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Review

Extensive vineyard management and semi-natural habitats increase biodiversity and ecosystem services: insights from a global meta-analysis

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ABSTRACT

Biodiversity erosion is a key challenge that requires major adaptations in land use for sustainable agriculture. Globally, vineyards are among the most intensive farming systems with negative impacts on biodiversity and associated ecosystem services (ES). Nature-based solutions need to reconcile biodiversity conservation with grape production from the field to the landscape scale. In this study, we conducted a hierarchical global meta-analysis to assess the impact of various practices related to extensive management such as establishing vegetation cover, organic farming or low pesticide use on biodiversity and ES. Our analysis is based on 822 datasets extracted from 221 articles. Overall, extensive management increased biodiversity and ES provision by 14.2 % in comparison to more intensive practices. While provisioning ES, such as grape quantity and quality, showed heterogeneous reponses, biodiversity and most other ES benefited from maintaining vegetation cover in vineyards. We identified the strongest positive response to extensive management in carbon sequestration (+37.8 %), followed by erosion control (+26.4 %), soil fertility (+19.9 %), and pest control (+16.4 %). Our analysis revealed that farming practices modulated the effects of extensive management, with high-diversity cover crops enhancing, and herbicide use diminishing, the beneficial impact on biodiversity and ES. Maintaining semi-natural habitats in the landscape significantly boosted the positive effect of extensive management on pest control. Finally, organic management reduced grape yield by 20 % but it did not affect grape quality. Nature-based solutions in viticulture should be based on extensive vegetation management, diverse cover-crops and low pesticide use combined with significant amounts of semi-natural habitats in the landscape, while minimising yield loss.

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1. Introduction

Climate change and biodiversity erosion are the main challenges of the Anthropocene exerting major pressure on socio-ecosystem functioning (Pecl et al., 2017). Agroecosystems in particular have to face these major pressures and reduce their environmental footprint while meeting the global food demand (Tscharntke et al., 2012a). These challenges require major adaptations of farming systems and land use management to design sustainable agrifood systems (Yang et al., 2024). Nature-based solutions refer to the sustainable use and management of ecosystem processes to tackle societal challenges that simultaneously provide environmental, social and economic benefits to society (Cohen-Shacham et al., 2016; Rusch, 2025). Such solutions already exist and offer a promising approach to building functional landscapes providing benefits to multiple stakeholders while addressing major challenges (Miralles-Wilhelm, 2023; Rusch, 2025). However, the adaptation of such solutions remains low, particularly for measures related to field management, also due to concerns about potential yield loss (Bailey et al., 2015). Widespread adoption of nature-based solutions by farmers can only be achieved by showcasing that such measures promote synergies between economic viability, biodiversity and ecosystem services over the long term in multiple farming systems (Morandin et al., 2016).

Vineyards are among the most important perennial farming systems in the world covering 7.1 million ha (OIV, 2025) with a large range of different grape varieties and production systems adapted to the local edaphoclimatic conditions. Historically, vineyards were managed as low-input multifunctional systems shaped by local traditions and biodiversity (Altieri and Nicholls, 2002). Due to the regular introduction of pathogens and pests in vineyards across the world, viticulture is nowadays a very intensive system, among the most pesticide-dependent land use types (Gensch et al., 2024) with major impacts on the environment (Martinez-Nuñez et al., 2025). For example, in France and Italy, vineyards receive more than 13–16 annual pesticide treatments on average in both organic and conventional systems (Nascimbene et al., 2012; Rusch et al., 2017), thereby accounting for about 20 % of total pesticide use at the national scale, even though they occupy less than 3 % of the total agricultural area (Saint-Ges and Bélis-Bergouignan, 2009). Fungicides are the most frequently applied pesticides in vineyards accounting for more than 85 % of all sprayings (Möth et al., 2023; Nascimbene et al., 2012; Rusch et al., 2017), both in conventional and organic systems, with documented negative effects on ecosystem services such as pest control (Möth et al., 2021; Nash et al., 2010; Pennington et al., 2018; Reiff et al., 2024) or soil fertility (Giffard et al., 2022) and biodiversity (Reiff et al., 2023; Zielonka et al., 2024). In addition, vineyards are land cover types which have the highest soil erosion risk index in many parts of Europe, especially in zones with low precipitation (Panagos et al., 2015). Identifying key nature-based solutions promoting biodiversity and ecosystem services to limit the environmental footprint of viticulture is therefore urgently needed (Rusch, 2025).

Several management options across scales, from the field to the landscape, are known to have beneficial effects on biodiversity and ecosystem services in vineyard landscapes (Giffard et al., 2022; Zielonka et al., 2024; Stemmelen et al., 2025). First, extensive within-field vegetation management and increased plant diversity (e.g., cover crops) have clear benefits for biodiversity and a range of ecosystem services, such as limiting soil erosion, increasing carbon sequestration, pollination and supporting natural enemies of grape pests (Beaumelle et al., 2021; Kehinde and Samways, 2014; Kratschmer et al., 2019; Payen et al., 2021; Rusch et al., 2017; Winter et al., 2018). However, maintaining vegetation in vineyard inter-rows might influence grape production through competition for water and nutrients (Pardini et al., 2002). This potential ecosystem disservice depends on local edaphoclimatic conditions and can be mitigated through management practices, such as irrigation (Winter et al., 2018). Besides the simple differentiation of vegetated versus bare soil management, plant community composition may also influence biodiversity (Eckert et al., 2020) and services provided (Beaumelle et al., 2021; Möth et al., 2021).

Second, organic farming at the field scale has been shown to increase biodiversity (Katayama et al., 2019; Puig-Montserrat et al., 2017) and ecosystem services (Coll et al., 2011; Muneret et al., 2019), while it is known to reduce crop yield on average (Beaumelle et al., 2023; Katayama et al., 2019; Marja et al., 2024). This benefical effect of organic farming most likely results from the lower pesticide use compared to conventional farming (Nascimbene et al., 2012; Ostandie et al., 2021). Overall, it is now well known that it is the actual farming practices such as pesticide use (and inorganic fertilisers), vegetation cover by weeds or cover crops and the preservation of semi-natural habitats to increase landscape complexity (Estrada-Carmona et al., 2022; Hole et al., 2005), that shape the effect of farming system on biodiversity more than the organic certification scheme (Hole et al., 2005; Kaczmarek et al., 2023a, 2024, 2023b; Möth et al., 2021; Reiff et al., 2023).

Third, landscape context, and especially the amount and spatial configuration of semi-natural habitats in particular, has been shown to be a key driver of biodiversity dynamics (Billeter et al., 2008; Priyadarshana et al., 2024) and ecosystem service provision in agricultural landscapes (Barbaro et al., 2017; Uzman et al., 2020). This beneficial effect originates from the fact that semi-natural habitats provide resources, overwintering sites, refuges and act as source habitats for many beneficial organisms in agricultural landscapes (Tscharntke et al., 2021; Holland et al., 2016). In addition, local and landscape context are known to strongly interact and shape local species assemblages and the level of ecosystem services. The landscape context shape the overall species pool while local management may act as filters explaining local assemablages (Tscharntke et al., 2012b). Thus, landscape context can mitigate the relative effect of local management on biodiversity or ecosystem services (Concepción et al., 2012; Tscharntke et al., 2012b). For instance, high landscape diversity might compensate for unfavourable local conditions, such as low flower cover for pollinators (Kratschmer et al., 2019) or intensive soil management for multiple taxa in olive farms (Rey et al., 2019). Alternatively, benefical effects of local management such as organic farming or cover crops may operate in sufficiently diversified landscapes supporting a minimal species pool. Although individual empirical studies have demonstrated that landscape context can moderate the effects of local management, there is a lack of quantitative assessments identifying the most effective combinations of practices across scales to enhance biodiversity conservation and ecosystem service delivery.

The effects of different nature-based management practices on biodiversity and multiple ecosystem services in vineyards were, for a long period, poorly investigated. However, in the last decade, more and more research has been published while quantitative assessment of the relative importance of these management options across scales is lacking. In order to provide robust recommendations about the relative effects of nature-based solutions, meta-analyses are useful tools for aggregating evidence-based knowledge across various environments and socio-economic contexts (Doré et al., 2011). Building on a previous meta-analysis (Winter et al., 2018), we expanded our research by incorporating a significant amount of new studies, along with additional moderators, to examine the effects of various management options on biodiversity, regulating, provisioning, and supporting ecosystem services in vineyard landscapes. Using this updated database we quantified for the first time the effects of (i) various vegetation management options such as cover crops, spontaneous vegetation, tillage regime and herbicide use, (ii) different farming systems by comparing organic to conventional management, (iii) pesticide application intensity, and (iv) landscape context on biodiversity and ecosystem services. We address the following research questions: (1) Which local vineyard management practices are most beneficial for biodiversity and ecosystem service provision? (2) Which management practices result in trade-offs between provisioning versus supporting, regulating ecosystem services and biodiversity? (3) To what extent does landscape context modulate the expected positive effects of local extensive management practices?

2. Material and methods

2.1. Literature search

We performed a systematic literature search in two major scientific databases, SCOPUS and the Web of Science Core Collection Database according to the PICO (Population, Intervention, Comparator and Outcome) combination of search terms (Higgins and Green, 2008), to identify studies investigating the effects of (a) different farming systems (organic, conventional and integrated), (b) vegetation management (spontaneous vegetation versus seeded cover crops differing in species richness, bare soil management) in the inter-row (INT) and (c) in the row (IN), and (d) pesticide use in vineyards on ecosystem services (ES) and biodiversity (initial database query 7.10.2020; updates from Web of Science alerts of the initial search string included until 22.12.2022). The initial search of the merged results from both databases resulted in 2637 articles. This literature search is an update and extension of the initial meta-analysis (covering finally 72 articles originating from a search until January 25, 2016) presented by Winter et al. (2018) justified by the aim to: (i) evaluate the effects of both landscape-scale effects and (ii) a range of management practices spanning farming systems, vegetation management and pesticide use which is also reflected in the extension of the search terms (see Appendix S1). After title screening, the number of articles was reduced to 990, and after abstract screening 412 articles remained for full-text screening in the current meta-analysis (see the PRISMA flow chart Fig. S4). These articles were then screened by a team of nine experts from different fields according to pre-defined inclusion and exclusion criteria (Koricheva et al., 2013; Moorhouse et al., 1993; O'Dea et al., 2021).

We only included articles that verified the following inclusion criteria: (i) included empirical measurements from commercial or experimental vineyards in the field, (ii) included at least three spatially independent replicates per treatment level, and (iii) did not only differ with respect to fertilisation level. In addition, all datasets needed to report mean and dispersion values (e.g., SD, SEM or CI), and the management variants needed to differ in intensity, allowing us to categorise them into the treatment (more extensive type of management, e.g., vegetation cover, organic management, no use of insecticides) and control (more intensive type of management, e.g., bare soil, conventional management, insecticide use, etc.). If important information (e.g., irrigation details or exact location) or dispersion parameters were missing, we contacted the corresponding authors of recently (until 2009) published articles. From 72 contact attempts, only 23 authors answered and provided missing parameters.

2.2. Data extraction and categorisation

For full-text screening, we screened the articles thoroughly according to our expertise in grape production (CH), soil biota and soil parameters (MS, DD, RH, MK), pest control (AR, DP), biodiversity (SW, LB, AR, DP) and climate regulation (YC). In addition to the current search, all previously extracted data (except for two datasets which were excluded due to an overlap between the presented data of the same authors) of the meta-analysis (Winter et al., 2018) were also included.

Each researcher documented the reason for exclusion (most frequently due to missing replication or the lack of reported statistical parameters). If articles could be included, we extracted all relevant statistical data and related covariates in a common database according to a shared manual. Mean and dispersion values were extracted from tables, text or figures with the WebplotDigitizer tool (URL: https://automeris.io/).

Control and treatment (cf. Higgins and Green, 2008) were defined based on management intensity differences with respect to (a) the farming system, with higher intensity in conventional or integrated (merged to conventional as control C) compared to the organic farming system (treatment T); (b) intensive (bare soil or single species cover crops) in comparison to extensive vegetation management with spontaneous vegetation cover, or seeded cover crops differing in species-richness (single = 1, low = 2–9 (mean: 4), high = 10–35 (mean: 22) species) in the inter-rows (INT) and (c) in the rows (IN); and finally, (d) higher-intensity pesticide applications in control compared to low-intensity in the treatment (T). When articles reported the outcomes of different treatments, we chose the largest contrast to the control (e.g., species-rich cover crops in the treatment versus bare soil management of the control).

However, if several treatments were reported with a similar level of complexity (e.g., different cover crops with the same number of species in the mixture), we computed a combined effect across those using established statistical methods for combining multiple studies, as described in Borenstein et al. (2009). The same procedure was used if parameters were reported separately for several localities within a study region or if parameters were measured multiple times within one year. When articles reported the results of multiple years, we selected the last year of the treatment only; this restriction sometimes also led to the exclusion of articles if the same authors published the same experiment several times, differing only with respect to the duration of the experiment. If several soil parameters from different depths were reported, we only used the measurements from the topsoil layer. If articles reported several independent measurements of biodiversity or ecosystem services, we extracted those datasets separately, for example: different taxonomic groups (e.g., birds, plants, insects,etc., but not for taxonomic subgroups within the same order), different ecosystem services (e.g. grape yield, grape quality parameters, soil fertility parameters), different experimental treatments not differing in respect to management intensity (e.g., spontaneous and cover crop mixtures, irrigated and rainfed vineyard plots) or different countries. The extracted data were afterwards screened by the first author for correctness and completeness. In order to reduce complexity and maximise the number of observations per category, we merged the following management types: (i) integrated and conventional management were classified as conventional management, and (ii) bare soil in every other inter-row was merged with bare soil management.

The current meta-analysis covers 221 articles; of these, we were able to extract 822 datasets covering biodiversity data, regulating, provisioning, and supporting ecosystem services. This represents a more than a threefold expansion of involved articles and 4.7-fold increase of datasets compared to the first meta-analysis (Winter et al., 2018). Table 1 provides an overview of the related sample sizes of the different ecosystem service types and biodiversity parameters captured in the overall dataset. In contrast to Winter et al. (2018), soil respiration was categorised as an ecosystem disservice contributing to greenhouse gas emissions and consequently also to increasing atmospheric carbon dioxide emissions (Raich et al., 2002), whereas soil microbial biomass was considered an ecosystem service contributing to carbon sequestration (Liang et al., 2017). The sign of effect sizes, which can be defined as ecosystem disservices (e.g., pest and disease-related parameters or soil loss), was reversed to account for the negative effect in the overall analysis.

2.3. Landscape analysis

To characterise the landscape context associated with the vineyards in the primary studies, we first extracted the spatial coordinates reported in each study. Among the 221 studies, 188 provided location information (33 did not); in 88 % of these cases, only a single coordinate was available per study, and the landscape context was characterised around that coordinate using a 1000 m radius buffer. When multiple coordinates were provided (22 studies), an average location was calculated. For studies without coordinates, we extracted information based

Table 1
Overview of the ecosystem service types and categories (according to the Millennium Ecosystem Assessment, 2005) and biodiversity parameters with the associated number of extracted datasets (first number) and studies (second number) in parenthesis (pollination is not beneficial for vines but other crop and wild plants).

Ecosystem service category/ biodiversity	Ecosystem service type/ biodiversity	Subset of variables (number of datasets included)	Variable
Biodiversity (*N* = 178/72)	Biodiversity (*N* =178/72)	Flora (*N* = 49/27)	Plant species richness, plant flowering species richness, Shannon index, plant species richness of annual and perennials
		Fauna (*N* = 102/47)	Species (S) and/or morphospecies (MS) richness of: arthropods (MS, S), predators (MS, S), parasitoids (MS), phytophagous (MS), pollinators (MS, S), ants (S), beetles (MS, S), hemiptera (MS, S), bats (S), birds (S), butterflies (S), moths, (cavity nesting) bees, wasps, grasshoppers, hymenoptera, beetles (MS), carabids, monkey beetles, Collembola, spiders (MS, S), earthworms Shannon index of birds, insects, Collembola, earthworms, nematodes Simpson index of carabids
		Fungi (*N* =17/11)	Fungal richness or Shannon index, Yeast species richness; mycorrhiza richness, endomopathogenic species richness
		Eukaryotes (*N* =1/1)	Soil Eukaryotes Shannon index
		Bacteria (*N* =10/5)	Bacterial richness, Shannon index, endophytic bacterial richness
Provisioning (*N* = 183/62)	Grape yield	Grape quantity (*N* = 73/57)	Grape yield
	Grape quality	Grape quality (*N* = 110/39)	Must quality (sugar content, total titratable acidity, yeast assimilable nitrogen)
Regulating (N = 356/139)	Carbon sequestration (*N* = 71/52)	Soil carbon (*N* = 71/52)	Soil carbon content
	Climate regulation (*N* = 25/18)	Greenhouse gas emissions (*N* = 25/18)	CO_2, N_2O emissions, soil respiration
	Pest control (*N* = 145/53)	Natural enemies related parameters (*N* = 101/45)	Abundance (occurrence, activity) of potential natural enemies like spiders, harvestmen, carabids, wasps, bats, predatory mites, nematodes, ants, parasitoids (*N* = 72, 34) Parasitism and predation rate, parasitoid survival (*N* = 30, 18)
		Pest related parameters (*N* = 44/26)	Pest abundance of cicada, mites, hemiptera, grape moths, thrips (N = 39, 23) Damage per vine and plot (N = 2, 1) Pest survival or fecundity (N = 4, 3)
	(Plant) Disease control (*N* = 24/8)	Disease related parameters (*N* = 24/8)	Severity, incidence or infestation of diseases like Botrytis, downy or powdery mildew, sour rot infection or black rot
	Pollination* (*N* = 10/6)	Pollination (*N* = 2/2)	Flower visitations Seeds per plant
		Pollinator abundance (*N* = 8/4)	Pollinator abundance (bees, hoverflies)
	Erosion control (*N* = 52/25)	Soil loss (*N* = 11/8)	Soil loss, runoff
		Erosion related soil parameters (*N* = 41/19)	Aggregate stability, percolation stability, saturated hydraulic conductivity, topsoil penetration resistance, total porosity, wettability, water retention, root reinforcement
	Water regulation (*N* = 29/21)	Soil water balance and content (*N* = 29/21)	Water capacity, water loss, (volumetric) soil water content, saturation degree of the topsoil
Supporting (*N* = 105/51)	Soil fertility (*N* = 105/51)	Soil biota (*N* = 41/24)	Soil fauna abundance (nematodes, earthworms, Oribatida, Collembola, mesofauna, microarthropods, bacteria, yeast), arbuscular mycorrhiza abundance, soil fauna feeding activity, soil biological quality indicator
		Decomposition (*N* = 4/4)	Decomposition index and rate
		Nutrient cycling (*N* = 60/27)	Soil macronutrient content and availability (K, N, P) Soil microbial biomass (N or phospholipid fatty acids)

on the location details given in the text or contacted the authors directly. To test the influence of the landscape context in the statistical analyses, we then extracted the proportion of (semi-)natural habitat (SNH) within the 1000 m buffer. Different land use datasets were used across sources, and categories corresponding to natural habitat were pooled to obtain a single metric for the proportion of SNH (see Table S1).

To obtain data regarding the different land uses surrounding vineyards, we utilised various publicly available raster maps covering the whole world. For Europe, we used CORINE land cover (EEA, 2018); for the United States, we used National Land Cover Data (NLCD, 2021); and for the rest of the world, we used ESA World Cover (ESA, 2021). Although we could have used ESAWC data for all sampling points, this repository only has data for the years 2020 and 2021, and our purpose was to match the year of the study with the closest year when data about land use was characterised. Therefore, to describe the landscapes of

Europe and the USA more accurately, we decided to use dedicated repositories for these continents, as they contain information for many years.

To determine the surrounding natural habitat proportions for each study/dataset, we established a 1000 m buffer around the coordinate provided in the study. Since patches closer to the sampling point may have more influence on ecosystem services than distant ones, we assigned different weights to landscape patches based on their proximity to the sampling location. This process involved evaluating natural habitat within 20 concentric rings, each 50 m wide, spanning a 1000-m radius. Following Karp et al. (2016), we calculated a weighted average for all rings around each location using Gaussian decay functions. Each ring received a weight, denoted as 'W', calculated as follows: $W = \exp(-I^2/(2 \times d^2))$. Here, 'I' represents the distance between the centre of the sampling point and the outer edge of the ring, and 'd' is the decay rate indicating how quickly the weightings decrease with distance. We calculated the total weighted area for each land use type by summing the weighted proportions within the concentric rings. For comparison, we used three different decay rates to define small, medium, and large influence areas. In the first scenario ($d = 250$), closer landscape features had more importance, making elements beyond 600 m irrelevant (Fig. S1). In the second scenario, the weight also favoured nearby landscape features, but it decreased gradually with distance, maintaining the relevance of all landscape elements within an 800–900-m radius. In the third scenario ($d = 1250$), the weight gradually decreased with increasing distance from the buffer's centre (I), ensuring all landscape elements remained similarly relevant (Fig. S1).

2.4. *Effect size calculation and statistical analyses*

Effect size calculation and statistical analysis were performed with R (R Development Core Team, 2023). We computed the log-response ratio as an estimate of the effect size in accordance with the previous meta-analysis (Winter et al., 2018). In order to account for the relatively small sample sizes of individual datasets, we adjusted the log-response ratio with a small-sample bias estimator using the Delta method (see Appendix S2 for the formulas) presented by Lajeunesse (2015). As we often extracted several datasets from one source, we considered the publication ID as a random effect in the mixed-effects model with the rma.mv function of the "metafor" package (Viechtbauer, 2010) to account for the non-independence of those datasets. In addition, we also included models with varying amounts of residual heterogeneity (τ^2) in each subset (moderator level) and tested whether those levels of residual heterogeneity significantly improved model fit using analysis of the variance (ANOVA) (Rubio-Aparicio et al., 2017). We considered the effects of the treatment and moderators to be significant if the confidence interval (CI) did not overlap with zero (Borenstein et al., 2009). To identify significant differences between multiple moderator levels while considering the simultaneous inference in parametric models, we used the general linear hypotheses (glht) function from the "multcomp" package (Hothorn et al., 2008). We reported the heterogeneity values, Akaike's Information Criterion for small sample size (AICc), Bayesian Information Criterion (BIC) of the models with significant moderators in Table S2 (R syntax see Appendix S3). Estimates and 95 % CI of the effect sizes were created with the "plotrix" package (Lemon, 2006) and with orchard plots with the "orchaRd 2.0" package (Nakagawa et al., 2023).

We analysed this large dataset using different sets of explanatory variables as moderators in the mixed-effects models: (1) climate types according to Köppen-Geiger (Kottek et al., 2006: arid and steppe, Mediterranean, continental, oceanic, subtropical), (2) ecosystem service categories and types (cf. Table 1), (3) study type (farming systems, vegetation management in the inter-row (INT) and in the row (IN), and pesticide use), (4) irrigation, and (5) amount of semi-natural habitats in the landscape (see 2.3). For the subset analysis of inter-row vegetation management, we used the following moderators: (1) cover crop type and diversity, (2) tillage and (3) herbicide use of the treatment. We also evaluated the effects of insecticide use for the pest control and biodiversity subset. To assess the impact of moderators in comparison to the null models of the respective datasets (or subsets), we used the ANOVA function with refit = TRUE to identify significant differences (see Table S2).

2.5. *Assessment of publication bias and sensitivity analysis*

To identify potential publication bias originating from the fact that studies reporting significant effects ("positive results") are generally more often published than articles reporting non-significant findings, we used different graphical presentations of the data with funnel plots and statistical tests. We computed regression tests with sample size as a predictor (Rothstein et al., 2005) and Rosenthal's fail safe number (Rosenthal, 1979), which estimates the number of unpublished studies that would nullify the effect of the meta-analysis. To identify potential outliers, we computed hat values and standardised residuals (Viechtbauer and Cheung, 2010) and plotted the results (Fig. S2). Neither funnel plots with Precision and effective sample size as measures of uncertainty (Fig. S3), nor the fail-safe number of 208,349 or Egger's regression test indicated any clear signs of publication bias ($p = 0.6766$) of the overall dataset (for details see Fig. S3 Online Supplementary Material).

We found no potential outliers whose standardised residuals exceeded three and were at the same time two times larger than the average hat value (Fig. S2; only two datasets exceeded the standardised residual of three and those were not influential). However, three data points had exceptionally high Cook's distances and large hat values. Nevertheless, if those individual datasets were excluded, effect sizes did not differ considerably, and therefore, we did not exclude those few outliers (Viechtbauer and Cheung, 2010).

3. Results

Overall, we extracted 822 datasets from 221 articles (see Appendix S4) from wine-growing regions across the northern and southern hemispheres. We retrieved 104 new articles in the systematic search query of the current meta-analysis in addition to the original 72 published articles from the first meta-analysis. The screening of the search alerts until December 2022 resulted in 45 additional publications that could be included in this meta-analysis, supplemented by two unpublished datasets (see PRISM flow chart Fig. S4). The datasets were published between 1992 and 2023, with 69 % of all studies being recently published from 2014 onwards and 111 studies (34 %) being published between 2017 and 2022, which were not included in Winter et al. (2018) (see Fig. S5). In accordance with most ecological meta-analyses, there was also a strong geographical pattern (see Fig. 1), with a majority of studies originating from Europe (68 % of all studies) and North America (20 % of all studies) representing the world's biggest wine producers except for China, Russia and Argentina. However, we were also able to obtain high-quality datasets from 12 studies from South Africa, 7 from Australia and New Zealand, 6 from South America and 2 from Asia (Turkey and Israel). The different climatic zones where grape production is possible are well represented in the dataset: arid-steppe: $N = 72$, continental: $N = 145$, Mediterranean: $N = 302$, oceanic: $N = 226$ and subtropical: $N = 70$ datasets. Overall, 211 datasets were collected from irrigated and 391 from rainfed vineyards. Most studies provided datasets on regulating ecosystem services (43 %), provisioning (22 %), biodiversity (22 %) and only 13 % on supporting ecosystem services.

Overall, extensive vineyard management significantly increased biodiversity and ES provision by approximately 14.2 % compared to the control (Fig. 2). Climate zones also influenced effect size, with significantly higher effect sizes in oceanic, Mediterranean and subtropical climates (Fig. S6), whereas irrigation did not show any effect on the effect size (not shown). Biodiversity benefited most from extensive

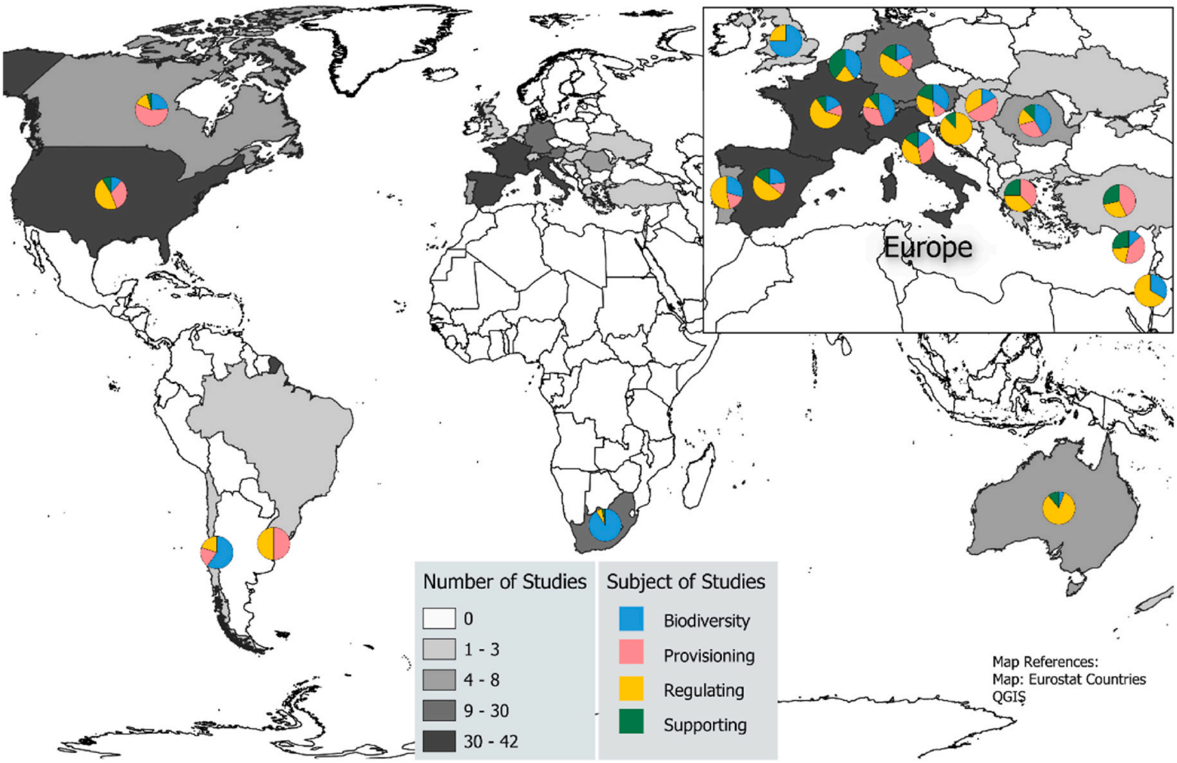

Fig. 1. Location of extracted datasets across the world, darker shading of the countries indicates higher number of studies; pie charts show the share of observations according to the ecosystem service category.

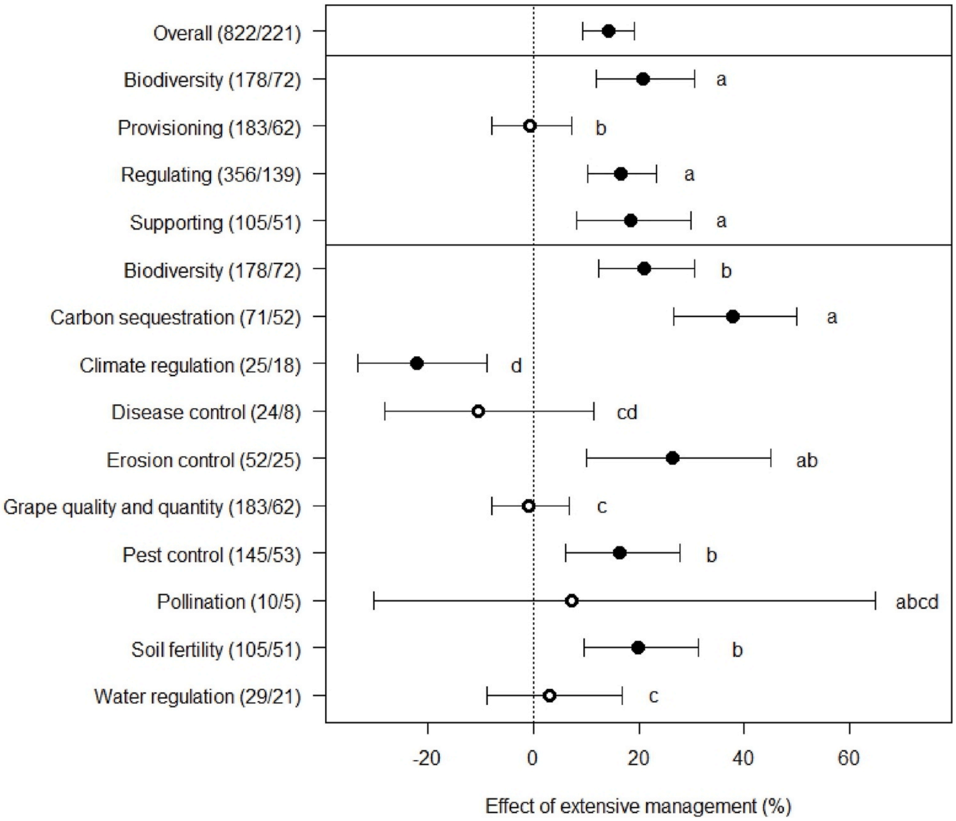

Fig. 2. Effects of extensive management (%) and confidence intervals (95 %) of the overall mean effect of extensive vineyard management, in respect to the ecosystem service category (middle panel) and ecosystem service types (lower panel). Number of observations and studies are indicated in brackets and significant differences at $p < 0.05$ between different moderator levels considering different heterogeneity (tau) within subgroups of the moderators are indicated with different letters. Non-significant effects are indicated with open circles.

management (20.9 %), closely followed by supporting (18.5 %) and regulating ES (16.7 %). Provisioning ES were not significantly affected by extensive vineyard management and decreased by −0.6 % due to extensive management practices (see Figs. 2 and 3a). ES category levels significantly differed only between the provisioning and the other ES categories and biodiversity.

Looking more closely at ecosystem service types, we found the strongest positive response to extensive management for carbon sequestration (+37.8 %), followed by erosion control (+26.4 %) and soil fertility (+19.9 %) (see Fig. 2). In contrast to the former meta-analysis (Fig. S7), we found a significant increase of pest control due to extensive management practices (+16.4 %). However, we did not find a significant effect for disease control, pollination and water regulation. Only one ecosystem service, climate regulation, decreased under extensive vineyard management (−22.0 %), which was mainly related to higher soil respiration and CO2 emissions under extensive management.

Further breaking down ecosystem service types, extensive vegetation management resulted in the largest overall increase of soil loss compared to bare soil vineyard inter-rows (+173.8 %; Fig. S8). The second and third strongest change due to extensive management were recorded from studies measuring the effects of extensive management on soil biota (+31.2 %) and carbon sequestration (+30.5 %). Interestingly, we found a significant increase of grape quality in response to extensive management (+7.7 %). The only negatively affected ecosystem service types were greenhouse gas emissions (-17.2 %) and disease-related parameters (-16.6 %).

3.1. *Effects of local management practices on biodiversity and ecosystem services*

The largest subset of studies investigating the effects of extensive vegetation management (Fig. 3b) and the effects of different farming types (organic versus conventional; Fig. 3c), resulted in similar results compared to the total dataset (Fig. 3a). Extensive management significantly increased ecosystem services across all categories with the exception of provisioning ecosystem services, i.e. grape yield and quality. Organic management showed a stronger negative effect on provisioning services (−9.6 %) compared to extensive inter-row management (−0.6 %). However, this effect was not statistically significant, likely due to high variability and the limited number of datasets and studies available. Interestingly, organic farming led to the most pronounced increase in supporting ecosystem services (+25.3 % in comparison to +17 % of biodiversity and 10.5 % of regulating services). Extensive inter-row vegetation management increased biodiversity (+25.2 %) services most significantly, followed by regulating ecosystem services (+20.6 %).

The subset analysis of studies investigating the effects of different vegetation types and bare soil as the control on overall biodiversity and ecosystem services showed significantly higher effect sizes of high-diversity cover crop mixtures (+41.4 %) in comparison to single-species cover crops of the treatment (+8.2 %; Fig. 4). Spontaneous vegetation increased biodiversity and ecosystem service provision by 11.6 % and low-diversity cover crops (2–9 seeded species) by 13.5 %. Low-diversity cover crops had higher benefical effects on biodiversity and ecosysytem sercices than single-species cover crops (Fig. 4).

When examining vegetation management effects, we found a stronger positive effect when the vegetation in the treatment was neither tilled (+16.0 %) nor removed by using herbicides (Fig. 4). The differences between herbicide use in the treatment (which could be restricted to the area underneath the vines) were significant (+14.3 %), resulting in a non-significant effect of the treatment if herbicides were applied (−0.3 %). However, (infrequent) tillage in extensively managemend vineyards still significantly increased biodiversity and ecosystem services by 8.7 % in comparison to bare soil management.

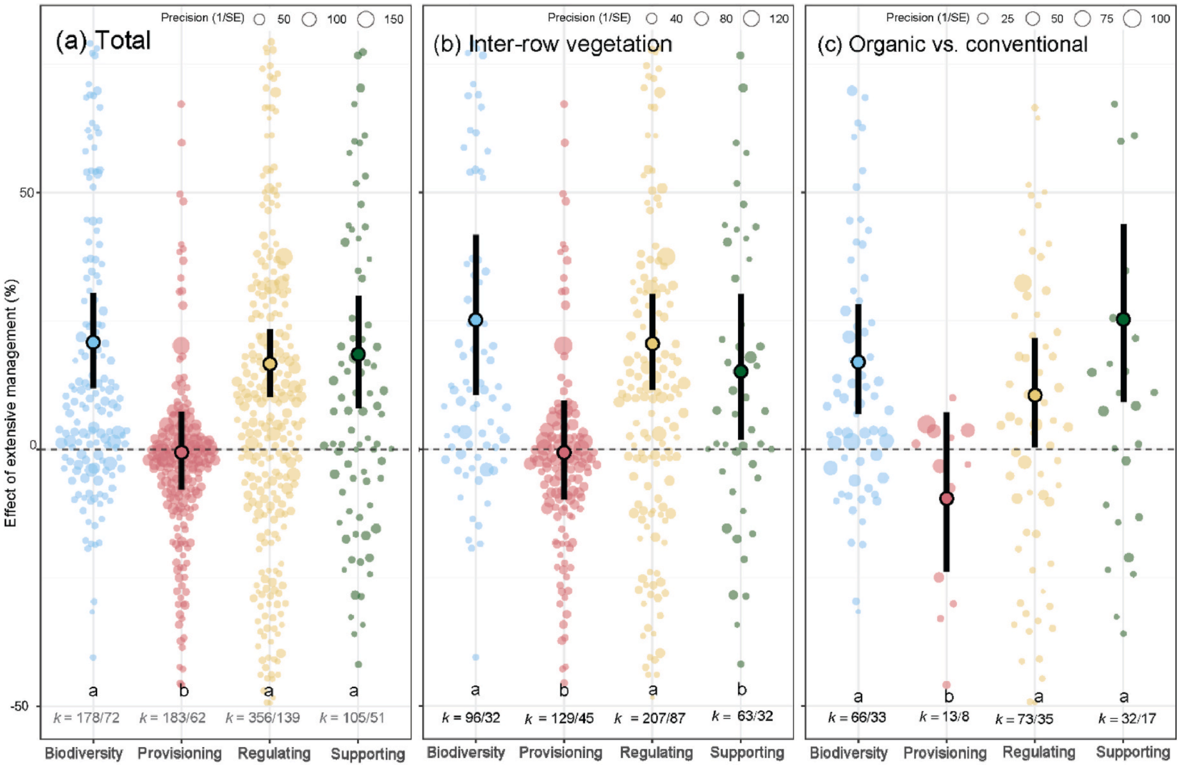

Fig. 3. Orchard plots showing effects of extensive management (%) and confidence intervals (95 %) on biodiversity and ecosystem services for the total dataset (a), the subset of studies comparing only vegetation management intensity (b), and the effect of organic versus conventional management (c). Point size is proportional to the variance of the respective effect size. The number of datasets/studies are shown at the bottom and significant differences at $p > 0.05$ between different ecosystem service categories and biodiversity, considering different heterogeneity (tau) within subgroups of the moderator ecosystem service categories, are indicated by different letters. Y-axis is cut off at −50 and + 80 to improve clarity of the figure.

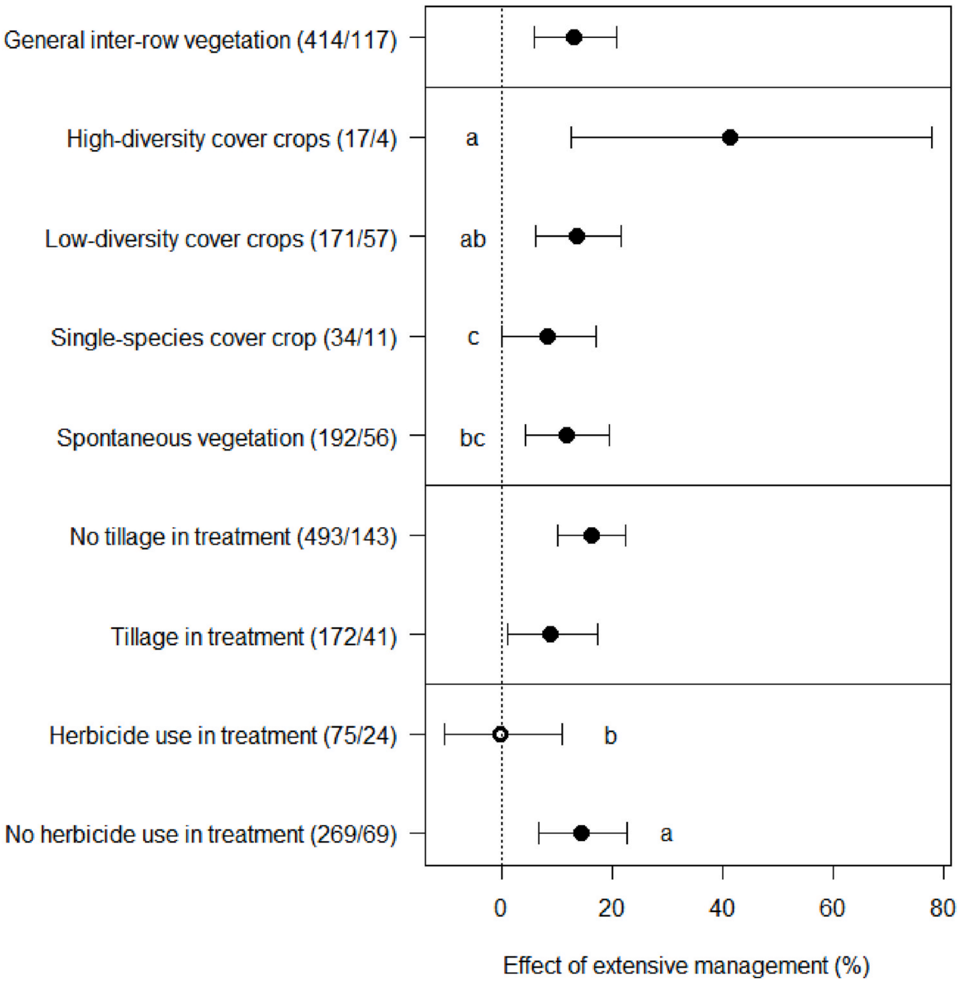

Fig. 4. Estimates and confidence intervals (in %) of the effects of extensive inter-row vegetation management, tillage, or herbicide use in the treatment on overall biodiversity and ES (number of datasets/studies in brackets). Significant differences between cover-crop diversity and spontaneous vegetation compared to bare soil management of the control as well as difference of the vegetation management of the treatment are indicated with by different letter combinations ($p < 0.05$). Non-significant effects are indicated with open circles.

3.2. Moderator effects on grape quality and quantity

Neither the study type nor the farming type of the treatment significantly influenced both grape quality and quantity (Fig. S9). Whereas the analysis of the overall dataset with the moderator ecosystem variable, showed a significant increase of grape quality in response to extensive management (+7.7 %, Fig. S9), the subset analysis showed no effect on grape quality but a significant decrease of grape quantity (yield) of −6.8 % due to extensive management (Fig. S9). Contrary to expectations, irrigation in vineyards had a significant negative effect on grape quality and quantity (−5.1 %), which was related to negative effects on grape quality rather than quantity when these two aspects were considered independently (Fig. S9). Organic farming and no pesticide use (N = 2) significantly decreased grape quantity (yield) datasets by −20.4 % and −40.8 %, whereas extensive vegetation management in the inter-row and rows did not signficiantly impact grape yields. Arid-steppe and subtropical climates significantly decreased grape yields when vineyards were managed extensively (but note the low number of 3/5 studies), whereas extensive management in continental climates resulted in a non-significant positive response of +8.9 % of grape yield.

3.3. Moderator effects on pest control

Extensive vineyard management clearly increased pest control compared to the control (+15.6 %; Fig. 5). The largest significant positive effect was related to extensive vegetation management in the inter-row (+18.8 %; Fig. 5) and low (or no) pesticide use (+24.5 %; Fig. 5). Interestingly, the farming type (organic vs. conventional) did not yield any significant results despite a relatively large number of involved datasets and studies. The mean effect of extensive management on pest control was similar when insecticides were applied or not (no: 16.1 %, yes: 15.6 %), however, the application of insecticides resulted in a non-significant effect of extensive vegetation management. Different climate zones also affected the response of pest control to extensive vineyard management, with the highest significant positive response found in subtropical climates (+120.1 %; Fig. 5), followed by Mediterranean climates (+25.2 %; Fig. 5).

3.4. Landscape-scale effects

To assess the effects of landscape composition on biodiversity and ES, we used a subset of datasets with available geographic coordinates, resulting in a total in 729 datasets. In general, higher shares of semi-natural habitats within the whole landscape (d = 1250) showed a non-significant positive effect of the meta-regression slope (12.2 % [−2.1, 28.8]). Landscapes supporting higher amounts of agricultural cover near the sampling point (d = 250) resulted in a weak, non-significant decline of biodiversity (estimate = −14.4 % ([−27.4, 1]; p-value = 0.066)) (data not shown).

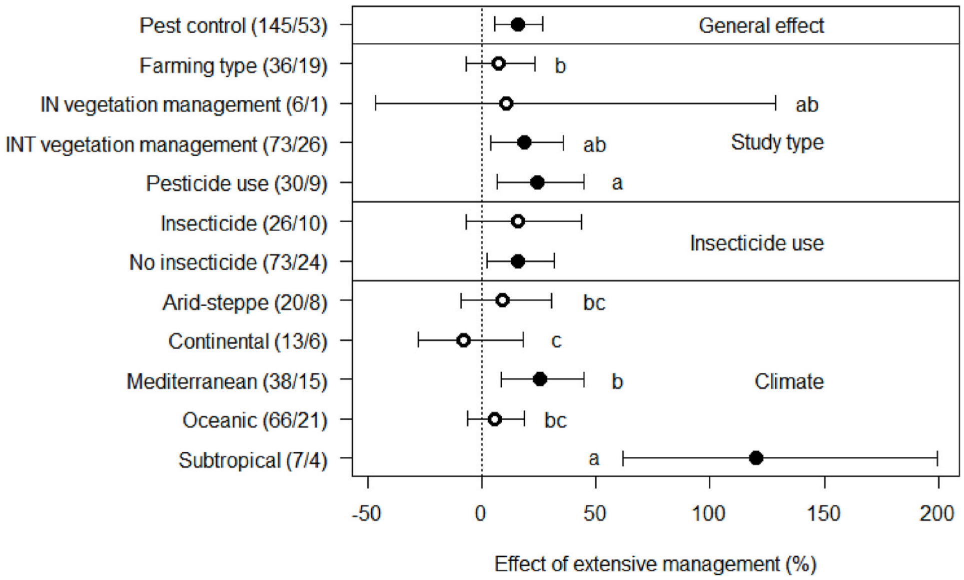

Fig. 5. Estimates and confidence intervals (in %) of the effects of extensive vineyard management on pest control, showing the effects of different study types (IN = in-row, INT = inter-row), insecticide use in the treatment and climatic zones (number of datasets/studies in brackets). Letters relate to significant differences at $p < 0.05$. Non-significant effects are indicated with open circles.

However, considering only pest control studies, we found a significant positive effect of higher shares of semi-natural habitats at the broader landscape scale (d = 1250) of 39.6 % on this ecosystem service ($p = 0.03$) (Fig. 6).

4. Discussion

Our meta-analysis demonstrates the overall strong positive effects of extensive vineyard management on biodiversity and ecosystem service provision and highlights key on-field and off-field management options that can benefit biodiversity in vineyards. On average, we found that extensive management resulted in a 14.2 % increase in biodiversity or ecosystem services. Overall, maintaining vegetation cover in the inter-row, high plant diversity and lower management intensity of the inter-row vegetation had a strong positive effect on biodiversity and all ecosystem service categories except on provisioning services (i.e. grape yield). Even though, inter-row vegetation did not compromise grape yield and must quality. In addition, we found that organic farming resulted in the highest supporting ES but at the same time also significantly decreased grape production illustrating a clear trade-off between those services in organic farming systems. Interestingly, our study highlights that the landscape context significantly modulates the beneficial effect of local extensive management on key ecosystem services, as demonstrated by the more positive effect of extensive management on pest control in complex landscapes with higher amounts of semi-natural habitats.

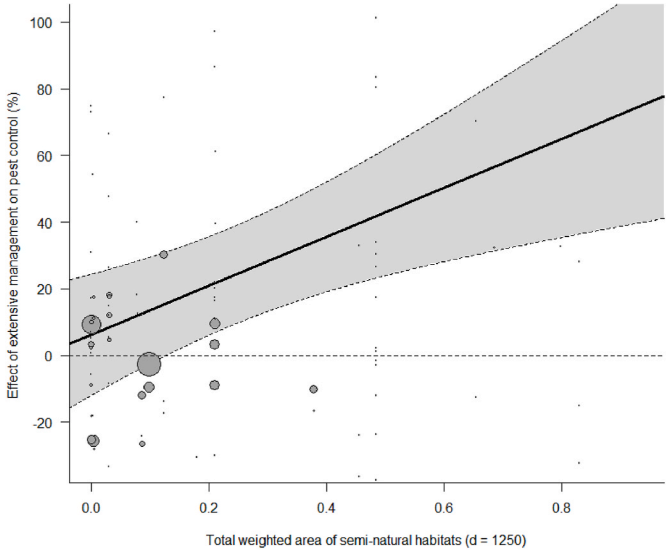

Fig. 6. Meta-regression of the effects of extensive vineyard management in response to total weighted area of semi-natural habitats across the whole landscape (d = 1250) on percentage change of pest control (N = 124). Point size is proportional to the variance of the respective effect size (point size = 10/sqrt(back-transformed variance). The grey-shaded area bordered by the dashed lines indicates the 95 % confidence interval of the estimated effect size of the solid line.

4.1. *Vegetation management effects on biodiversity and ecosystem services*

Our meta-analysis shows that extensive vegetation management has a positive impact on biodiversity and ES without significantly affecting grape yield, as there was no significant effect within the subset of grape quantity with extensive interrow management, and overall no effect when excluding the few studies conducted in arid and subtropical regions (Fig. S9). This effect of extensive vegetation management on provisioning services and grape quantity, was already shown in a range of previous publications (e.g., Baumgartner et al., 2008; Ruiz-Colmenero et al., 2011). However, local edaphoclimatic conditions, age of the vineyard, cover crop type and management have demonstrated to influence the competition between the herbaceous vegetation and grape vines and consequently the yield (Raffa et al., 2022; Ruiz-Colmenero et al., 2011).

Our study indicated systematic positive effects of vegetated inter-rows on biodiversity and ecosystem services compared to bare soil management, with the largest positive effect found for high-diversity cover crop mixtures and the lowest for single-species cover crops. Unfortunately, the number of observations for high-diversity and single-species cover crops were relatively low, therefore, results need to be confirmed in future studies. Our results in perennial vineyard systems confirm the positive effects of functionally diverse cover crops obtained in annual cropping systems for two key ecosystem services, nutrient cycling and weed suppression (Reiss and Drinkwater, 2022). These findings stress the importance of policies supporting the establishment of vegetation cover in vineyards, especially in regions which are production-oriented with low proportions of SNHs and lack adequate agri-environmental programmes (Chen et al., 2024).

Herbicide application in the treatment cancelled out the overall positive effects of extensive vegetation management. In contrast, tillage also reduced the benefits of established vegetation cover, but a net positive effects on biodiversity and ecosystem service still remained. These results are in line with previous empirical studies showing negative effects of herbicide use compared to tillage or vegetation crop on plant species richness (Fried et al., 2019), arthropod activity-densities (Renaud et al., 2004; Sanguankeo and León, 2011), nematode abundance, soil web structure (Sánchez-Moreno et al., 2015) and predation rates (Sanguankeo and León, 2011). Furthermore, high herbicide application rates might change weed communities with higher proportions of troublesome weeds (Fried et al., 2019; Guerra et al., 2022). The combination of low-intensity mowing and tillage seems most promising to foster diverse weed communities that maintain biodiversity and ecosystem service provision(Steenwerth et al., 2016).

4.2. Benefits and trade-offs of organic farming for biodiversity and ecosystem service provision

Our meta-analysis confirms previous findings on diverse cropping systems, showing that organic farming significantly promotes biodiversity but involves a trade-off with reduced yields (Katayama et al., 2019; Seufert et al., 2012; Tuck et al., 2014). In addition, in wine production there is often a trade-off between maximising production and producing high-quality wines, which limits the maximum amount of harvested grapes per hectare. Consequently, reduced yields due to organic management or vegetation cover may not be a disservice but may be beneficial in the high-quality wine production sector, as they can reduce the costs related to fruit thinning before harvest (Steenwerth and Guerra, 2012). positive effects of organic farming in perennial systems is assumed to mainly come from the fact that no synthetic pesticides nor artificial fertilizers are used which usually lead to higher organic matter in the soil and larger plant diversity with positive bottom-up effects on multiple trophic levels (Bengtsson et al., 2005; Scherber et al., 2010). However, several studies in perennial systems such as grasslands, orchards or vineyards, also reported highly variable effects of organic farming on biodiversity and some even reported insignificant effects (Kaczmarek et al., 2023a, 2024, 2023b; Katayama et al., 2019; Tuck et al., 2014). This large variability of the effect of organic farming could originate from the missing organic regulations concerning vegetation cover in vineyards, which plays a vital role in providing habitat and resources for biodiversity (Geldenhuys et al., 2021; Saenz-Romo et al., 2019). In addition, the benefits of establishing vegetation to improve trafficability, soil fertility and erosion (reviewed in Giffard et al., 2022) have led to the establishment of cover crops in both farming systems across many wine-growing regions limiting the contrast between the two treatment.

Furthermore, even though synthetic pesticides are banned from organic farming, it is known that organic vineyards can use a lot of non-synthetic pesticides (e.g., copper and sulphur) and may have a higher number of farming interventions (e.g., mechanical weeding, sulphur and copper as fungicide applications) that might result in a higher disturbance regime compared to conventional vineyards (Polge de Combret-Champart et al., 2013). This high disturbance frequency might counteract the positive effects of organic farming on biodiversity and ecosystem service provision (Ostandie et al., 2021). Furthermore, the non-specific fungicides sulphur and copper certified for organic farming have well-documented non-target effects on a wide range of arthropods and natural enemies (Kaczmarek et al., 2023a; Möth et al., 2021; Rusch et al., 2015).

4.3. Effects of extensive management, climate and semi-natural habitats at the landscape scale for pest control

Our results provide strong evidence that extensive vineyard management practices significantly enhance pest control services, which are vital for sustainable agriculture. The subset analysis focusing on pest control identified extensive vegetation management in inter-rows and reduced pesticide use as key drivers of these positive effects. Practices such as high-diversity cover cropping provide refugia, alternative prey, and nectar resources that sustain populations of natural enemies like predatory arthropods and parasitoids, thereby enhancing pest regulation (Landis et al., 2000). This finding aligns with the known positive bottom-up effects of plant diversity on higher trophic levels (Scherber et al., 2010) and with empirical studies highlighting the benefits of habitat complexity in fostering functional biodiversity and ecosystem services (Letourneau et al., 2011; Plata et al., 2025). Several empirical studies in perennial cropping systems have reported that maintaining spontaneous vegetation or using diversified cover crops mixtures increased the abundance or diversity of natural enemies with potential beneficial impatcs on pest control (Beaumelle et al., 2021; Danne et al., 2010; Geldenhuys et al., 2021; Judt et al., 2023). Interestingly our results suggest that the effectiveness of extensive local management practices is not uniform and depend on pesticide use, climate characteristics and landscape context.

Reduced pesticide use was particularly impactful, as avoiding insecticides mitigated the suppression of beneficial arthropods, allowing their populations to flourish and enhancing their predation and parasitism rates(Geiger et al., 2010). This underscores the importance of minimising chemical inputs to maintain the natural enemy communities essential for pest control (Tscharntke et al., 2016). However, while reduced pesticide use is beneficial, it is important to recognise that pesticide use may also be of major importance to mitigate the negative impacts of some practices on yield. These challenges highlight the need for alternative approaches, particularly conserving and promoting semi-natural habitats at landscape scales, while maintaining diverse ground vegetation cover.

The response of pest control services to management practices varied significantly across climate zones, with subtropical regions showing the most substantial positive effects, followed by Mediterranean climates. This gradient likely reflects the baseline biodiversity and climatic conditions in these regions. Due to favourable temperatures and extended growing seasons, subtropical climates generally support higher natural enemy diversity and activity (Bischoff et al., 2022). In contrast, temperate regions often have shorter active periods for natural enemies, which may limit the efficacy of extensive practices (Rasmann et al., 2014). Additionally, climate influences plant-insect interactions, including shifts in natural enemy dynamics and pest suppression along latitudinal and altitudinal gradients (Rasmann and Agrawal, 2011). These findings emphasise the need to tailor vineyard management strategies to specific ecological contexts, with pesticide use being a particularly critical factor in achieving sustainable pest control outcomes. Unfortunately, many studies have not reported pesticide use. Consequently, we could not perform an in-depth analysis of the effects of pesticide load or toxicity. Looking ahead, climate change is likely to reshape these interactions by intensifying pest pressures, altering the seasonal activity and density of natural enemies, and modifying the relative importance of different habitat types in supporting taxa across regions. Anticipating these shifts will be essential to ensure that conservation planning and agri-environmental schemes remain effective under future conditions of global change (van Leeuwen et al., 2024).

In addition, the capacity of management practices to sustain these interactions also depends on the availability of specific semi-natural habitats, as hedgerows and field margins primarily support arthropod natural enemies (Gaigher et al., 2024), forests and woodlots enhance bird- and bat-mediated predation (Korányi et al., 2025), and grasslands sustain pollinators (Vujanović et al., 2023). Identifying which habitat types contribute most under different climatic contexts will be crucial for developing priority conservation strategies.

Critically, the analysis of landscape composition revealed that higher shares of semi-natural habitats in the broader landscape significantly enhance the effectiveness of extensive management for pest control services (Martin et al., 2019). These habitats play a critical role in providing essential resources already mentioned for cover cropping but at a broader spatial scale (Chaplin-Kramer et al., 2011; Landis et al., 2000; Martin et al., 2019). Importantly, semi-natural areas can help overcome the transient phases of community assembly that typically occur in newly established vineyards, where soil biota, pollinators, and natural enemies accumulate only gradually (Fialas et al., 2023). Our results suggest that the positive influence of semi-natural habitats on pest control reflects recolonization processes from nearby source habitats (Hogg and Daane, 2010), which are particularly important during the early stages of vineyard establishment and help sustain ecosystem services until stable local communities are fully developed. Conversely, landscapes dominated by high agricultural cover weaken pest control by reducing habitat complexity and limiting resource availability for natural enemies and allowing specialist pest populations to rapidly build and disperse (O'Rourke and Petersen, 2017; Paredes et al., 2023; Root, 1973). To counteract these effects, research increasingly advocates for landscape-level measures such as crop diversification, smaller field sizes, and maintaining at least 20 % semi-natural habitats within agricultural landscapes (Gagic et al., 2021; Tscharntke et al., 2021).

Integrating local management practices with broader landscape-level strategies enhances pest control services by leveraging the synergy between actions like cover cropping and reduced pesticide use with the ecological benefits of semi-natural habitats (Etienne et al., 2023; Geppert et al., 2024; Paredes et al., 2021; Tscharntke et al., 2024). This approach ensures sustainable pest control by aligning local and landscape-level complexity and addressing challenges at multiple scales (Beaumelle et al., 2021).

4.4. *Negative effects of extensive management on single ecosystem services*

Our results indicate that organic farming significantly decreased grape quantity, whereas vegetation cover did not significantly reduce grape yields. The negative effect of organic compared to conventional management on yield is well-documented for most farming systems (Seufert et al., 2012; Katayama et al., 2019; Röös et al., 2018). However, with the increased number of studies included in this meta-analysis, the overall positive effect on provisioning services (Winter et al., 2018) became non-significant, suggesting that yield responses may be more context-dependent than previously assumed. Additionally, depending on the production and marketing system of the wine growers, yields are anyways reduced prior to harvest to produce lower quantities of high-quality wines, whereas if solely grapes or bulk wine is sold, yield loss is a very negative outcome (Chen et al., 2022).

Although, Chapela-Oliva et al. (2022) found a significant negative effect only for provisioning ecosystem services in non-irrigated vineyards (11 rainfed and 13 irrigated observations), the present comprehensive analysis showed a significant negative effect only for irrigated but not for rainfed vineyards. This was mainly due to the response of grape quality not quantity which could be explained by the quantity-quality relationship and a potential negative effect of irrigation, especially late in the season or during flowering, on grape quality (Hamman and Dami, 2000). In addition, irrigation may increase vine vigour, reduce berry sugar content thereby reducing berry quality (Irvin et al., 2016). However, these effects depend heavily on the irrigation system, the timing, the grape variety, management and edaphoclimatic conditions and, therefore, the effects of irrigation on grape quality are still debated among researchers (Rouxinol et al., 2023). Due to the low number of observations, the negative effects of arid and steppe and the subtropical climate on yields have to be interpreted with great care.

Disease regulation was also negatively affected by extensive management. Especially fungal diseases like downy and powdery mildew may reduce yields up to zero in high-disease pressure years (Fermaud et al., 2016) and also decrease wine quality (Pons et al., 2018). Therefore, farmers need to apply fungicides preventively to reduce the risk of infections and consequently also losses of grape yield and quality. Unfortunately, the effect of vegetation management could not be assessed due to a lack of studies comparing disease regulation. However, a recent Italian study showed that cover crops significantly increased disease control of downy and powdery mildew(Hasanaliyeva et al., 2024).

Finally, extensive management significantly reduced climate regulation, mainly due to higher soil respiration in extensively managed vineyards. In contrast, besides soil loss, carbon sequestration showed the strongest positive response to extensive management. Elevated rhizosphere carbon inputs, along with increased microbial activity and carbon sequestration also increased with higher plant diversity in a long-term grassland biodiversity experiment (Lange et al., 2015). Similarly, no-tillage systems also resulted in the highest soil respiration in a Spanish experiment in corn (Pareja-Sánchez et al., 2017).

5. Conclusion

This global meta-analysis reveals the beneficial impact of extensive management in vineyards on biodiversity and ecosystem services through the implementation of vegetation cover. Our study also demonstrates that several management options, from the field to the landscape, modulate the beneficial effects of extensive management on biodiversity and ES. Higher plant species-richness of the cover crops, few(er) pesticides as well maintainging high amount of semi-natural habitats in the landscape resulted in large positive effects on biodiversity and several ecosystem services. Although trade-offs between biodiversity conservation and yield appear for some management options (i.e., organic), our results support the idea that farming practices benefical for biodiversity do not always lead to compromises in grape production. We found a general lack of studies reporting detailed management practices, particularly regarding pesticide application, which limits the assessment of their effects on biodiversity and ecosystem services. Moreover, many studies fail to provide basic information about sample size, mean and measures of variability, preventing their inclusion in meta-analysis (Koricheva et al., 2013). We strongly advocate future studies to systematically report these essential data. Further studies are now needed to fully understand how to combine management options across scales to favor synergies between biodiversity conservation and multiple ecosystem sercices in vineyard-dominated landscapes. In addition, we lack detailed knowledge on the types of semi-natural habitats.

CRediT authorship contribution statement

Silvia Winter: Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Daniel Paredes:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Lea Beaumelle:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Rafael Alcalá Herrera:** Writing – review & editing, Investigation. **Yang Chen:** Writing – review & editing, Investigation. **Christoph Hoffmann:** Writing – review & editing, Investigation. **Mignon Sander:** Writing – review & editing, Investigation. **Dascalu Dumitraţa:** Writing – review & editing, Investigation. **Péter Batáry:** Writing – review & editing, Methodology. **Adrien Rusch:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data file of the article: Combining extensive vineyard management with semi-natural habitats in the landscape to support biodiversity and ecosystem services: insights from a global meta-analysis (Original data) (Zenodo)

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.128029.

Data availability

Data will be shared on ZENODO

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