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Potential of temperate agroforestry systems to deliver ecosystem services: an evidence map

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Abstract

Agroforestry systems are promoted as multifunctional land-use strategies, yet evidence of their benefits, especially in temperate regions, remains fragmented. This umbrella review maps 42 meta-analyses to quantify the effects of agroforestry on environmental, climate, and productivity outcomes, with a focus on temperate pedo-climates. Our evidence map reveals a strong consensus on key regulating ecosystem services: a clear majority of assessments (over 65%) reported significantly positive effects on soil carbon sequestration and multiple indicators of soil quality (154 results). In contrast, effects on provisioning services are more variable. However, the most reported metrics (e.g. single-crop yield) hardly represent the integrated provision of different food or non-food products on the same land, while more comprehensive indicators are rarely used (e.g. land equivalent ratio). Mapping outcomes to the CICES framework highlights several relevant knowledge gaps and a total absence of meta-analytical evidence for Cultural Ecosystem Services. Methodological quality was variable, with frequent shortcomings in reporting study selection and statistical analysis. We provide a list of 1500 primary literature references and a global map of geolocations highlighting the experiments available for temperate pedo-climates. This synthesis provides a robust evidence base for policymakers, pinpointing both established benefits and critical research gaps needed to fu32lly leverage agroforestry in temperate regions.

Highlights

- comprehensive review on 42 meta-analyses of temperature agroforestry practices across sustainability outcomes conducted
- Effects on soil health and carbon stocks were most often studied with mostly positive results
- comparison to CICES classification revealed that only 8 out of 38 ecosystem service groups were covered by empirical evidence
- Most reviews do not provide direct empirical evidence of the effects of AFS on the ecosystem services defined by the CICES classification

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- Socio-cultural outcomes, effects on water balances, as well as long-term studies were underrepresented such as studies on agroforestry with fish/insects, agrosilvopastoral, and hedge systems

- Quality assessment revealed mixed quality of published meta-analyses with lack of robustness checks, control of publication bias and pure documenting of complete information

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Introduction

Agroforestry - the deliberate integration of trees into cropping and livestock systems - has garnered increasing attention as a multifunctional land-use strategy to address multiple global challenges simultaneously. These include climate change mitigation, biodiversity conservation, soil health regeneration, and sustainable food production (Beillouin et al., 2021; Castle et al., 2022; Nair et al., 2021; Tamburini et al., 2020). Agroforestry encompasses a broad range of practices and systems, including silvoarable, silvopastoral, and agrosilvopastoral systems, each with distinct environmental and productivity implications (Castle et al., 2022; Kuyah et al., 2019). The integration of trees with crops or livestock has often been shown to significantly enhance biodiversity, carbon sequestration, soil health, and overall system resilience, particularly in subtropical and tropical regions (Ngaba et al., 2024). The effectiveness of agroforestry practices or systems (hereafter simply called “agroforestry”) in delivering ecosystem services varies considerably depending on the type of system, tree species, spatial arrangement, management intensity and the pedo-climatic conditions (Kim et al., 2016; Shi et al., 2018). This entails the need of region-specific research to optimize and assess agroforestry outcomes.

However, most available evidence, as synthesized by published meta-analyses (MAs) pertains to agroforestry in tropical and subtropical latitudes (tropical, arid or semi-arid pedo-climates), primarily in the southern hemisphere, whereas information remains comparatively scarce for temperate latitudes (including pedo-climates: temperate, mediterranean, boreal, continental, polar, etc.) (Torralba et al., 2016). In the EU, agroforestry is traditionally applied particularly in Mediterranean regions, as nature-based solutions for climate adaptation, biodiversity conservation, and rural development. For example the Montado systems (Spain and Portugal) that combine holm oaks or cork oaks with grazing (sheep, pigs) and cereal cultivation. Therefore, continuous update of the available evidence, especially in these contexts, is of primary importance. However, extensive and robust evidence on the impacts of agroforestry on the nexus of sustainability outcomes in these regions is still lacking.

Previous evidence syntheses have, in parallel, mapped the effects of agroforestry on various outcomes, including biodiversity, soil properties, productivity (Beillouin et al., 2019; Mathieu et al., 2025; Tamburini et al., 2020). Other evidence maps (Castle et al., 2022; Köthke et al., 2022) revealed that linear boundary plantings, such as hedgerows and windbreaks, have been extensively studied for their impacts on biodiversity, soil and water quality, and carbon

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sequestration. However, gaps remain in our understanding of agroforestry's effects on a broad range of sustainability outcomes, particularly for northern-hemisphere pedo-climates. Importantly, the continuous update of literature is a serious issue. For instance, the most recent map of meta-analyses was published in 2025 (Mathieu et al., 2025); however, this analysis is based on a literature search performed in the year 2021. Given the rapid evolution of synthesis literature in this field (see Figure 1), it is of pivotal importance to keep evidence maps up to date and increase collaboration across scientists to share standardized and high-quality data.

It is also unclear how robust is the available empirical evidence to explain the potential contributions of agroforestry to the provision of ecosystem services, especially in temperate regions. According to some systematic literature maps (Mathieu et al., 2025; Tamburini et al., 2020), agroforestry in temperate regions provides numerous ecosystem services, including carbon sequestration, soil fertility enhancement, and biodiversity conservation. For instance, European studies highlight the benefits of wood pastures in Mediterranean, Atlantic, and Continental landscapes, focusing on habitat provision, climate regulation, and aesthetic value (Fagerholm et al., 2016). However, most reviews do not provide transparent linkages between empirical metrics (used in field experiments) and ecosystem services, as defined by the CICES classification (Sauer et al., 2021; Tamburini et al., 2020).

Another issue regards the quality of the MAs published on agroforestry. The increasing number of MAs,reporting on agroforestry and more in general in agricultural and environmental sciences, underscores their value for informing policy and practice by quantitatively synthesizing numerous experimental results (Schievano et al., 2024). Ideally, MAs should adhere to a rigorous, transparent systematic review process—encompassing clear scoping, comprehensive literature searches, unbiased study selection, standardized data extraction, appropriate statistical analysis, and thorough bias assessment—to ensure the validity of their conclusions. However, previous assessments in the field of agricultural sustainability (including on agroforestry) have revealed significant shortcomings (Beillouin et al., 2018; Fohrafellner et al., 2023). For instance, crucial steps like publication bias assessment are often overlooked (reported in only 16-40% of MAs in some reviews), and replicability is frequently compromised by limited data sharing (18-35% providing datasets) and inadequately documented search and selection strategies (Beillouin et al., 2018; Fohrafellner et al., 2023). This lack of transparency contravenes FAIR (Findability, Accessibility, Interoperability, and Reusability) data principles, hindering the scientific

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community's ability to re-analyse data, integrate new studies, and foster a virtuous data ecosystem essential for robust, cumulative evidence and bias reduction.

This work was performed in the context of a wider synthesis of MAs reporting on a broad range of sustainable agricultural practices, performed by the European Commission, Joint Research Centre. A first version of this map was already available within the "JRC-Farming Practices Evidence Library" (European Commission. Joint Research Centre., 2025; Schievano et al., 2024), based on a comprehensive dataset including a collection of around 570 MAs (version 2023) reporting on the effects of farming practices. However, the agroforestry data in the JRC dataset were collected in early 2020 and have become outdated due to the rapid advancement of research in this field. This paper aims at mapping of potentials of agroforestry to provide ecosystem services, as well as at identifying the knowledge and quality gaps. While drawing from global evidence, the review has a specific focus on agroforestry within temperate pedoclimatic zones. Specifically, we aim at:

1. Update a map of the published MAs reporting on the effects of agroforestry at a global scale and specifically including articles regarding temperate pedo-climates;

2. characterizing how existing meta-analytical evidence is distributed across different agroforestry practices/systems and sustainability outcomes, as quantified by empirical metrics;
3. linking empirical metrics to the Common International Classification of Ecosystem Services version 5.2 and pinpointing knowledge gaps across the whole range of ecosystem services (CICES).
4. assess the methodological quality of the included MAs and examining potential trends in quality over time or across sustainability outcome types.
5. recompile the underlying primary studies references, determine the extent to which they overlap between different MAs and deliver a unique list of references for future further literature analyses, including a map the geographical location of the experiments.

By addressing these objectives, this study aims to provide policymakers, researchers, and practitioners with a robust, synthesized, and current evidence based on agroforestry knowledge in temperate pedo-climates. This information is intended to highlight areas of strong consensus, identify critical research gaps, and ultimately support the development of effective agroforestry

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for sustainable land management, biodiversity conservation, climate change adaptation and mitigation, and food security.

Methods

We update and expand upon previous efforts in mapping empirical evidence synthesis on agroforestry based on published meta-analyses (MAs) (Beillouin et al., 2019; Castle et al., 2022; Köthke et al., 2022; Mathieu et al., 2025; Tamburini et al., 2020; Terasaki Hart et al., 2023) and the current version of the "JRC-Farming Practices Evidence Library" (European Commission. Joint Research Centre., 2025; Schievano et al., 2024).

Search strategy and inclusion/exclusion criteria

Our systematic review of MAs was performed in accordance with a methodological framework developed in the context of the JRC Evidence Library (Schievano et al., 2025). In brief, we followed the PRISMA statement guidelines (Page et al., 2021) and the Cochrane Handbook, to comprehensively identify MAs on agroforestry published before June 2024 in Web of Science and Scopus. We developed specific search equations, combining keywords related to agroforestry practices and meta-analytical methods (Supplementary Table 1). To update the first search run in 2020 (European Commission. Joint Research Centre., 2025), we performed three successive searches between 2023 and 2024 with refined keywords, (Figure 1). We also incorporated MAs identified by previous systematic maps (Beillouin et al., 2019; Castle et al., 2022; Köthke et al., 2022; Tamburini et al., 2020). Four reviewers independently screened titles and abstracts, followed by full-text assessment based on predefined inclusion criteria (a complete list of the selection (exclusion/inclusion) criteria is reported in Supplementary Table 2). We included peer-reviewed MAs that reported quantitative results on the effects of agroforestry compared to tree-less agriculture or, in few cases, silvopastoral systems are compared to monocultural timber plantations (Feliciano et al., 2018; Pent, 2020). During the data extraction process, we included MAs that provide evidence on agroforestry in temperate, including specific pedo-climates and biomes, such as temperate, boreal, continental, and Mediterranean. We excluded from MAs focusing solely on either tropical or arid/semi-arid pedo-climates from the final data extraction (typically these are datasets that include only agroforestry studies performed in tropical or subtropical arid zones). As some global MAs provide data from temperate and other pedo-climates, we mapped the following in the present manuscript: 1) main results (global MAs including at least some temperate studies) and 2) results (e.g. of subgroup analysis) specifically including temperate studies.

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Data extraction and classification

Data extraction was conducted using a standardized spreadsheet, developed in the context of the JRC-Farming Practices Evidence Library dataset (Schievano et al., 2025, 2024), to capture study characteristics, methodological details, quality and reported outcomes. In accordance to the methodology used in the JRC-Farming practices Evidence Library (European Commission. Joint Research Centre., 2025), the effect sizes were classified as significantly positive, significantly negative, non-significant, or lacking formal statistical testing. Extracted metadata included systematic review methods, characteristics of original experiments (intervention, comparator, outcome metrics, population variables), key results and conclusions, and quantitative effect size data (means, confidence intervals, sample sizes, effect size type, and statistical models).

Several MAs had global coverage, i.e. experimental sites were spread across many different pedo-climatic conditions and geographical locations across the globe. Other MAs were more specifically focused on geographical areas or pedo-climatic zones (however, according to our selection criteria, at least including temperate pedo-climates). We extracted the main assessments (i.e. mean effect sizes), as calculated by the authors of each MA, i.e. reflecting the overall original population (sometimes grand means pooling together different types of agroforestry practices and systems). We also extracted effect sizes reported for data subgroups regarding specific types of agroforestry practices and systems. We also extracted effect sizes reported by MAs for data subgroups regarding specific pedo-climatis conditions and zones.

To facilitate synthesis across studies, we classified intervention-comparator pairs and outcome metrics into harmonized categories: the main classes of agroforestry were categorised according to the JRC classification of farming practices (Angileri et al., 2024) and the EURAF Agroforestry Typology (Worms and Lawson, 2024), as follows: i) silvopastoral systems, ii) silvoarable systems, iii) agrosilvopastoral systems, iv) landscape woody features and v) others. Each class may include several specific practices. For instance, “Landscape woody features” would include e.g. hedgerows, buffer stripes. We report an updated classification in Table 1.

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Table 1 - Classification of agroforestry systems and practices used in this study, as adapted from the JRC classification of farming practices (Angileri et al., 2024) and the EURAF Agroforestry Typology (Worms and Lawson, 2024).

Main agroforestry systems	Specific agroforestry practices
Silvoarable	Alley cropping
	Alley coppice
Silvopastoral	Wood pasture & Orchard grazing
Landscape woody features	Hedges/wooded strips
	Buffer strips
	Trees in line (Windbreaks and shelterbelts)
	Isolated trees
Agrosilvopastoral	Settlement agroforestry (Homegarden)
Other Systems	Shaded perennials
	Improved fallow
	Woodlot

In total, 80 empirical metrics (e.g. soil organic carbon stock, soil nitrogen concentration, soil sediment loss, forage yield, etc.) were grouped into 16 “impact categories” (e.g. increase carbon sequestration, increase soil nutrients, decrease soil erosion, increase crop yield, respectively), which contribute to 6 independent “sustainability outcomes” (e.g. carbon sequestration, soil health, agricultural productivity) (see supplementary material Table S4 for a full list and assortment of sustainability outcomes, impact categories and metrics). This classification of outcomes is currently adopted by the JRC-Farming practices Evidence Library (European Commission. Joint Research Centre., 2025) and matches the main thematic areas published in the Food System Sustainability Model (European Commission. Joint Research Centre., 2024), developed for the EU Food System Monitoring Framework (European Commission. Joint Research Centre., 2024).

Subsequently, we matched the empirical metrics retrieved from the selected MAs (as defined by the authors of each meta-analysis) to the most recent version of the ecosystems services classification (CICES 5.2). We used the most disaggregated category (CICES classes of four digits) to match the metrics (the full list of metrics matched to the CICES classes can be found in Supplementary Table 4).

Quality assessment and primary literature overlap

We evaluated the quality of included MAs using 16 criteria (Supplementary Table 5), that cover aspects of the systematic review process, statistical analysis, and risk of bias, in accordance with

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the JRC-farming practices dataset (Schievano et al., 2024). For MAs reporting metrics belonging to multiple impact categories, we assessed separately the quality per each impact category.

To evaluate the overlap of studies included in MAs, we extracted all primary-study references from the included MAs. Missing bibliographic metadata were retrieved using a custom R-based pipeline that accessed the Crossref metadata database via the rcrossref package (Chamberlain et al., 2025). For entries with missing DOIs but known titles, we implemented a looped query system that matched candidate records using a Jaro-Winkler string similarity algorithm (threshold ≥ 0.95). For references lacking both title and DOI, full citation strings (APA, Chicago, or AYJ styles) were parsed using regular expressions to extract key metadata fields such as author, year, journal, volume, and pagination. These were then used to reconstruct missing information through targeted queries to Crossref. All records were subjected to internal consistency checks and harmonised into a standardised format. We then quantified the overlap of primary studies across MAs and tracked the accumulation of unique studies over time.

GPS coordinates of experimental sites were systematically extracted from the methods sections of primary studies using a combination of automated text mining and pattern-matching algorithms designed to recognize diverse coordinate formats, including decimal degrees, degrees-minutes-seconds, and other common notations. In cases where exact coordinates were absent, site locations were inferred from reported locality information, such as cities, villages, or regions, and, when necessary, the country of the experiment was recorded. To ensure data completeness and accuracy, missing or ambiguous locations were further curated manually through an interactive Shiny-based annotation interface, leveraging contextual information from titles, abstracts, and external databases (see Supplementary materials). This multi-tiered approach allowed for comprehensive harmonization and high-confidence georeferencing across the assembled dataset.

Statistical tests

We applied a Bayesian ordinal regression framework to quantify and compare the probabilities of observing Negative, Neutral, and Positive effects across “Temperate-only” and “Main” dataset. Models were implemented in R using the `brms` package (Bürkner, 2017), with effect categories treated as ordered factors, and study-level variability modeled as a random intercept, while adjusting for the number of primary studies. Groups with only two observed outcomes (Positive and Negative) were modeled with a Bernoulli distribution, whereas groups with three or more

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categories were modeled using a cumulative logit link. Posterior predictions were used to estimate the probability of each effect category and the posterior distribution of the difference between Positive and Negative effects for each dataset, yielding mean differences, 95% credible intervals, and the probability that Positive effects are more likely than Negative. WWe next quantified, for each CICES group, the difference in Positive-minus-Negative probabilities between the "Full" and "Temperate-only" datasets using posterior draws. All results were visualized with density plots and group-level comparisons, highlighting probabilistic evidence and associated uncertainty (see Supplementary materials).

Results

A total of 340 records were found and 42 meta-analyses (MAs) meeting our inclusion criteria were selected (Figure 1), published between 2007 and June 2024. Of these, 29 MAs report results at global scale (including results on temperate systems) and 13 MAs focus specifically on agroforestry systems in temperate pedo-climates. Further 32 MAs were identified that focus specifically on agroforestry studies located in tropical/subtropical or arid/semi-arid regions, which did not undergo data extraction (Supplementary Table 3). The full PRISMA statement diagram (Page et al., 2021) on the review workflow is reported in Supplementary Figure 1 and the full critical appraisal in Supplementary Table 3.

Overview of available assessments

Figure 1 provides a synthetic glance of the main effects of agroforestry, as reported by MAs across the Groups of Ecosystem services (3-digits of the CICES classification). In parallel, we report the distribution of results across empirical metrics (see Supplementary Figure 2), as named in the original MAs and as classified in the JRC-Farming practices Evidence Library (European Commission. Joint Research Centre., 2025).

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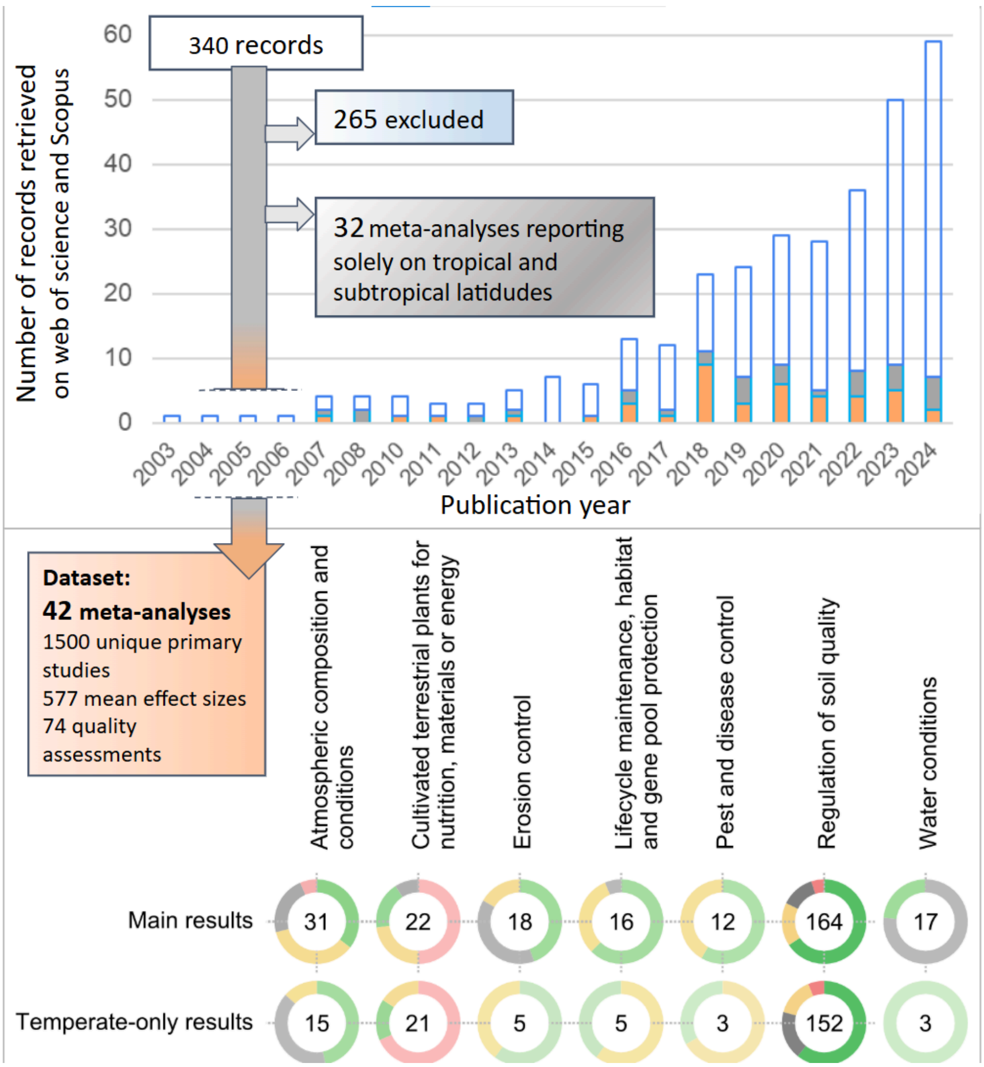

Figure 1 – Chronological distribution of the systematic review of meta-analyses (MAs), schematic PRISMA diagram and overview of the main results. Results (i.e. mean effect sizes extracted from the select MAs) were extracted for main assessments, as well as for temperate-only subgroups. Metrics used in empirical studies were linked across classes of Ecosystem services (CICES classification). Donut plots show the share of results showing significant positive (green) or negative effects (red), non-significant effect (yellow) or non-statistically-tested results (grey), as presented by the selected MAs. The numbers report the total count of effect sizes reported by the selected MAs. The full PRISMA statement diagram (Page et al., 2021) is reported in Supplementary Figure 1. Detailed classification of specific metrics belonging to each class of outcomes is available in Supplementary Table 4.

Both the main results (i.e. mean effect sizes estimated using the full dataset of each MA) and the temperate-only (i.e. mean effect sizes estimated using only subgroups of experiments located in

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temperate pedo-climates) cover seven classes of ES. By far, the majority of assessments (i.e. estimated effect sizes) were published on "Regulation of soil quality" (main: n = 164; temperate: n = 152). The large majority of these assessments were reported for the empirical metrics (see Supplementary Table 4): Organic carbon stock (soil), Organic carbon sequestration rate (soil), Organic carbon content (soil); fewer results were available for other metrics such as Soil water, Soil phosphorous/nitrogen and Soil biological quality (e.g. Taxonomic parameters (microbes)). High shares of these assessments (i.e. around 65% for both temperate-only and main results) reported significant positive effects.

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The ES group "Atmospheric composition and conditions" (main: n = 31; temperate: n = 15) showed a moderate share of positives (35-50%), while many results lacked statistical analysis (Figure 1). These results were mainly assessed through metrics related to organic carbon sequestration in trees biomass and to soil GHG emissions (Supplementary Table 6). A small share (5%) of negative effects were reported for specific metrics related to soil GHG emissions (such as N2O and CH4, see Supplementary Figure 2).

A fair coverage of assessments is also available on metrics related to the ES "Erosion control" (main: n = 18; temperate: n = 5), "Pest and disease control" (main: n = 12; temperate: n = 6), "Lifecycle maintenance" (main: n = 16; temperate: n = 5) and "water conditions" (main: n = 17; temperate: n = 3). Up to over 65% of positive effects (and zero negative effects) were reported for these ES groups.

For the ES group "Cultivated terrestrial plants for nutrition, materials or energy" (main: n = 22; temperate: n = 21), around 50% of negative effects were reported, with lower shares of positive effects (8% and 25% for main and temperate-only results, respectively). These results were mainly related to the metrics "Crop yield (arable crops)" and "Net primary productivity (grass)", which hardly reflect the overall productivity of an agroforestry system, rather than of fractions of land dedicated to either single arable crops or pasture. Very few assessments reported results for more holistic assessments of the agricultural productivity of the whole agroforestry system (e.g. "Land equivalent ratio (LER)", which includes the assessment of the intercropped trees and arable crops or livestock production.

We quantified the likelihood that interventions produce beneficial versus detrimental outcomes across ecosystem services. Using the main results (global dataset), interventions on Atmospheric composition and conditions were somewhat more likely to be beneficial than harmful, with a mean probability difference of 0.21 (95% CI –0.53 to 0.83, posterior probability 0.77), indicating a 21-percentage-point higher chance of positive effects. For Cultivated terrestrial plants for nutrition, materials or energy, the global dataset slightly favored negative outcomes (mean –0.37, 95% CI –0.82 to 0.27, posterior probability 0.094). In contrast, interventions targeting Regulation of soil quality were strongly likely to be beneficial, with a 69-percentage-point higher probability of positive effects (95% CI 0.54–0.83, posterior probability 1).

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Restricting the analysis to the temperate subset yielded broadly consistent patterns. Cultivated terrestrial plants showed no detectable difference between positive and negative outcomes (mean 0.016, 95% CI –0.34 to 0.41, posterior probability 0.53), whereas Regulation of soil quality interventions remained strongly positive (mean 0.48, 95% CI –0.03 to 0.83, posterior probability 0.97). Comparisons between the global and temperate datasets revealed only minor differences, indicating that focusing on temperate regions does not substantially alter predicted effect probabilities. Overall, soil quality interventions consistently show a high likelihood of positive outcomes, while results for other services are more variable and context-dependent.

Available assessments on classes of agroforestry

While most meta-analyses (MAs) presented aggregated results, pooling effect sizes from various agroforestry systems (referred to as "unspecified agroforestry types"), Figures 2 and 3 provide visual summaries of the evidence base disaggregated by agroforestry class (following Table 1) and CICES Ecosystem Service (ES) Groups. "Unspecified agroforestry type" is the most frequently represented category overall, particularly within the temperate climate results (Figure 3), covering approximately one third of the findings. Silvoarable and silvopastoral systems are also prominent, with a high number of assessments in both global (Figure 2) and temperate-specific contexts (Figure 3). Conversely, "Landscape woody features" consistently show fewer results across both climate groups.

A consistent pattern across all agroforestry classes is a positive effect on the ES Group "Regulation of soil quality." For instance, silvopastoral systems contribute positively to "Soil nutrients" and "Soil physico-chemical quality" (Figure 2). Figure 2 highlights a concentration of meta-analytical evidence on the ES Group "Atmospheric composition and conditions," primarily driven by carbon sequestration, which stands out with the highest number of synthesized results across nearly all agroforestry types, particularly for silvopastoral and silvoarable systems. Other ES Groups receiving significant attention include aspects of "Regulation of soil quality," notably "Soil nutrients" and "Soil physico-chemical quality," as well as "Lifecycle maintenance" (biodiversity) and "Cultivated terrestrial plants for nutrition, materials or energy" (specifically grassland production under silvopastoral systems). Conversely, ES Groups like "Atmospheric composition and conditions" (direct GHG emissions and biomass carbon stocks, distinct from soil carbon stocks), "Pollination," and overall farming system productivity appear less frequently assessed.

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Regarding the nature of the findings (Figure 2), "Atmospheric composition and conditions" predominantly shows positive effects across agroforestry types. However, for silvopastoral systems, a substantial proportion of these results are non-significant, and a considerable portion of carbon sequestration results lack formal statistical testing. Similarly, positive impacts are frequently reported for "Soil nutrients," "Soil physico-chemical quality," "Soil biological quality," and "Lifecycle maintenance," suggesting a general consensus in the MAs on benefits in these areas.

However, outcomes related to "Cultivated terrestrial plants for nutrition, materials or energy" show more variability. For instance, grassland production under silvopastoral systems yields a mix of significantly positive, negative, and non-significant results, while crop yield under silvoarable systems includes both significantly negative and non-significant findings. Furthermore, the prevalence of non-significant findings in ES Groups like "Erosion control" and "Pest and disease control," alongside the significant proportion of results lacking statistical testing across multiple ES Groups (e.g., "Global warming potential," "Nutrient leaching"), underscores the need for cautious interpretation and highlights areas where the synthesized evidence remains inconclusive or requires more rigorous assessment.

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Figure 2 – Meta-analytical evidence regarding the effects of main classes of agroforestry systems, reporting the main effect sizes estimated by the selected meta-analyses. Results (i.e. mean effect sizes extracted from the select MAs) were extracted for main assessments, as well as for temperate-only subgroups. The effects are classified for Ecosystems services (ES) groups (i.e. 3-digits of the CICES classification). The chart illustrates the distribution of results showing significant positive (green) or negative effects (red), non-significant effect (yellow) or non-statistically-tested results (grey), for the selected combination of practices and ES. The numbers represent the count of effect sizes reported by the selected MAs. When the same MA reports results at different aggregation levels, we did not double count these results in the same donut graph.

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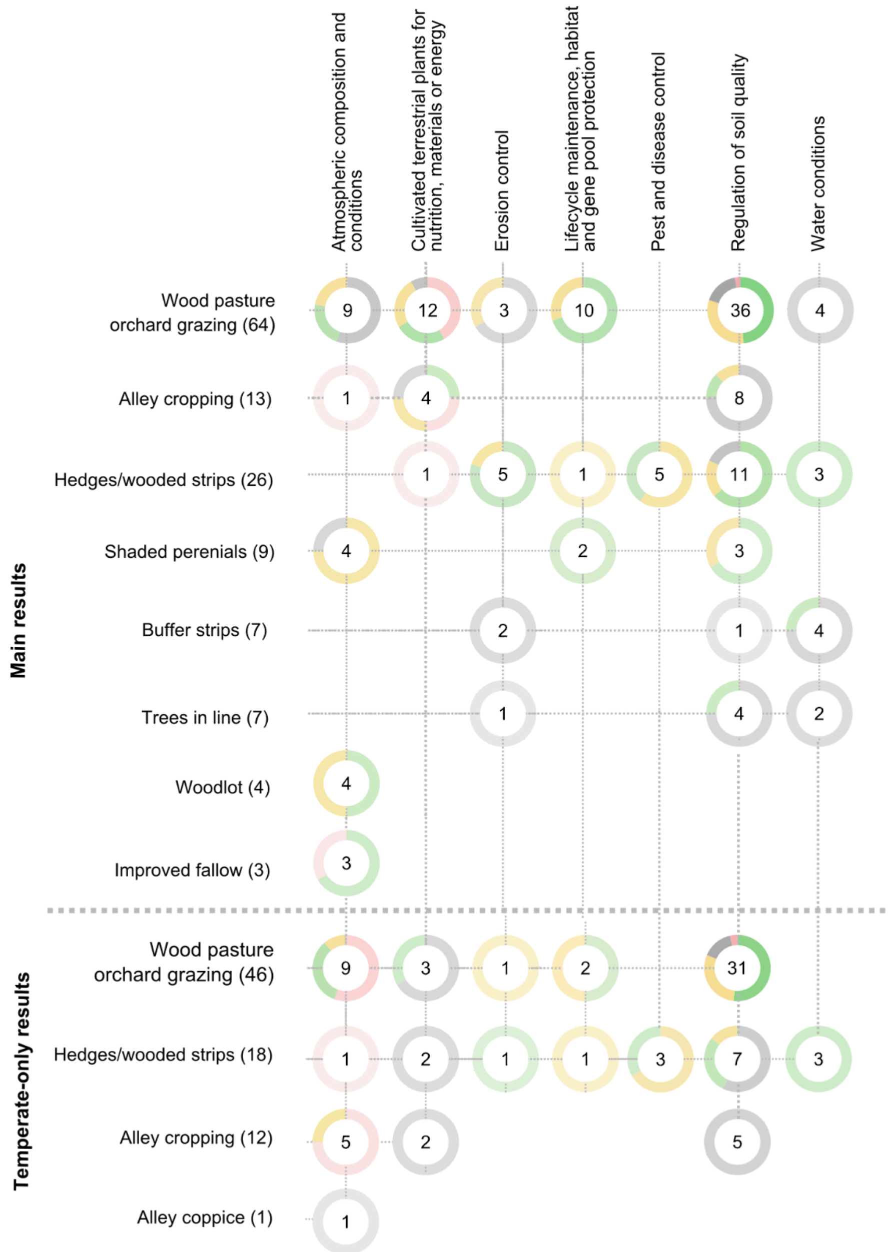

Figure 3 –Meta-analytical evidence regarding the effects of specific classes of agroforestry systems. Results (i.e. mean effect sizes extracted from the select MAs) were extracted for main assessments, as well as for temperate-only subgroups. The effects are classified for Ecosystems services (ES) groups (i.e. 3-digits of the CICES classification). The chart illustrates the distribution of results showing significant positive (green) or negative effects (red), non-significant effect (yellow) or non-statistically-tested results (grey), for the selected combination of practices and sustainability

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outcomes. The numbers represent the count of effect sizes reported by the selected MAs. When the same MA reports results at different aggregation levels, we did not double count these results in the same donut graph.

Knowledge Gaps across CICES classification

Results reported by MAs were associated with the CICES classifications, namely with 2 (out of 6) sections and 3 (out of 19) divisions (represented graphically in Figure 4) and with 7 (out of 38) groups and 10 (out of 99) classes (see detailed report in Supplementary Table 6). This means that 66% of sections, 84% of divisions, 85% of groups and 91% of classes are not covered by any result reported in MAs. Even if a large majority of "Abiotic/Geophisical" services might be not affected by the implementation of agroforestry systems, "Biotic/Biophisical" services are also relatively uncovered, with only 4% coverage rate for "Provisioning" services, 32% for "Regulation & maintenance" services and no coverage at all for "Cultural" services.

The division with highest coverage rate (32%) is "2.3 - Regulation of physical, chemical, biological conditions", with 8 out of 14 classes covered by evidence (Figure 4). However, the largest majority of results regards soil-related services, while very important classes remain either uncovered (e.g. for "Control of wind erosion rates", "Regulation runoff and base flows", "Seed dispersal", "Maintaining or regulating refuge habitats", "Regulation of temperature and humidity, including ventilation and transpiration at local scales", "Wind protection", "Fire protection") or underrepresented (e.g. "water conditions", see Figures 1,2,3). This highlights a particular research void concerning agroforestry's potential key role in enhancing biodiversity, improving water quality/management and hydrological cycles and driving resilience, which are especially pertinent given increasing concerns about biodiversity losses, water quality, fire risks and extreme weather events.

Provisioning services remain relatively uncovered by evidence in many relevant classes (4% coverage rate for "biotic" services, Figure 4), such as for instance "Fibres and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials)" (1.1.1.2), "Animals reared for nutritional purposes" (1.1.3.1). The available results within provisioning services are narrowly focused on crop-yield or grassland/forage-productivity metrics, typically at plot or field scales for a limited number of main crops (see supplementary Figures), neglecting the broader spectrum of products and services that agroforestry systems may provide (e.g. timber, fruit, essential oils, etc.).

Furthermore, cultural services (both Biotic and Abiotic) have been entirely overlooked in published meta-analyses on agroforestry. This represents a critical void, as agroforestry systems often hold significant social, aesthetic, recreational, and spiritual value, which are crucial for

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holistic sustainability assessments and might often be crucial to enhance the level of uptake and economic success of agroforestry systems. The absence of evidence in this domain underscores a need for research methodologies that can effectively capture these less tangible, yet profoundly important, benefits.

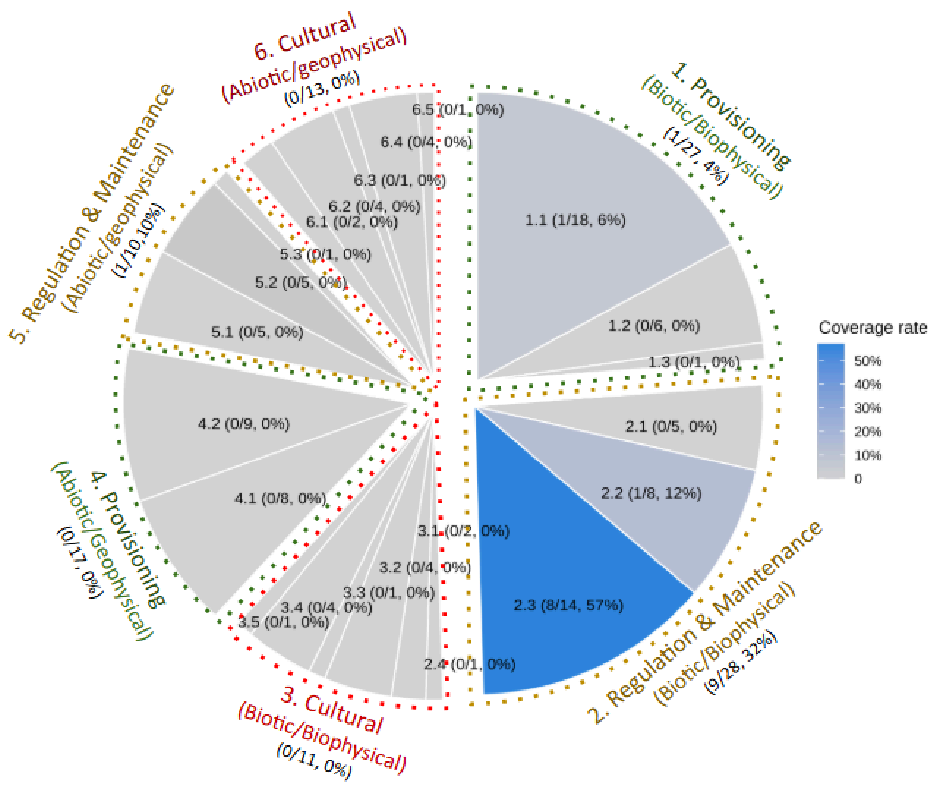

Figure 4 – Graphical glance of how current evidence reported in meta-analyses cover the full list of CICES classes (4-digits code, e.g. 1.1.1.1 - Cultivated terrestrial plants grown for nutritional purposes). Sectors of the pie-chart represent CICES Divisions (indicated with the corresponding 2-digits code, e.g. 1.1 - Biomass), and grouped by dotted lines into CICES Sections (1-digit code, e.g. 1 - Provisioning (biotic/biophysical). For each Section or Division, the figures between brackets report the coverage rate (as ratio and as percentage and represented with blue color scale) of classes covered by evidence. Knowledge gaps across the CICES classification are shown as pie-chart sectors in grey color. Supplementary Table 6 reports the list of specific CICES sections, divisions, groups and classes covered by results of meta-analyses.

Quality assessment of the meta-analyses

The methodological quality of MAs was assessed for 74 combinations of practice-impact (Figure 5A). Our evaluation of the quality revealed that the majority of papers reported on the procedure

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of data search and selection and on funding sources. While statistical methods are described in most of the assessments, a correct reporting of MA-statistics, such as reporting and application of individual effect sizes, weighting of studies and assessment of the heterogeneity of results is neglected in around half of the studies (Figure 5A). Only 40 assessments reported consequently the details of the selection process according to the PRISMA statement. Importantly, substantial progress should be made in the communication of a retrievable list of included primary studies (e.g. including DOIs), as around 1 out of three MAs do not publish a consistent list. Even more, the primary dataset is not available for nearly 2 out of 3 MAs. The assessment of the publication bias and the reporting of individual effect sizes were the least fulfilled criteria (with 30 and 22 out of 74 assessments).

Figure 5B shows that only 6 assessments (8%) considered fulfilled all 16 quality criteria and around 80% of assessments met at least 8 criteria. All assessments fulfill at least 4 out of 16 criteria, while about 93% fulfill at least 7 criteria. The curve shows a steep decline after meeting a quality threshold of 10 out of 16 criteria. These visualizations reveal that while most MAs meet basic reporting standards, there's significant room for improvement in more rigorous criteria like individual effect sizes, dataset availability, and publication bias analysis.

Between 2015 and 2024 the number of MAs reporting on agroforestry increased consistently (Figure 5C). This increase over time has, however, been accompanied by a non-homogeneous increase in quality level (Figure 5C). While the average quality of the MAs increased over time, some MAs with lower quality (less than 50 % of criteria met) were also published in the most recent years.

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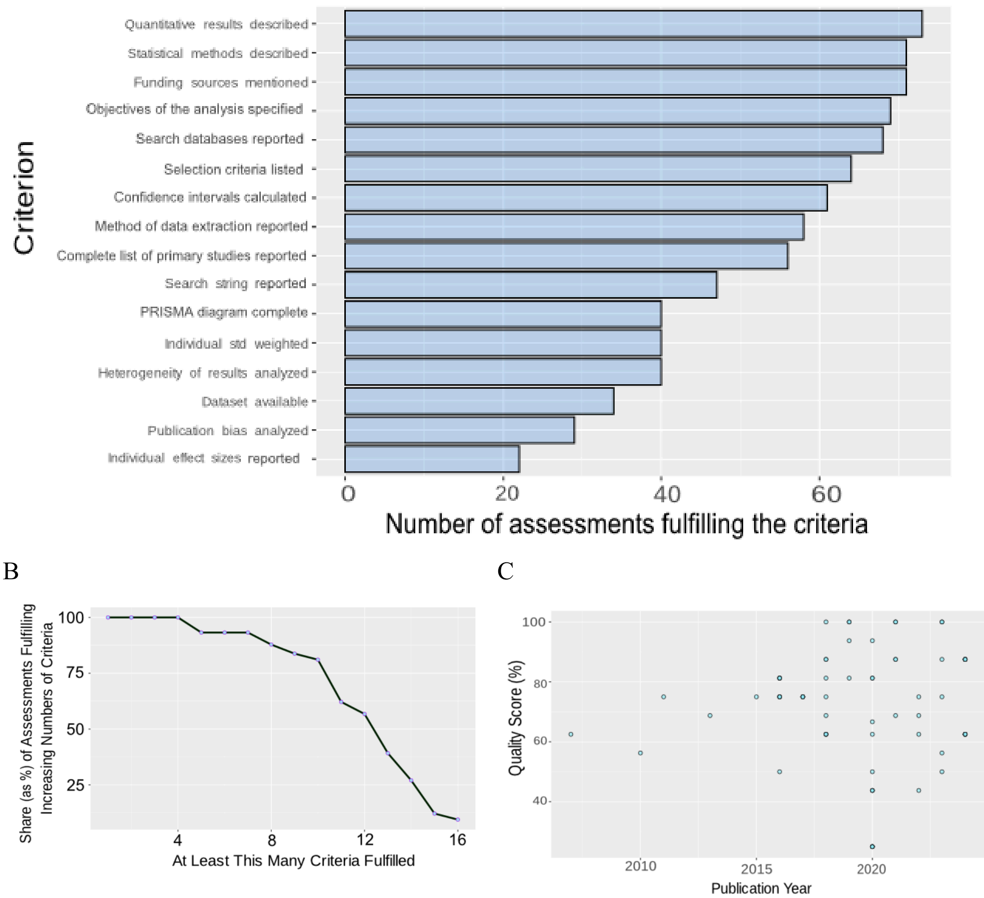

Figure 5 – Distribution of quality assessments performed on each selected meta-analysis reporting on one or more impact categories (n=74). A) Number of assessments fulfilling each of the 16 quality criteria; B) Share of assessments fulfilling an increasing number of criteria; and C) distribution of quality scores (% of fulfilled criteria) over time (publication year).

No statistical significant differences in quality scores was detected across impact categories by the application of ANOVA and Kruskal-Wallis test ($p > 0.05$) (Supplementary Figure 6A). It should be noted, though, that the number of assessments per impact category is rather low, leading to relatively high standard deviations.

Primary literature map

In total, we collected 2066 references, of which 161 were not processable (lack of sufficient information, such as doi code or title) and 1905 were retrieved using our workflow querying the

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Crossref database (https://www.crossref.org). Of these, 1495 were the unique primary papers, synthesized by the 42 selected MAs. The full list of references is available in the JRC - Farming practices data collection (European Commission - Joint Research Center, 2025).

Figure 6A shows the overlaps of primary literature papers across the 42 selected MAs. Most primary literature has been applied in one study only (over 1200 primary studies over 1495, and over time new primary studies almost constantly add up as additional literature sources. Particular overlap in synthesis occurred in the years 2019-2021 with several MAs published with limited increase of unique primary studies added to the cumulate curve (Figure 6A).

The extraction of geographical coordinates (from direct mention in the original primary paper text or inferred from reported place names such as cities or villages) yielded 625 out of 1495 studies (Figure 6B). Interestingly, 435 of them were temperate pedo-climatic zones and 190 were located in other pedo-climates. The distribution of temperate studies is mostly concentrated in North America (USA mainly), Europe and China. Few temperate studies are also located in global-south Countries (e.g. Chile, Australia, New Zealand).

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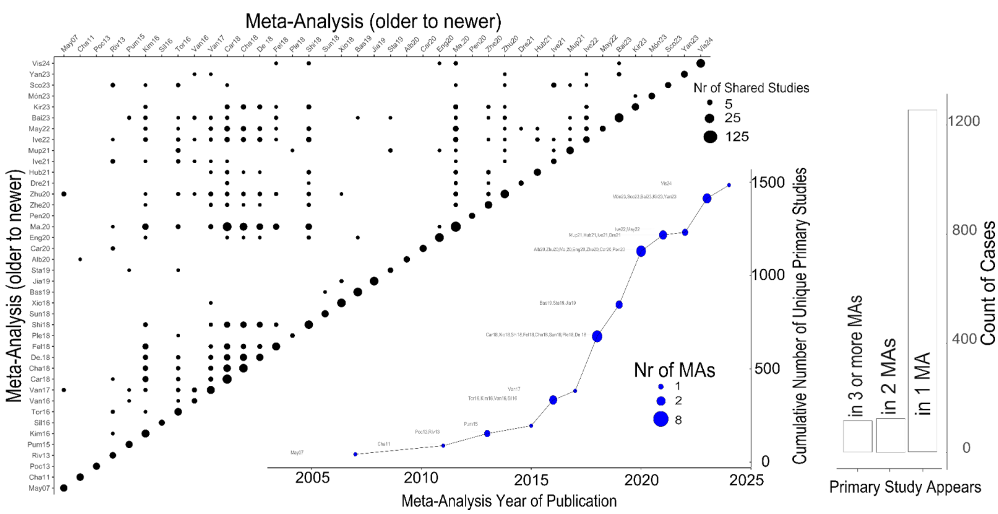

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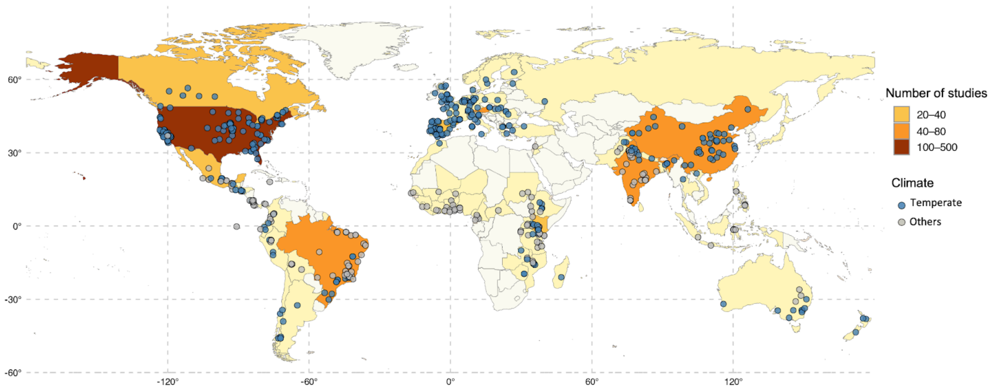

Figure 6 - Primary literature studies map (whole dataset obtained from the selected 42 meta-analyses, including temperate and non-temperate studies). (A) Accumulation over time and overlap of primary studies across the 42 meta-analyses; The size of the dots represent the number of shared primary literature papers, i.e. in common for each pair of MAs. (B) Global map showing GPS coordinates extracted from primary studies. Points on the map are marked using different colours and counted distinguishing between studies performed in temperate and non-temperate pedo-climatic conditions. Studies are counted per Country (represented with color scale).

Discussion

This synthesis aimed to provide a comprehensive overview of the current state of meta-analytical evidence on the potentials of agroforestry to enhance ecosystem services, identifying well-researched areas as well as critical knowledge gaps requiring further investigation, with a specific focus on temperate pedo-climates. Our findings offer a robust evidence map for policymakers and researchers, guiding future efforts to strengthen the understanding and implementation of agroforestry. Our analysis reveals that temperate agroforestry systems demonstrate significant potential to enhance several key ecosystem services, particularly in the realms of soil health and carbon sequestration.

However, the consistency of positive effects is not universal. Furthermore, a considerable portion of findings across various ES or impact categories, especially for temperate-only assessments, were either non-significant or lacked formal statistical testing (grey segments in Figure 1, 2, and 3). This indicates that while many studies exist, their conclusions are not always robustly established, or the effects are highly context-dependent.

Provisioning services through agricultural productivity outcomes exhibit relatively high variability. Grassland production under silvopastoral systems, for instance, shows a mix of significantly positive, negative, and non-significant results, while crop yield under silvoarable

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systems includes both significantly negative and non-significant findings reported in the MAs (Figure 2). It's crucial to note that the the indicators used to quantify provisioning services linked to agricultural production are often limited exclusively to crop or grass yields, overlooking the broader system productivity that includes tree yields or overall Land Equivalent Ratio (LER) (Dupraz et al., 2018; Pent, 2020). Many MAs do not explicitly define how agroforestry system boundaries are considered for productivity metrics (e.g., yield per hectare of cropped area vs. total agroforestry area), hindering consistent interpretation of "negative" impacts on specific crop yields. This highlights a significant knowledge gap in assessing whole agroforestry system productivity in the existing meta-analytical literature.

Agroforestry systems are distinguished by their multidimensional character, incorporating diverse components such as trees, crops, and animals. However, prevailing research methodologies frequently limit themselves to the measurement of one-dimensional effects, thereby overlooking the potential for comprehensive, multidimensional impact assessment. It is imperative to consider whether the extant research methodologies are capable of accurately and reliably capturing the complexity, diversity and long-term nature of agricultural systems. This issue was also raised by Douxchamps et al. (2017). The authors reviewed models focusing on monitoring and evaluating the climate resilience of agriculture, and found that the models failed to assess 'stability', 'transformation' and the topic's overall complexity.

Are existing meta-analyses methodologically sound?

Our assessment of methodological quality across 74 combinations of practice-impact revealed mixed results, with significant room for improvement, echoing findings by Beillouin et al. (2018) and Fohrafellner et al. (2023). While most MAs adequately reported on data search and selection procedures and funding sources, crucial aspects of rigorous systematic review were often neglected. Only 40 out of 74 assessments consistently reported selection details according to PRISMA statement guidelines (Page et al., 2021).

A major concern is the reporting and application of MA statistics, including the assessment of heterogeneity and robust publication bias analyses. Furthermore, accessibility and transparency of underlying data remain a challenge. Approximately one-third of MAs failed to provide a retrievable list of included primary studies (e.g., with DOIs), and nearly two-thirds did not make their primary datasets available. This lack of transparency contravenes FAIR data principles and compromises the replicability and reusability of these valuable syntheses (Figure 5A).

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While the number of MAs on agroforestry has consistently increased between 2015 and 2024 (Figure 1), the improvement in quality has been non-homogeneous. The average quality has risen over time, but some MAs with very low quality (less than 50% of criteria met) were still published in recent years (Figure 5C). This suggests a need for stricter adherence to methodological standards in evidence synthesis, as also highlighted by Schievano et al. (2024), to ensure robust and credible conclusions that can effectively inform policy and practice.

What critical knowledge gaps limit our understanding of agroforestry in temperate regions?

Our evidence mapping exercise revealed several significant and pressing knowledge gaps that limit a comprehensive understanding of agroforestry's potential in temperate regions.

Certain types of agroforestry systems (especially the most diversified) are underrepresented. While silvopastoral systems (e.g. orchard grazing) and silvoarable systems (e.g. alley cropping) are well-studied (Castle et al., 2022), there is a notable scarcity of meta-analytical evidence for agro-silvopastoral systems and improved fallows. Hedge systems and other types of woody features also receive comparatively limited academic attention, despite their recognized potential (Figure 2, Figure 3). This imbalance restricts our ability to provide a holistic assessment of agroforestry's benefits across its diverse forms.

A critical void exists in the assessment of socio-cultural and cultural ecosystem services (ESS) provided by agroforestry. As highlighted in Figure 4, cultural services (both Biotic and Abiotic) are entirely overlooked in the published meta-analyses. This aligns with findings by Köthke et al. (2022) and represents a significant limitation, as agroforestry systems often hold profound social, aesthetic, recreational, and spiritual value that are crucial for holistic sustainability assessments and public acceptance.

Despite the increasing concerns about water availability, quality, and extreme weather events, our study revealed a significant lack of meta-analytical information regarding the impact of agroforestry on water balances and hydrological cycles. The CICES classification clearly shows "water conditions" as underrepresented, and critical classes like "Control of wind erosion rates," "Regulation of runoff and base flows," and "Regulation of temperature and humidity" remain either uncovered or underrepresented (Figure 4).

Agroforestry systems are distinguished by their multidimensional character, incorporating diverse components such as trees, crops, and animals. However, prevailing research methodologies, as synthesized in MAs, frequently limit themselves to the measurement of one-dimensional effects. This oversight hinders the potential for comprehensive, multidimensional impact assessment, as

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also raised by Douxchamps et al. (2017), regarding the assessment of climate resilience. There is a need for methodologies capable of capturing the complexity, diversity, and long-term nature of these integrated systems.

Overlap in primary literature and geographical coverage

Our review found considerable overlap (Figure 6A) in the primary literature across different meta-analyses, particularly for widely studied practices like alley cropping. While new primary studies are constantly being added to upcoming meta-analyses, indicating an ongoing expansion of the evidence base, this overlap suggests a need for more diverse primary research to explore novel aspects of agroforestry impacts. A certain degree of overlap is unavoidable, and therefore needs to be assessed when comparing and combining different MAs. MAs focusing on narrower indicators, however, often show lower overlap, suggesting a broad and not yet sufficiently explored research field where individual MAs specialize in different aspects or regions. The geographical distribution of primary studies included in MAs reveals an uneven picture (Figure 6B). While our review specifically focused on MAs including temperate regions, the global map highlights that much of the research is still concentrated in North America (mainly USA), Europe, and China. This uneven distribution limits our understanding of agroforestry's potential across diverse temperate climatic conditions and management contexts, particularly in other temperate zones.

Implications for temperate pedo-climates

The current evidence map, while comprehensive for meta-analytical syntheses, underscores the unique challenges and opportunities for agroforestry in temperate pedo-climates. The generally positive evidence for soil health and carbon sequestration provides a strong foundation for promoting agroforestry in these regions as a climate change mitigation and adaptation strategy. However, the identified knowledge gaps – particularly the underrepresentation of certain practices, the scarcity of long-term studies, and the neglect of socio-cultural and water-related impacts – are critical for optimizing agroforestry adoption and policy formulation in temperate zones. Policy recommendations must consider not just ecological benefits but also the economic viability (profitability studies are lacking for high-income countries, Castle et al., 2022) and social acceptance of these systems.

Recommendations for future research and policies

This study's strength lies in its comprehensive review of 42 meta-analyses, following a rigorous protocol aligned with the PRISMA statement and Cochrane Handbook guidelines. It provides a

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detailed classification of outcomes against the CICES framework and includes a quality assessment of the MAs themselves. A limitation of this study is surely that it only includes meta-analytical evidence. However, we provide here (see Supplementary materials) the list of references of all primary studies that were selected by these MAs. We strongly encourage the scientific community to engage in the reconstruction of the literature base, ideally using a common and standardized dataset. In line with FAIR principles, the authors of these 42 MAs should agree in sharing the primary data and make an effort in merging their structured datasets.

Henceforth, endeavours in the realm of research should concentrate on two primary objectives. Firstly, they should strive to bridge the existing lacunae in our understanding of hedgerow and silvopastoral systems. Secondly, they should direct their efforts towards the development of novel methodologies that can effectively encapsulate the multifaceted nature of agroforestry, thereby ensuring that its comprehensive value is duly recognised.

The predominantly favourable image of agroforestry systems that has been obtained through this study can assist policy-makers and practitioners in their present efforts. However, the knowledge gaps identified should encourage policymakers to develop new explicit (support) systems and thus motivate practitioners to promote more and new agroforestry systems. This will expand our knowledge and ensure that our agriculture is fit for the future and fit for climate change.

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Declaration of generative AI and AI-assisted technologies in the writing process.

During the preparation of this work the author(s) used Google AI studio in order to re-phrase and improve readability of sentences. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility.

Data statement

All data are available in the JRC-Farming Practices Data collection (European Commission - Joint Research Center, 2025).

Authors' contributions

Please see table reported in the supporting materials.

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