Scavo et al. 2022). This practice can restore biotic interactions that support yield and essential ESs (Nicholls et al. 2001; Steenwerth and Belina 2008; Garcia et al. 2018). Studies consistently highlight the positive effect of CCs on soil health, carbon sequestration (Payen et al. 2021), and water management (Celette et al. 2008), although the impact on grape yield and quality is context-dependent. While some research reports slight reductions in vegetative growth and yield due to competition for water and nutrients, others find no significant impact or even potential benefits in grape quality attributes, such as higher polyphenol content and better aroma profiles (Celette et al. 2008; Garcia et al. 2024). However, careful selection of CC species and strategic management practices (e.g., mowing at the right time) are recommended to optimize yield, quality, and ESs in vineyards (García et al. 2018; Fernández-Mena et al. 2021). Furthermore, poor seedbed preparation and inappropriate sowing methods can significantly hinder CC establishment, particularly when mixtures include CC species with varying seed sizes and weights. These challenges often result in uneven seed distribution, suboptimal germination, and irregular seedling emergence, ultimately compromising stand uniformity and the delivery of ESs (Garcia et al. 2018; Lamichhane and Alletto 2022).

While the effects of inter-row cover crops and climate variables on ecosystem services in vineyards have been systematically quantified (Winter et al. 2018; Chapela-Oliva et al. 2022), the role of cover crop management remains fragmented and insufficiently understood. Winter et al. (2018), analyzing 74 studies, reported that inter-row vegetation and herbicide-free management increased biodiversity and ESs by 20% compared with intensive agronomic practices. The strongest benefits were observed for soil loss mitigation, improvements in carbon sequestration, pest control, and soil fertility, without decreasing grape yield. Chapela-Oliva et al. (2022) updated the previous meta-analysis using almost the same dataset, adding the influence of climate variables on vineyard performance. They reported that PESs were slightly reduced in rainfed vineyards but remained stable with irrigation. SESs thrived in acidic soils and were further increased by precipitation of the wettest quarter, which is probably associated with more favorable conditions for soil biota due to higher soil moisture. In contrast, RESs were enhanced in alkaline soils and locations with lower temperatures in the wettest quarter, likely due to the lower development of pests, including fungal diseases, which are supported by high temperature and humidity. Despite these findings, a broader understanding of further drivers supporting multiple ESs is lacking.

To provide a more comprehensive understanding of the effects of cover crops (CCs) on ESs in vineyards, we, therefore, systematically quantified, for the first time, the influence of multiple explanatory variables on provisioning (PESs), regulating (RESs), and supporting ecosystem services (SESs) in global temperate vineyards. Although CCs may also contribute to cultural services (e.g., landscape esthetics, recreation; García et al. 2018), these fall outside the scope of the present agronomic-focused study. The explanatory variables considered include edaphic and climatic conditions (soil texture, aridity index), vineyard management (farming system, irrigation, grape density, time since conversion of vineyard to cover cropping), and CC management (CC type, CC spatial growth, and CC termination method). Using a meta-analytic approach, we aim to provide a comprehensive assessment of the ecological and agronomic benefits of cover cropping in vineyard systems. Notably, our analysis is based on a distinct dataset compared with the previous meta-analyses due to different inclusion criteria. This reinforces the complementarity of the present study and provides novel insights into the existing evidence.

2 Materials and methods

2.1 Study selection

The objectives of this meta-analysis were developed following the PICO (Population, Intervention, Comparison, Outcome) framework (Tawfik et al. 2019), as outlined in Table S1. The methodological protocol was based on the guidelines proposed by Fohrafellner et al. (2023). The bibliographic search was performed following the “Preferred Reporting Items for Systematic Reviews and Meta-Analyses” (PRISMA) guidelines (Page et al. 2021), selecting relevant scientific literature in the Scopus (Elsevier B.V.) and Web of Science Core Collection (WoS, Clarivate) databases. Table 1 shows the search strings used in both databases, and the detailed PRISMA flow diagram is depicted in Fig. 2.

Table 1 Searching string used in Scopus (Elsevier B.V.) and Web of Science Core Collection (WoS) databases

Database	Searching string
Scopus	((*vineyard* OR *grape* OR *grapevine* OR *vines* OR “grape *orchard*”) AND (*intercrop* OR “cover *crop*” OR “mixed *farm*” OR “mixed *crop*” OR *agroforestry* OR *mulch* OR “green *mulch*” OR “dead *mulch*” OR “minimum *till*” OR “no *till*”) AND (*multifunctionality* OR “ecosystem *service*” OR “ecosystem *functions*” OR “carbon *sequestration*” OR “nutrient *cycling*” OR “water *regulation*” OR “soil *biology*” OR “GHG *abatement*” OR “erosion *resistance*” OR “climate *regulation*” OR *biodiversity* OR *yield* OR “crop *productivity*”))
WoS	((vineyard OR grape OR grapevine OR vines OR grape OR orchard) AND (intercrop OR cover crop OR mixed farm OR mixed crop OR agroforestry OR mulch OR green mulch OR dead mulch OR minimum till OR no till) AND (multifunctionality OR ecosystem service OR ecosystem functions OR carbon sequestration OR nutrient cycling OR water regulation OR soil biology OR GHG abatement OR erosion resistance OR climate regulation OR biodiversity OR yield OR crop productivity))

The first screening was carried out in January 2024, resulting in a total of 615 articles, 492 from Scopus and 123 from WoS. After refinement by article type (original research), source type (journal papers), language (English), and temperate climates within the BSk (cold semiarid or steppe), Cfa (humid subtropical), Cfb (temperate oceanic), Csa (hot-summer Mediterranean), and Csb (warm-summer Mediterranean) zones of the Köppen-Geiger climate classification (Peel et al. 2007), 390 articles remained. Then, 49 duplicates were removed, yielding 341 articles. A second screening was performed in January 2025 using the same search strings and refining as the first screening, with the addition of the publication time (from 2024) to capture the latest papers on the topic. The second search yielded 49 articles, 26 from Scopus and 23 from WoS, which were reduced to 26 records after duplication removal.

Overall, 367 records were screened for eligibility following the protocol of Fohrafellner and coauthors (2023), consisting of a three-stage approach. First, the title and keywords were checked to assess whether the article fit the aims of this meta-analysis. The abstracts were subsequently screened, and if eligible, the full texts were screened according to the eligibility criteria reported in Table S2. The number of documents excluded due to a lack of fulfillment of one or more eligibility criteria was 311: outside the study area

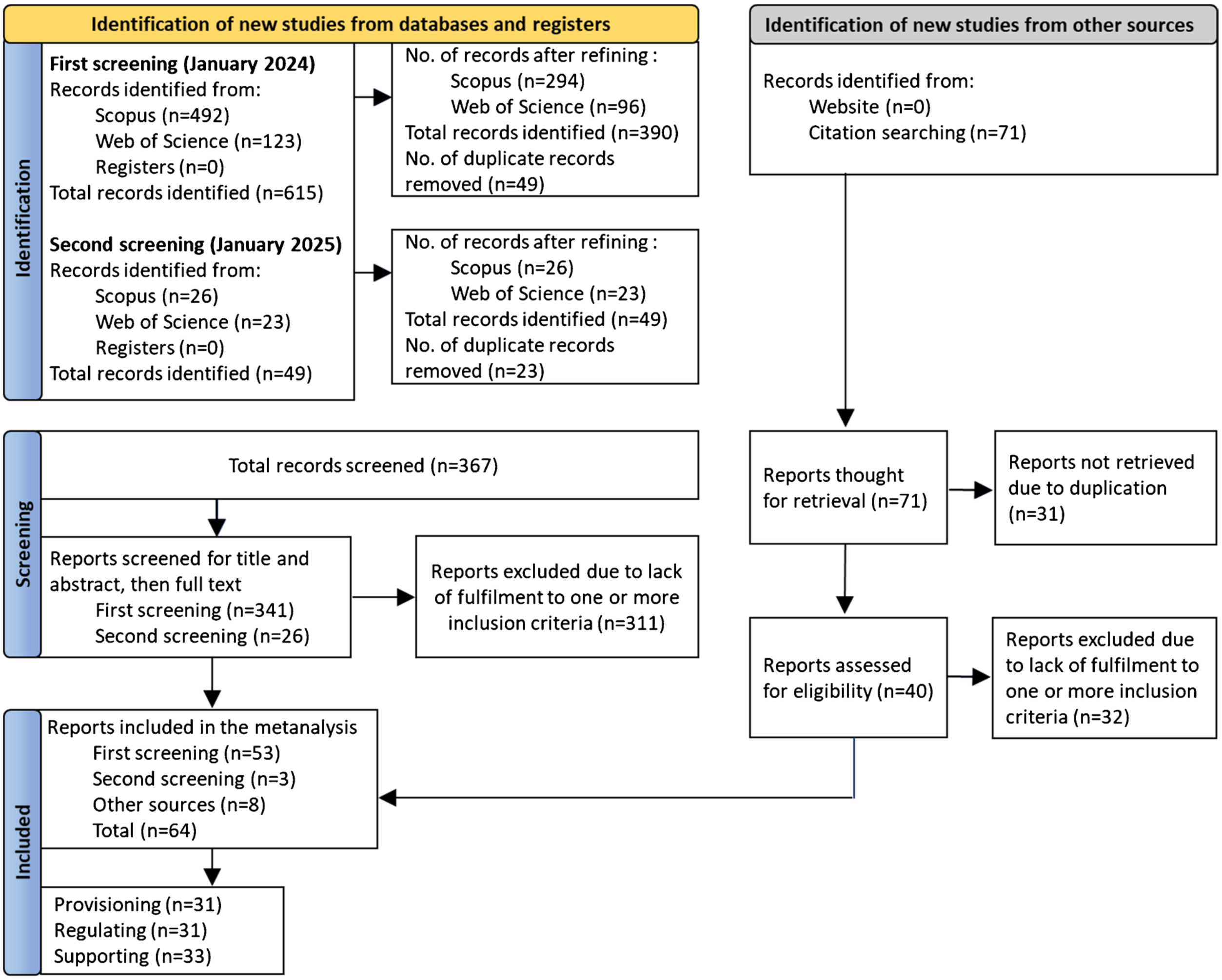

Fig. 2 Flow diagram according to the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (Page et al. 2021).

(n = 44), not available (n = 1), not original research papers (n = 29), modeling studies not including empirical methods (n = 16), greenhouse and pot trials (n = 5), different treatments than CCs (n = 60), the absence of a control (n = 13), economic, environmental, and social science studies not including measurable ESs (n = 106), 1-year experiments (n = 6), and different cropping systems than vineyard (n = 31).

Additionally, the articles (n = 71) included in the meta-analysis by Chapela-Oliva et al. (2022) (updating the meta-analysis of Winter et al. 2018) were also checked. Among these records, 31 were excluded because of duplication, and 40 were assessed for eligibility following the three-stage approach. Thirty-two studies (n = 32) were excluded because of a lack of fulfillment of one or more eligibility criteria, resulting in eight (n = 8) eligible studies included in this meta-analysis. The final number of studies that fulfilled the inclusion criteria was 53 from the first screening, 3 from the second screening, and 8 from other sources, totaling 64 studies distributed across temperate climatic zones (Fig. 3). Studies were further sub-grouped for the main ESs, namely, PESs (n = 31), RESs (n = 31), and SESs (n = 33).

2.2 Data collection

Data were extracted from studies based on the inclusion criteria reported in Table S2, which included PESs, RESs, or SESs in both CC (treatment) and no-CC (control) management in temperate vineyards. Numerical data from plots, figures, and maps were extracted through the WebPlot Digitalizer (Rohatgi 2017). The final number of studies selected for data collection included 1308 paired comparisons (CC *vs* no-CC) from diverse vineyard systems (Table S3).

Within PESs, RESs, and SESs, relevant explanatory variables (moderators) were developed, such as edaphic and climatic (i.e., soil texture and aridity index), vineyard management (i.e., farming system, irrigation, grapevine density, time since conversion of vineyard to cover cropping), and

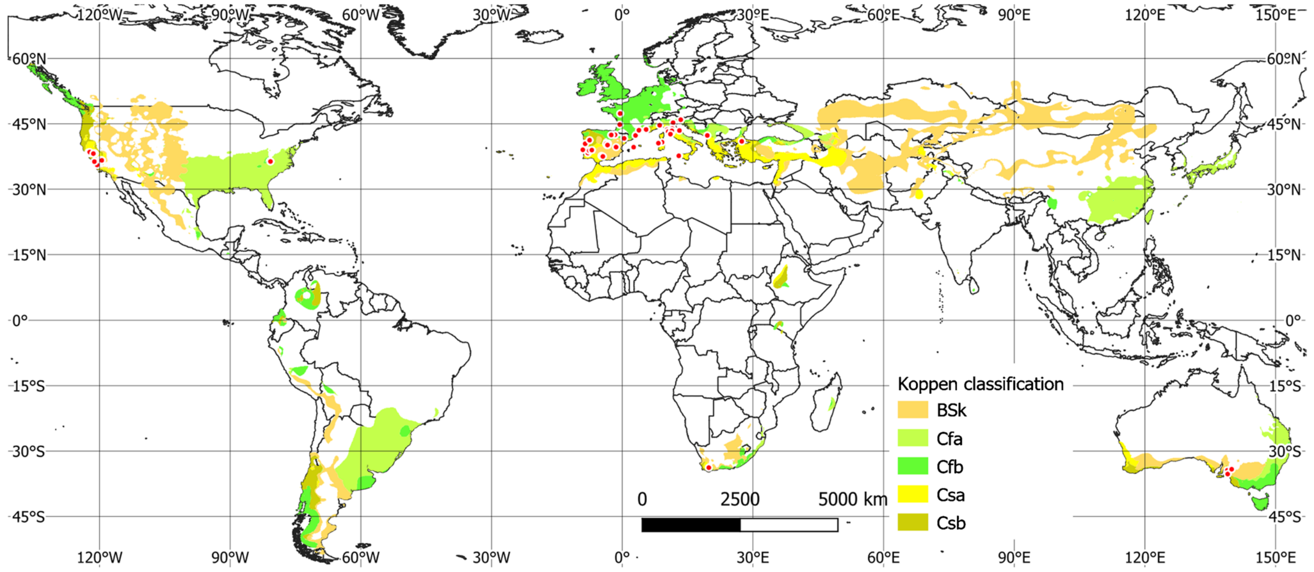

Fig. 3 Distribution of experimental field trials with cover crop management in global temperate vineyards (red dots). BSk (cold semiarid or steppe), Cfa (humid subtropical), Cfb (temperate oceanic), Csa (hot-summer Mediterranean), Csb (warm-summer Mediterranean) zones of the Köppen-Geiger climate classification (modified from Peel et al. 2007). White areas are climatic zones outside the boundaries of this study.

Table 2 Explanatory variables (moderators) and their ranges or groups

Explanatory variable	Groups/ranges
Edaphic and climatic	
Soil texture class (USDA)	Clay; loam; sand; silt
Aridity index (P/ET)	Hyper arid <0.03; arid 0.03–0.2; semiarid 0.2–0.5; dry subhumid 0.5–0.65; humid >0.65
Vineyard management	
Irrigation	YES; NO
Grape density	Low (≤1999 plants ha^{-1}), medium (from 2000 to 3499 plants ha^{-1}), high (from 3500 to 5499 plants ha^{-1}), and very high (>5500 plants ha^{-1})
Farming system	Conventional; organic
Conversion time to cover cropping	Short (2 to 3 years); medium (4 to 6 years); long (>7 years)
Cover crop management	
Cover crop type	Grass (one or more grasses); legume (one or more legumes); mixture (at least one grass and one legume species); spontaneous (natural vegetation); others (sown species other than grass or legume, e.g., melliferous plants)
Cover crop growing system	In-row; alley; in-row and alley
Cover crop termination method	Green manure; mowed; not mowed (not terminated CC); rolled

CC management (i.e., CC type, CC spatial arrangement, and CC termination method), which were ranged or grouped as follows (Table 2): (i) soil texture, according to the USDA soil texture classification, was classified as clay, loam, sandy, or silty (Fohrafellner et al. 2023); (ii) climatic conditions were grouped according to the aridity index (based on the annual precipitation and annual evapotranspiration ratio), as arid, semiarid, dry subhumid, and humid (Zomer et al. 2022). When precipitation and evapotranspiration were not available in a study, information was gathered from the Climate Information tool of AQUASTAT (FAO's Global Information System on Water and Agriculture) (n.d.); (iii) the farming system was ranked as organic or conventional; (iv) irrigation, irrespective of the volume or distribution system, was ranked as YES when reported, whereas when irrigation was not stated in a study or when the system was rainfed, it was ranked as NO; (v) grapevine density (i.e., the density of the plants) was ranked as low, medium, high, or very high; (vi) the time since conversion to cover cropping was ranked as short, medium, and long term; (vii) the CC type was ranked as grass, legume, mixture, other, or spontaneous; (viii) the CC spatial arrangement within vineyards was ranked as in-row, alley, or in-row and alley; (ix) the CC termination method was ranked as green manuring, mowing, not mowing, or roller-crimping.

2.3 Response variable

The response variable was the response ratio (RR), namely, the mean value of PESs, RESs, and SESs provided by CC in vineyards (treatment) relative to the no-CC management in vineyards (control):

$$\mathrm{RR}_{ij} = \frac{X1_j}{X2_j}$$

where RR_{ij} is the response ratio i in study j; $X1_j$ is the mean value of PESs, RESs, or SESs provided by CC i in the vineyard system in study j; and $X2_j$ is the mean value of PESs, RESs, or SESs in control i in study j. The control includes traditional in-row and inter-row (alley) management of vineyards, such as soil tillage and chemical herbicide application without CC, or not managed spontaneous vegetation. Since RR was not normal according to the Anderson–Darling test for normality, the natural logarithm transformation of RR [Ln(RR)] was carried out to normalize the response variable:

$$\mathrm{Ln(RR)} = \ln\left(\frac{x_1 j}{x_2 j}\right) = \ln(x_1 j) - \ln(x_2 j)$$

positive values of Ln(RR) indicate that PESs, RESs, or SESs were favored by CC in vineyards, whereas negative values indicate a higher value in the control (i.e., ESs were disfavored by CC). The Ln(RR) was weighted as described by Borenstein et al. (2009) to account for different study sample sizes.

The variance of Ln(RR) was computed as follows:

$$V_{\mathrm{Ln(RR)}} = S^2_{\mathrm{pooled}}\left(\frac{1}{n_1\left(x_1\right)^2} + \frac{1}{n_2\left(x_2\right)^2}\right)$$

where S_{pooled} is the pooled standard deviation; n_1 and n_2 are the sample sizes of the CC and control, respectively; and x_1 and x_2 are the means of the CC and control, respectively. The approximate standard error is the square root of $V_{\mathrm{Ln(RR)}}$ (Borenstein et al. 2009).

The response variables were grouped into 11 PESs, RESs, and SESs categories (Table S3). The PES category included only the grape yield ($n = 312$). The RES categories included soil erosion control ($n = 44$), natural enemy promotion ($n = 32$), pollination ($n = 13$), pest and disease control ($n = 32$), water regulation ($n = 127$), and weed control ($n = 125$). Within the RESs, the changes in soil losses, cumulative soil losses, sediment erosion, runoff, and suspended sediments in runoff water were considered for soil erosion control. The change in total spiders, crab spiders, *Hololena nedra* Chamberlin & Ivie, *Neoscona* spp., *Trachelas pacificus* Chamberlin & Ivie, *Cheiracanthium* spp., *Oxyopes* spp., *Theridion dilutum* Levi, *Theridion melanurum* Hahn, predators, phytophagous, parasitic wasps, syrphids, ladybird adults, and parasitoids was considered for the promotion of natural enemies. The changes in *Botrytis cinerea* Pers., sour rot, black aspergilli rot, entomopathogenic nematodes, free-living nematodes, nematophagous fungi, ectoparasite bacterial species, *Paenibacillus* spp., *Planococcus ficus* Signoret, *Erythroneura elegantula* Osborn eggs, *Erythroneura variabilis* Beamer eggs, and *Plasmopara viticola* (Berk. & M.A. Curtis) Berl. & De Toni were considered for pest and disease control. In terms of pollination, changes in *Apis mellifera* L., *Lasioglossum* (*Dialictus*) spp., and wild bees were considered. The water regulation took into account the changes in the soil water content, saturated hydraulic conductivity, water depletion, daily and total water use, and water retention. For weed control, changes in weed cover, ground cover, species richness, weed biomass, and weed relative biomass were considered.

The SESs category included the habitat for living organisms ($n = 39$), microbial activity ($n = 38$), nutrient cycling ($n = 331$), and soil fertility ($n = 215$). Within the SES, we considered the nutrient cycle as the increase or decrease in soil inorganic elements (N, NO_3-N, NH_4-N, P, K, Ca, Mg, K, Na, Mn, Al, Fe, and Cu) due to cover cropping. Soil fertility included changes in organic matter and physical–chemical properties (soil organic matter, soil organic carbon, soil compaction, aggregate stability, bulk density, total porosity, dissolved organic carbon, humic and fulvic acids, and humin). For microbial activity, the changes in microbial biomass C, total microbial biomass, gas emissions, dehydrogenase activity, β-glucosidase, urease, alkaline phosphatase, and arylsulfatase were considered. The habitat for living organisms included changes in total invertebrates and biodiversity, microarthropods (Oribatida, Astigmata, Prostigmata, Mesostigmata, and Collembola), insect larvae, millipede-like arthropods (Pauropoda), potworms (Enchytraeidae), earthworms, species richness, activity density, and Simpson's diversity index. When higher values of the effect sizes would mean negative impacts on certain ESs (e.g., pest control, weed control, erosion control, and water regulation), we reversed the sign of the response (Tamburini et al. 2020).

2.4 Statistical analysis

The means and standard errors (SEs) of the treatment (CC in vineyards) and control (non-CC in vineyards) samples were extracted from studies, and the standard deviations (SDs) were calculated as follows:

$$\mathrm{SD} = \mathrm{SE}\sqrt{n}$$

where n is the sample size. If data were given a mean and a confidence interval (CI), the SDs for each group were obtained by dividing the length of the confidence interval by 3.92 ($\alpha = 0.05$) and then by the square root of the sample size. In studies without data variance, the SD was assumed to be 1/10 of the means (Shi et al. 2017).

A random-effects model for meta-analysis was employed since data were obtained from studies performed independently. Hence, it is assumed that the true effects from studies have been sampled randomly from a distribution of potentially infinite true effects (Borenstein et al. 2009; 2010):

$$Yi = \mu + \zeta i + \varepsilon i$$

where Yi is the response variable Ln(RR) of study i, μ is the overall effect size, ζi is the true variation in the effect size of study i, and εi is the sampling error of study i.

The distance from μ to each Yi depends on the SD of the distribution of the true effects across studies, namely, τ or τ^2 for its variance (i.e., the between-study variance). The same value of τ^2 applies to all studies in this meta-analysis (Borenstein et al. 2009). The between-study variance was computed according to the DerSimonian and Laird (1986; 2015) method. Under the random-effects model, the weight assigned to each study (Wi) is the inverse of the within-study variance (V_{Yi}) and the between-study variance (τ^2):

$$w_i = \frac{1}{Vy_i + \tau^2}$$

The study effect size and the overall summary effect estimate were calculated through the software Comprehensive Meta-Analysis Version 4 (Biostat Inc., Englewood, NJ, USA), which computes the lower and upper 95% confidence intervals (CIs), the Z value to test the null hypothesis that the effect size is zero, and the corresponding p value to reject the null hypothesis. An effect size was considered significant if the 95% CIs did not overlap with zero, and the corresponding p value ≤ 0.05.

The existence of publication bias was assessed by inspecting funnel plots of the standard error by Ln(RR). Duval and Tweedie's Trim and Fill method was used to determine where the missing studies are likely to fall, add them to the analysis, and then recompute the combined effect (Duval and Tweedie 2000). The test of the null hypothesis that all studies in the analysis share a common effect size was analyzed by the Q-test for heterogeneity at $\alpha = 0.10$ (Higgins and Thompson 2002; Higgins 2008). The absolute amount of dispersion of the effect size was assessed by prediction intervals (Borenstein 2022). The sensitivity of estimates of the effect size to each study of the dataset was assessed by removing the study with the highest effect size, and models were run with the remaining data. The change in the significance of the overall effect size or its biological meaning was used as an estimator of the quality of the statistical models (Borenstein et al. 2009).

To identify factors that are associated with the size of the effect, explanatory variables on PESs, RESs, and SESs were compared via subgroup analysis with pooled τ^2 to reduce the amount of error associated with a low number of studies in subgroups. A mixed-effects model was used since subgroups were combined by a fixed-effects model and a random-effects model within subgroups (Borenstein et al. 2010). Computations and graphical presentations were carried out using the software Comprehensive Meta-Analysis Version 4 (Biostat Inc., Englewood, NJ, USA).

A subset of 36 studies ($n = 93$ paired effect sizes) that concurrently reported the effects of cover cropping on grapevine yield (PES) and at least one other ES (RES and/or SES) was used to evaluate the occurrence of trade-offs and synergies among specific services. These were categorized into four outcome scenarios: win–win (multiple ESs improved), lose–lose (multiple ESs declined), and two types of trade-offs (one ES improved at the expense of another). Cases where effect sizes overlapped with zero were interpreted as having no significant effect of cover cropping on any ES (Tamburini et al. 2020).

3 Results and discussion

3.1 Overall study effect size, bias, and sensitivity overview

The pooled effect size (Fig. S1a–c) of cover crops (CC) on provisioning ecosystem services (PESs), such as grape yield, was not significantly different from zero (mean effect size: −0.056; 95% CI: −0.154 to 0.042), corresponding to an average yield change of −5.4% (95% CI: −14.3% to +4.3%) when back-transformed (Scordia et al. 2023). This suggests that cover cropping does not compromise grape production, aligning with experimental studies that report negligible or non-significant yield reductions (Celette et al. 2008; García et al. 2018). In contrast, cover cropping significantly enhanced regulating (RESs) and supporting ecosystem services (SESs), with mean effect sizes of 0.342 (95%

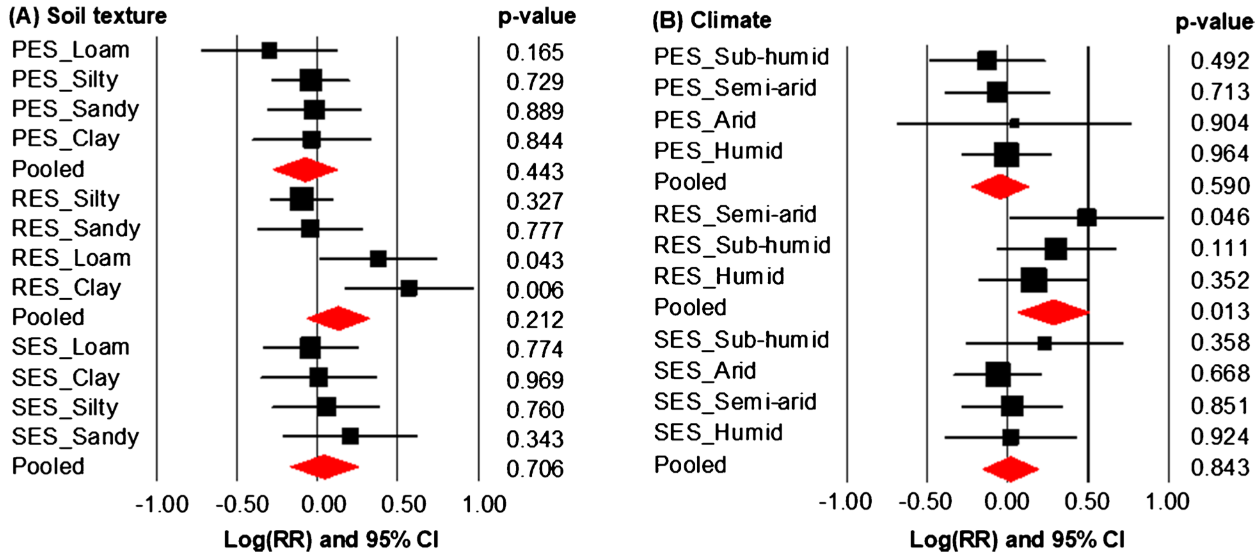

Fig. 4 Pooled (red diamonds) and mean effect size (black squares) of the natural logarithm of the response ratio [Ln(RR)] and 95% confidence intervals, and *p* value of provisioning (PESs), regulating (RESs), and supporting (SESs) ecosystem services (ESs) subgrouped by soil texture (clay, loam, silty, sandy) (**A**) and climate (aridity index: arid, semiarid, subhumid, humid) (**B**). Positive values of [Ln(RR)] indicate that PESs, RESs, or SESs were enhanced by cover crops in the vineyards, while negative values indicate a higher value in the control (i.e., ESs were reduced by cover crops). Different symbol sizes (squares or diamonds) represent different relative weights of the explanatory variable.

CI: 0.075 to 0.610) and 0.124 (95% CI: 0.008 to 0.241), respectively. These values translate to improvements of +40.8% for RESs and +13.2% for SESs. However, the magnitude of these effects was highly dependent on the moderator analyzed (as shown below), indicating the importance of context-specific factors such as soil, climate, vineyard, and cover crop management.

The precision intervals (95% PI) for the three ES categories were wide, ranging from −0.619 to 0.507 for PES, −1.180 to 1.865 for RES, and −0.481 to 0.729 for SES, highlighting substantial variability in the observed effects across studies. This heterogeneity was confirmed by the *Q*-test (PES: $Q = 21{,}146.98$, df = 30, $p < 0.001$; RES: $Q = 1675.52$, df = 30, $p < 0.001$; SES: $Q = 170.87$, df = 32, $p < 0.001$), rejecting the null hypothesis of a common effect size. It is worth mentioning that heterogeneity is inherent in agronomic and ecological research, which arises from differences in experimental design, site conditions, management practices, crop characteristics, and between-year variability from experimental works (Philibert et al. 2012).

Funnel plots (Fig. S2a–c) suggested a symmetrical distribution of studies. The Trim and Fill method imputed one missing study to the right for PESs and one missing study to the left for RESs and SESs, respectively. However, these adjustments did not alter the overall interpretation of the data, with revised point estimates of −0.038 for PESs (95% CI: −0.135, 0.0577), 0.251 for RESs (95% CI: 0.045, 0.582), and 0.101 for SESs (95% CI: 0.008, 0.240).

To assess the robustness of our findings, we conducted a sensitivity analysis by removing the study with the largest effect size. This exclusion did not change the pooled effect size or the statistical significance for any of the three ES categories (Fig. S3a–c), confirming that our results are not driven by a single study. Additionally, no individual study contributed more than 11% to the overall weight in the meta-analysis (Borenstein et al. 2009), indicating a balanced influence of the dataset and strengthening the reliability of our conclusions.

3.2 Moderators influencing ecosystem services due to cover cropping

3.2.1 Edaphic and climatic conditions

The soil texture influenced service delivery, with RESs significantly increased in clay (0.569, 95% CI: 0.167, 0.971) and loamy soils (0.378, 95% CI: 0.011, 0.745), corresponding to back-transformed averages of +81.5% and +45.9%, respectively, but not in sandy or silty soils (Fig. 4A). It can be inferred that finer-textured soils retain more moisture and nutrients, thus better supporting root growth and CC soil coverage and related regulations stimulated by CC residues (Tautges et al. 2019). In sandy and coarser soils, organic matter mineralizes more rapidly, reducing nutrient cycling and increasing the risk of nutrient leaching if residues are not properly managed (Nepal et al. 2024).

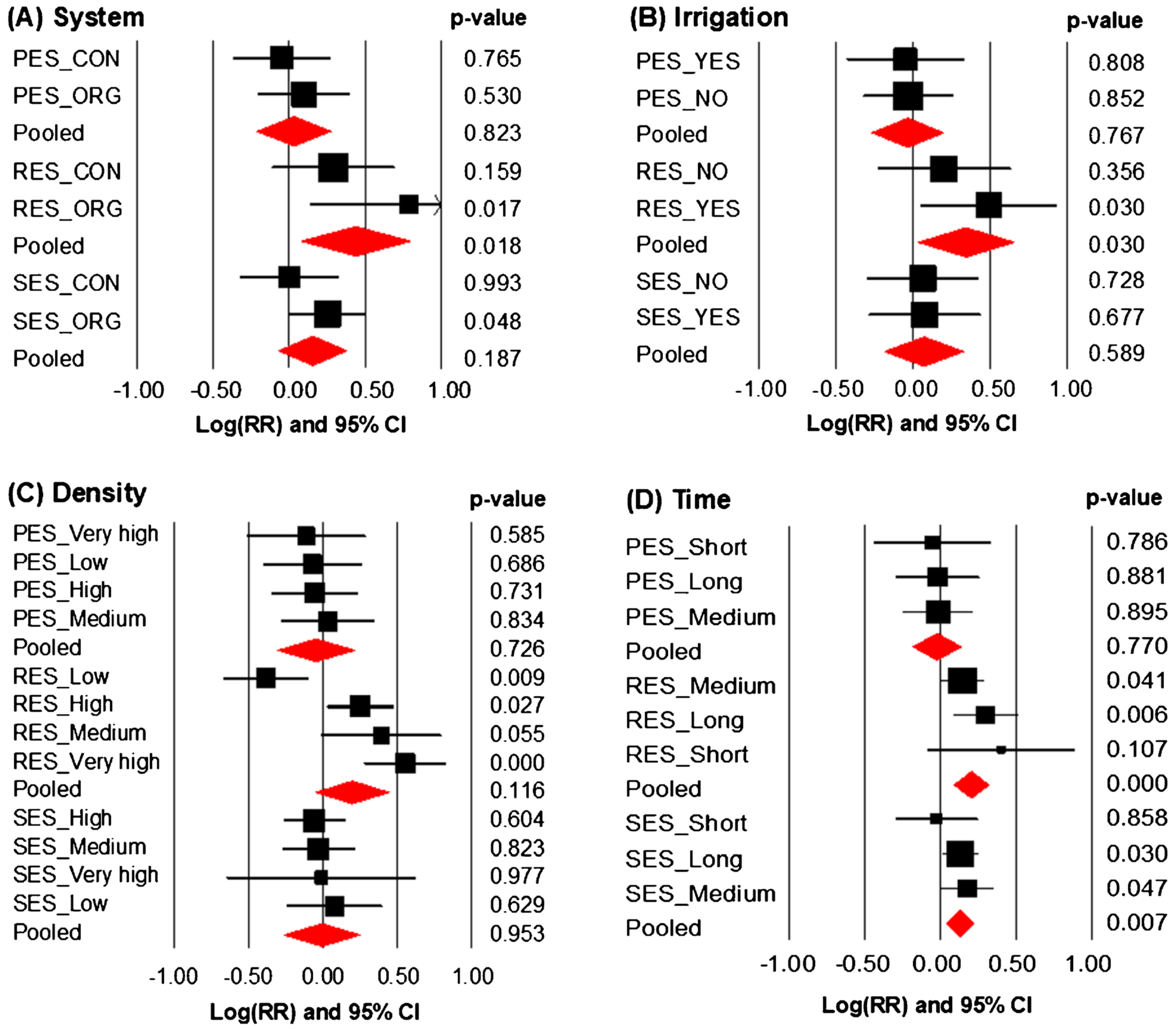

Fig. 5 Pooled (red diamonds) and mean effect size (black squares) of the natural logarithm of the response ratio [Ln(RR)] and 95% confidence intervals, and *p* value of provisioning (PESs), regulating (RESs), and supporting (SESs) ecosystem services (ESs) subgrouped by farming system (organic, ORG and conventional, CON) (**A**), irrigation (irrigation, YES and rainfed, NO) (**B**), grapevine density (low, medium, high, very high) (**C**), and time since conversion of vineyard to cover cropping (short, medium, long) (**D**). Positive values of [Ln(RR)] indicate that PESs, RESs, or SESs were enhanced by cover crops in the vineyards, while negative values indicate a higher value in the control (i.e., ESs were reduced by cover crops). Different symbol sizes (squares or diamonds) represent different relative weights of the explanatory variable.

In contrast to previous studies reporting yield reductions with cover cropping in dry climates (Winter et al. 2018), our analysis revealed that any climatic condition analyzed had no overall negative impact on PESs or SESs (Fig. 4B). In contrast, RESs (0.492, 95% CI: 0.010, 0.974) significantly improved in semiarid climates (+63%), likely because of the capacity of CCs to reduce soil erosion and regulate water dynamics and microclimate. This finding supports the results of Chapela-Oliva et al. (2022), who reported that RESs are particularly responsive to environmental variables such as rainfall distribution and temperature trends.

3.2.2 Vineyard management

The RESs mean effect size [0.793 (or +121%), 95% CI: 0.140, 1.446] and the SESs mean effect size [0.253 (or +28%), 95% CI: 0.002, 0.504] were significantly greater under organic than conventional farming systems (Fig. 5A). Although not significant, PESs also had a slightly positive mean effect size when CCs were used in organic compared with conventional vineyard systems (+10.3% and −4.8%, respectively). These findings align with previous research indicating organic systems often provide more favorable conditions for soil biota and biological processes (Steenwerth and Belina 2008; García et al. 2018). This reinforces the finding that the benefits of CCs are not only greater in magnitude under organic management but also extend across multiple ES categories, underscoring a stronger synergy when CCs are integrated into a broader agroecological framework (Altieri et al. 2015).

Irrigated vineyards significantly favored the mean effect size of RESs with CCs (0.490, 95% CI: 0.047, 0.933), while neither PESs nor SESs differed from zero in irrigated or rainfed systems (Fig. 5B). This contrasts with previous studies reporting a positive effect on PESs in irrigated vineyards (Winter et al. 2018; Chapela-Oliva et al. 2022). Interestingly, the back-transformed PESs in the rainfed vineyard with CCs averaged −2.7%, however, with a large variability (95% CI: −27.5%, 30.5%). This is consistent with experimental works demonstrating that CCs may compete with grapevines for water in rainfed systems unless managed carefully (Celette et al. 2008; Tesic et al. 2007). In general, irrigation and CCs should not overlap in vineyards. Ideally, CCs should be terminated before the critical periods of vine water demand (such as flowering and fruit set), ensuring that irrigation benefits the vines exclusively during these sensitive stages (Garcia et al. 2018). For instance, in warm temperate climates, irrigation is typically supplied as an emergency and not as a forcing technique, generally when CCs are in the senescence stage or just after CCs have been terminated. This timing helps prioritize water availability for vine development and fruit ripening. Because vine roots generally reach deeper into the soil profile than CCs, irrigation is more effective when it targets the deeper root zone, avoiding waste and competition in the shallower layers dominated by CC roots. Moreover, irrigation during CC senescence would have no impact on their growth (Poni et al. 2024). This implies that under water-limited conditions, the selection of less competitive CC species and the timing of CC termination may be essential for avoiding trade-offs with yield.

Interestingly, grapevine density (i.e., the density of the plants) emerged as an important moderator in our analysis (Fig. 5C). At low planting densities, CCs reduced RESs significantly [−0.384 (or −31.9%), 95% CI: −0.671, −0.097], likely due to increased space for weed competition with vines or being more subject to soil erosion. Furthermore, vineyards with wider row spacing tend to develop larger canopies, enhancing competition with CCs for key natural resources such as light, water, and nutrients, reducing the potential delivery of ESs (Celette et al. 2008). Indeed, at high (0.254, 95% CI: 0.030, 0.479) and very high-density (0.557, 95% CI: 0.280, 0.835) vineyard systems, RESs significantly improved (+28.9% and +74.5%, respectively), likely because less developed canopies facilitate better microclimatic conditions for CC growth and soil coverage, enhancing the effectiveness of CCs in delivering ecological benefits, such as improving soil coverage, erosion control, and biological activity (Garcia et al. 2018).

A trend was also observed with the time since conversion of vineyards to cover cropping (Fig. 5D). While this moderator did not affect PESs, RESs and SESs were significantly improved at medium [0.145, 95% CI: 0.006, 0.284, and 0.177, 95% CI: 0.084, 0.512, respectively] and long term [0.298, 95% CI: 0.084, 0.512, and 0.133, 95% CI: 0.013, 0.252, respectively]. These improvements correspond to back-transformed averages of +15.4% and +19.7% at medium, and +34.7% and +14.2% at long time since conversion to cover cropping for RESs and SESs, respectively. Schipanski et al. (2014) highlighted the importance of accounting for temporal dynamics when evaluating the effects of cover cropping on ES delivery. Over the long term, CCs can enhance the provision of ESs, the resilience of agroecosystems by reducing reliance on external inputs, and the overall sustainability (von Cossel et al. 2025).

3.2.3 Cover crop management

The spatial arrangement of CCs significantly influenced RESs (Fig. 6A). CCs grown in the vineyard row significantly improved RESs (0.382, 95% CI: 0.076, 0.688), while growing CCs in alleys or in-row plus alley showed a positive, but not significant, effect. These results align in part with the findings of Winter et al. (2018), who reported a 20% average improvement in biodiversity and ESs in vineyards adopting inter-row CCs. We found +46.5% RESs improvements by in-row CC growth, and although not significant, a +35.1% and +36.5% when CCs were grown in alleys or in-row and alley, respectively. This pattern could be explained since inter-row management in vineyards tends to be much more diverse and variable (95% CI: −20.9%, +130.7%) than in-row management (95% CI: +7.9%, +99%). Indeed, some growers might maintain permanent cover; others may mow periodically, till seasonally, or even leave the inter-row fallow. Such heterogeneity in practices affects the continuity, biomass production, and functional traits of CCs, resulting in more variable and less predictable impacts on ESs.

The CC type showed a slightly positive (but not significant) mean effect size for PESs with a mixture of grass and legume CCs [0.062 or (+6.4%)] compared with the grass, spontaneous, and legume CC types (Fig. 6B). SESs mean effect sizes were significantly favored by mixtures of CCs (0.246, 95% CI: 0.001, 0.491) and by species other than grasses or legumes (0.286, 95% CI: 0.022, 0.550). Furthermore, RESs mean effect sizes were significantly favored by the CC mixtures (0.450, 95% CI: 0.007, 0.893), by species other than grasses and legumes (2.170, 95% CI: 0.582, 3.758), and by spontaneous vegetation (0.750,

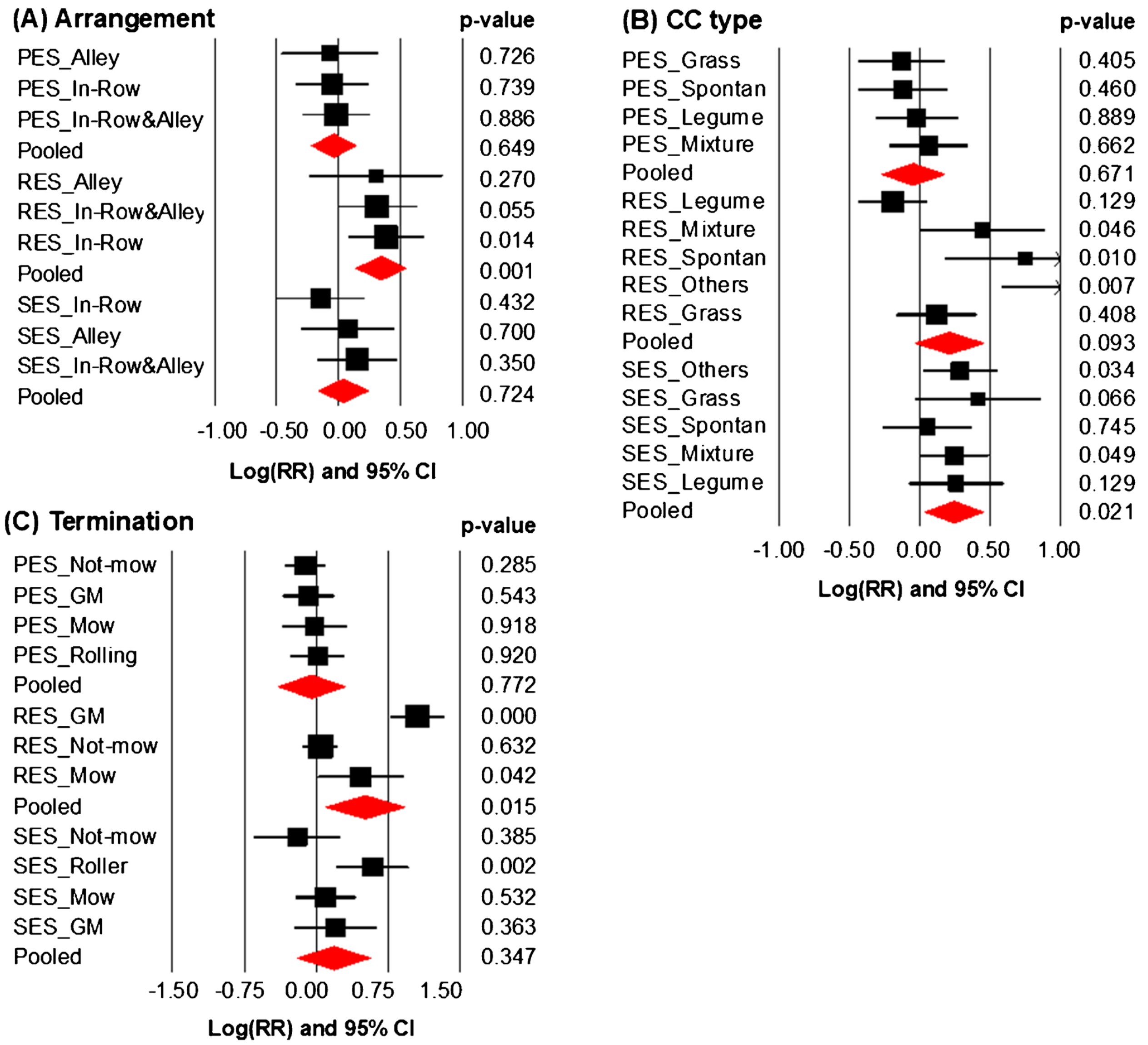

Fig. 6 Pooled (red diamonds) and mean effect size (black squares) of the natural logarithm of the response ratio [Ln(RR)] and 95% confidence intervals, and *p* value of provisioning (PESs), regulating (RESs), and supporting (SESs) ecosystem services (ESs) subgrouped by cover crop spatial arrangement (in-row, alley, in-row and alley) (**A**), cover crop type (grass, legume, mixture, spontaneous, others) (**B**), and cover crop termination method (green manuring, mowing, not mowing, roller-crimping) (**C**). Positive values of [Ln(RR)] indicate that PESs, RESs, or SESs were enhanced by cover crops in the vineyards, while negative values indicate a higher value in the control (i.e., ESs were reduced by cover crops). Different symbol sizes (squares or diamonds) represent different relative weights of the explanatory variable.

95% CI: 0.182, 1.318). These findings highlight the greater functionality of species diversity and locally adapted CCs. Indeed, mixtures of grasses and legumes enhanced SESs and RESs (+27.9% and +56.8%, respectively). Non-traditional species (neither grasses nor legumes, e.g., melliferous plants) had a strong effect on RESs (+775.8%) and also improved SESs (+33.1%). These combinations support a wider range of ecological functions, such as pollination, nitrogen fixation, nutrient cycling, microbial stimulation, and pest regulation, which single-species or grass-only CCs may not achieve (Finney et al. 2016; Tsonkova et al. 2020). Spontaneous vegetation also improved RESs (+111.7%), suggesting that site-adapted flora can provide substantial ecological benefits when not overly managed. Surprisingly, Brassicaceae CCs, an important functional group known for delivering key RESs, particularly in soil pest and disease control (Koudahe et al. 2022), were largely absent from our dataset. Only four studies (i.e., #25, 35, 100, and 308; Table S3) included Brassicaceae species, all in mixture with other botanical families (e.g.,

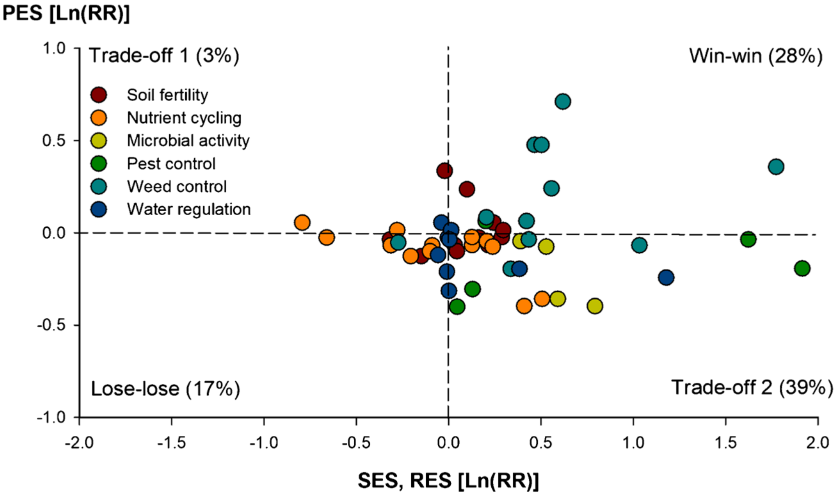

Fig. 7 Natural logarithm of the response ratio [Ln(RR)] showing synergies and trade-offs of provisioning (PES, y-axis), regulating and supporting (RES and SES, x-axis) ecosystem services (ESs) categories (figure legend on the left) according to 36 studies that simultaneously assessed at least one PES and one RES or SES (n = 93). Win–win scenario represents the % of studies that enhanced multiple ESs. Lose–lose scenario, the % of studies that reduced multiple ESs. Trade-off 1, the % of studies that enhanced PES and reduced RES and/or SES. Trade-off 2, the % of studies that enhanced RES and/or SES and reduced PES. ES categories overlapping dashed lines (vertical and horizontal lines at zero) show no effect of cover crops on ESs in vineyards.

Asteraceae, Papaveraceae, Compositae). Due to the limited number of studies and the absence of treatments testing Brassicaceae as a sole functional group, we were unable to analyze this group separately without compromising the robustness of the subgroup analysis.

The CC termination management was an important moderator in our analysis. Although the pooled effect size for SESs was not different from zero (0.180, 95% CI: −0.196, 0.557), the SESs mean effect size was significantly improved when CCs were terminated by roller-crimping [0.590, 95% CI: 0.218, 0.962] (Fig. 6C). Contrarily, the RESs mean effect sizes were significantly favored by CC terminated as green manuring [1.053 (or +186%), 95% CI: 0.777, 1.329] and mowing [0.464 (or +59%), 95% CI: 0.017, 0.911], which is consistent with the literature showing that biomass incorporation or surface retention improves soil organic matter and triggers biological activity (Basche et al. 2014). Interestingly, SESs were significantly improved only when CCs were terminated via roller-crimping (+80.4%), a low-disturbance method that maintains surface residue and habitat for the soil biota (Mirsky et al. 2012). These results suggest that less disruptive termination techniques can help preserve or enhance the benefits of cover cropping. Unfortunately, no data were available for the RESs by roller-crimper termination, but other studies have demonstrated the effectiveness of this method for weed suppression (Garcia et al. 2024), which also agrees with experimental observations this group is performing in the Mediterranean area (unpublished data). Furthermore, no soil incorporation of CC residues has been shown to reduce direct N_2O emissions from the soil surface (Basche et al. 2014), suggesting a more practical application of this termination method and further provisioning of regulating ESs.

3.3 Ecosystem services synergies and trade-offs due to cover cropping

By analyzing studies that simultaneously reported at least one provisioning ecosystem service (PES) and one regulating (RES) or supporting (SES) service, we identified 36 combinations ($n = 93$ effect sizes), revealing complex interactions among ecosystem functions under cover cropping (Fig. 7). These combinations underscore the multifunctionality of vineyard agroecosystems and the difficulty of simultaneously maximizing all services (MEA 2005). They also highlight a key research gap, as most studies assess only one or two ES categories in isolation.

A win–win scenario was observed in 28% of the cases, where CCs improved PES (i.e., grape yield) while simultaneously enhancing RESs or SESs, particularly through improved weed control and increased soil fertility. These synergistic outcomes are consistent with previous research showing that carefully managed CC mixtures can reduce weed pressure while improving soil nutrient dynamics (García et al. 2018). Similarly, Winter et al. (2018) documented positive interactions between yield and regulating services in vineyards managed without herbicides, reinforcing the potential of agroecological practices to deliver multiple ESs. Conversely, lose–lose scenarios occurred in 17% of the cases, where moderate reductions in PES were accompanied by declines in SESs or RESs, particularly nutrient cycling, soil fertility, and water regulation. Such negative outcomes may reflect poorly adapted or mismanaged CC systems, especially in water-limited environments where competition for water and nutrients between the CC and the grapevine can be detrimental (Ingels et al. 2005; Celette et al. 2008). These findings stress the importance of context-specific CC species selection, seeding density, and termination strategies to avoid adverse outcomes (Garcia et al. 2018, 2024).

In 42% of the cases, we observed trade-offs, where CCs improved at least one ES while negatively affecting another. The most common pattern (39%) involved enhancements in RESs or SESs, such as increased microbial activity, pest and disease control, or soil fertility, alongside small grapevine yield declines. These trade-offs mirror those reported by Chapela-Oliva et al. (2022), who noted that increased vegetation complexity in vineyards tends to enhance biodiversity and regulating services, but may slightly reduce yield in rainfed or arid systems. Similar challenges in balancing yield with ecological functions have been documented in other perennial cropping systems (Beillouin et al. 2019; Tamburini et al. 2020). With increasingly unpredictable climatic conditions, it is important to highlight the potential role of CCs in regulating major grapevine diseases in temperate regions, particularly downy and powdery mildew. Hasanaliyeva et al. (2024) reported that fall and spring-sown CCs (e.g., *Lolium perenne*, *Onobrychis viciifolia*, *Trifolium repens*, *Vicia sativa*, *Sinapis* spp.) delayed the onset (by 14–30 days) and reduced the severity (up to >90%) of downy and powdery mildew, particularly in untreated plots. Disease control varied by CC type and pathogen, but did not compromise grape yield or quality. This regulating effect is likely related to the physical barrier created by CCs, which limits pathogen dispersal by rain splash from the soil to the canopy, and to improved microclimatic conditions that reduce disease-favorable humidity.

Interestingly, only 3% of the studies reported an inverse trade-off, increased PES with reduced nutrient cycling (i.e., SES), which could reflect management choices favoring short-term yield (e.g., non-legume species, no residue incorporation) at the expense of long-term sustainability (Basche et al. 2014). Finally, 13% of the effect sizes showed no significant impact of cover cropping on any ES. These neutral outcomes likely stem from short-term trials, suboptimal species selection, or poor CC establishment and management (Schipanski et al. 2014; Lamichhane and Alletto 2022).

To prevent undesirable outcomes, it is crucial to account for vineyard phenology and seasonal dynamics, which significantly influence the ESs provided by CCs. These interactions are modulated by resource availability, management practices, and microclimatic conditions (Abad et al. 2021). The post-harvest and dormancy period, particularly in late-ripening regions, offers an optimal window for sowing winter CCs. During this phase, reduced grapevine activity minimizes competition, promoting CC establishment and enhancing their ability to deliver regulating and supporting services such as soil erosion control, runoff and nitrogen losses, nitrogen fixation, and weed suppression (García-Díaz et al. 2017; Abad et al. 2021). In contrast, during budburst and shoot development, grapevines exhibit high water and nutrient demands. Under these conditions, grapevine roots may avoid zones densely occupied by grass roots, extending deeper into the soil to access moisture and potentially alleviating summer drought stress (Linares Torres et al. 2018; Poni et al. 2024). However, this period may also necessitate early CC termination to prevent excessive competition for nutrients, which, although beneficial for vine performance, may limit nitrogen fixation and reduce flowering, ultimately diminishing the delivery of key ESs (Abad et al. 2021; Steenwerth and Belina 2008).

In Mediterranean climates, CCs are often terminated by mid-spring to facilitate nutrient cycling through residue decomposition. However, this strategy may compromise erosion control, especially where early vine growth overlaps with intense rainfall events. During summer (from veraison to ripening), CCs are frequently replaced by drought-tolerant species, yet under arid conditions, their capacity to regulate soil temperature and prevent erosion is notably reduced (Monteiro and Lopes 2007). Under these circumstances, less disruptive termination techniques, such as roller-crimping, can help preserve or enhance weed suppression and erosion control.

4 Conclusion

This meta-analysis aimed to provide a comprehensive quantification of how cover crops affect provisioning, regulating, and supporting ecosystem services in global temperate vineyards, by evaluating the influence of multiple explanatory variables related to climate, soil, vineyard management, and cover crop management. Our results demonstrated that cover crops consistently promoted regulating ecosystem services, such as pest control, erosion control, water regulation, pollination, and weed suppression. Furthermore, benefits for supporting ecosystem services, primarily nutrient cycling, microbial activity, and soil fertility, were also found. In addition, no overall effect on grape yield (provisioning) was observed, highlighting the neutral impact of cover cropping on productivity when averaged across studies.

Cover crop effects were highly context-dependent. Greater benefits were observed in semiarid climates, clay and loamy soils, organic systems, irrigated vineyards, and systems at high and very high grape density. Species mixtures (especially grasses and legumes, non-traditional species, and managed spontaneous vegetation) and low-disturbance termination methods (e.g., roller-crimping) or green manuring and mowing supported stronger multifunctional outcomes. In contrast, ecosystem benefits were limited in low-density vineyards and under conventional management practices, suggesting that competition for resources to cover crops is greater than facilitation in these growing systems. Regulating and supporting ecosystem services were also significantly improved with medium- and long-term vineyard conversion to cover cropping (>3 years), underscoring the importance of accounting for temporal dynamics in ecosystem service delivery.

This study highlights the ecological and agronomic benefits of cover crops in temperate vineyards and provides practical insights for their management across varying climates, soils, and vineyard systems. However, the frequent trade-offs observed among ecosystem services reveal the challenge of achieving full multifunctionality. To reduce these trade-offs, future research should focus on context-specific strategies that promote win–win outcomes. While provisioning services include key fruit quality traits (e.g., phenolic content, aroma), this meta-analysis focused solely on yield alongside regulating and supporting services. We acknowledge this limitation and recommend that future studies incorporate additional indicators to better capture the full scope of provisioning ESs. Moreover, there is a need for holistic experimental research evaluating multiple ESs simultaneously across diverse site-specific conditions and designs, and careful management strategies.

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Authors contributions Francesca Calderone: conceptualization; data curation; writing—original draft. Aurelio Scavo: conceptualization; data curation; writing—original draft; writing—review and editing. Fabio Gresta: writing—review and editing; funding acquisition. Filippo Ferlito: writing—review and editing. Corrado Dimauro: methodology; data curation; writing—review and editing. Danilo Scordia: conceptualization; methodology; data curation; writing—original draft; writing—review and editing; supervision.

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Data availability The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Code availability Computations were carried out via the software Comprehensive Meta-Analysis Version 4 (Biostat Inc., Englewood, NJ, USA). No codes are required to run the program.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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