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Are agroforestry systems more productive than monocultures in Mediterranean countries? A meta-analysis

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Abstract

Agroforestry is gaining interest due to its potential in enhancing climate resilience and sustainability of farming systems. In this meta-analysis, the crop yield in agroforestry system compared to the control (sole crop) from thirty-six experimental field trials in Mediterranean countries was assessed. The response variable $W\log(RR)$ (i.e., the weighted natural logarithm of the response ratio) was analyzed by the 95% confidence intervals of mean and by fitting eight linear mixed models. Fixed effects, namely the tree cover (low, medium, high), the tree species (ash tree, chestnut, cork oak, holm oak, olive, poplar, walnut), and the crop species (alfalfa, barley, durum wheat, faba bean, forage, oat, pasture, pea, winter wheat) were significant ($P = 0.030$, $P = 0.017$, and $P = 0.014$, respectively), while the system type (alley cropping, silvo-arable, silvo-pastoral) was not. Among management practices (variety, pruning, fertilization, irrigation, crop age classes, imposed warming and drought, harvest time), only the fertilization significantly improved the response variable ($P = 0.006$), while the interaction of pruning \times crop species was marginally significant ($P = 0.065$). Relatively large study heterogeneity was observed ($Q = 72.6$, $I^2 = 72\%$), which is quite common for agronomic meta-analysis. On the contrary, publication bias based on funnel plots and the Trim and Fill method suggested symmetrical distribution of studies. The sensitivity analysis for significant models identified room for improvements. Overall, we observed a negative effect of trees on crop yield that could be ascribed to the competition for light. Nonetheless, facilitation could be expected under extreme climate events, provided that agricultural practices will maximize synergies among tree cover, tree species, crop species, and management. Future works are encouraged to focus on the overall benefit agroforestry can provide at the field and landscape level, along with long-term monitoring to assess the whole lifespan of these systems and other companion planting options and designs in the Mediterranean region.

Keywords Mixed cropping · Tree/annual intercrop · Cropping system · Yield · Relative yield · Agroecology · Mixed-effect models

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1 Introduction

Unlike conventional agriculture, agroforestry addresses the current challenges of farming systems, harnessing synergy with natural and social resources in both time and space to produce food sustainably (FAO and ICRAF 2019). Agroforestry can contribute to the implementation of nine out of the seventeen Sustainable Development Goals (Andersson 2018), being mentioned explicitly in many strategies of the European Green Deal, such as the Farm to Fork Strategy [COM (2020)/381], the EU Biodiversity Strategy [COM (2020)/380], and the Circular Economy Action Plan [CO (2020)/98]. The eco-schemes set in the new common agricultural policy list agroforestry among the potential agricultural practices that support the transition towards a sustainable food system and the achievement of the EU's climate objectives (DG Agriculture, 2021).

Far from a new cropping system, modern temperate agroforestry is a revival of traditional agricultural practices operated by farmers for an efficient use of land in many parts of the world (Pacey 2008). In southern Europe, agroforestry systems, such as grazed open woodlands (*Dehesa* in Spain, *Montado* in Portugal, *Bocage* in France and *Coltura promiscua* in Italy) still cover a large area (den Herder et al. 2017; Casagrande et al. 2017; Paris et al. 2019). Also, in North African countries (Tunisia, Algeria, Morocco, Egypt, Libya), agroforestry has a long tradition, contributing to the well-being and livelihood of local communities (Santoro 2022). These are extensive forms of agroforestry where scattered trees (e.g., holm oak, cork oak, olive, argan, perennial crops), of high natural, socioeconomic, and cultural value, are intercropped with grass and legume species for fodder and hay (Moreno et al. 2007a; Moreno 2008; Cubera et al. 2009; Gea-Izquierdo et al. 2009; Daoui and Fatemi 2014). In contrast, more intensive systems, such as alley cropping, integrate trees in rows (such as fruit or timber-producing species), with annual or perennial crops (e.g., grain cereal and legumes, root crops and vegetables) in the interspaces (Wolz and

DeLucia 2018) (Fig. 1). Hedgerows, windbreaks and field shelterbelts are other agroforestry arrangements used throughout the world to increase crop yield and quality (Kort 1988; Baldwin 1988), where closely spaced shrubs or trees protect field crops from wind abrasion by reducing the speed and direction of wind, and in some circumstances enhancing soil water content and total soil organic carbon (Sánchez and McCollin 2015).

Irrespective of the degree of land use intensification, many researches have demonstrated that diversifying species on the same land at the same time enhances biodiversity, resilience to pests and diseases, and ecosystem service provisions compared to agriculture or forest monocrops (Kahane et al. 2013; Torralba et al. 2016; Veldkamp et al. 2023). The more effective use of sunlight, water, and nutrients from two or more vegetation layers in agroforestry mimics the dynamics of natural ecosystems, improving the land use efficiency (Leakey 1996). Indeed, the land-equivalent ratio (LER) (i.e., yield of agroforestry over sole crop) is usually higher than one, indicating that the relative land required in area under the sole cropping to give the same yield as under agroforestry is generally larger (Arenas-Corraliza et al. 2018; Pent 2020).

However, due to the complexity and high diversity of agroforestry practices, there is a substantial variability in the crop yield as a response to interspecific competition for natural resources, land use, environmental, weather, and edaphic conditions. In the Mediterranean region, which is a climate change hotspot (Tuel and Eltahir 2020), yield declines are expected for many crops due to the higher frequency and intensity of summer heatwaves, prolonged drought, and high evapotranspiration rates (Giannakopoulos et al. 2009). In this sense, agroforestry might mitigate weather extremes since the canopy of trees can protect the associated crop species against abiotic stresses, such as strong winds, buffering crop evapotranspiration (Kanzler et al. 2019; Markwitz et al. 2020). Trees can directly compete with crops for water resources, especially when crops are close (1.5 to 2 times the tree height) to trees with roots that take up soil moisture at high rates (Huth et al. 2010;



Fig. 1 **A** Alley-cropping system in Maraussan, France (photo courtesy of the AGS-CTFC); **B** silvo-pastoral system in Mallorca, Spain (photo courtesy of Jaime Coello); and **C** silvo-arable system in El Bosque, Cádiz, Spain (photo courtesy of Jaime Coello)

Luedeling et al. 2016). Nonetheless, in the absence of water stress, the moderate shading and evapotranspiration from trees can improve the microclimate, reducing air temperatures and atmospheric evaporative demand (Kanzler et al. 2019). In order to achieve the multiple productive and environmental benefits from agroforestry, appropriate planning must be adopted to maximize synergies between trees and associated crops, especially in areas subjected to water scarcity.

A meta-analysis of Rivest et al. (2013) demonstrated that the nature and extent of synergies between trees and pasture greatly depends on tree functional groups and precipitation levels mainly due to the spatial difference in root profiles between trees and pasture. It was found that under increasing drought pressure, deep tap root systems trees, like N₂-fixing species (i.e., *Acacia* spp.), can provide facilitation to the associated crops via hydraulic lift; on the contrary, the shallow root profile of *Eucalyptus* enhances competition for water (Rivest et al. 2013). Near-neutral net effects were observed with scattered deciduous and evergreen oak tree groups on pasture yields. In temperate alley cropping and hedgerows, the meta-analysis of Van Vooren et al. (2016) highlighted a significant effect of crop distance from trees on relative crop yield, which ranged from 70% over a distance of 1.64 times the tree height to 107% between 1.64 and 9.52 times the tree height. A counteracting effect of crop distance from trees on relative crop yield was also confirmed by the meta-analysis of Ivezić et al. (2021), in northern and southern European agroforestry; in addition, it was suggested that relative crop yield decreased with tree density (in alley cropping and Dehesa) and tree age (in alley cropping), that cereals performed better than fodder crops in alley cropping, and that relative crop yield response was similar in southern and northern European alley cropping.

Besides, tree phenology is important as there might be less competition if crop growth occurs largely prior to the budbreak of the considered tree species.

The scientific literature on agroforestry is steadily increasing in response to policy measures for preserving agroecosystems, providing a sustainable and resilient agriculture in line with agro-ecological transition paradigms in the context of global change. Given the considerable importance that agroforestry holds for the Mediterranean countries (den Herder et al. 2017), the present study reviewed the research evidence of crop yield in agroforestry systems in the regions within the Mediterranean basin, especially in southern Europe. To our knowledge, this study examined for the first time the impact of explanatory variables (system type, tree species, tree cover, crop species, and agronomic management) on crop productivity in agroforestry compared to the sole crop from semiarid to warm temperate Mediterranean studies using a meta-analytic approach.

2 Material and methods

2.1 Study selection

A systematic review on the Mediterranean agroforestry crop yield was carried out in September 2022 using the Web of Science Core Collection (WoS, Clarivate) and SCOPUS (Elsevier B.V.) databases. The search terms used in both databases are listed in the Table 1. Primary literature was identified by the “Preferred Reporting Items for Systematic Reviews and Meta-Analyses” method (Page et al. 2021). The search produced 1203 records, 503 from WoS and 700 from SCOPUS (Fig. 2). The search was further refined for article type (original research), language (English), and subject category (agricultural science, environmental science, plant science, soil science, dairy animal science, food science, and agricultural engineering), yielding 498 and 501 documents from WoS and SCOPUS, respectively. To produce a final number of primary studies from the two databases, duplicates were removed ($n = 372$) through the tool check for duplicates in Mendeley (Mendeley Ltd, Elsevier B.V.), resulting in 627 documents (Table SM-1).

Subsequently, a two-tier screening was conducted, looking for publications presenting replicated crop yield data from field trials in both agroforestry and control (sole crop) carried out within the geographic boundaries of this study, namely Bsk, Csa, and Csb of the Köppen-Geiger climate classification (Peel et al. 2007).

In the first-tier screening, title, keywords, and abstract were assessed, and 251 reports were excluded due to lack of representativeness [out of the study area ($n = 12$), not original research ($n = 12$), livestock management ($n = 39$), greenhouse, pots, and lab trials ($n = 5$), ecosystem service studies not including yield ($n = 62$), economic, environmental, and social science studies not including yield ($n = 52$), and modeling studies not including empirical methods ($n = 69$)]. Full texts ($n = 376$) were then assessed for eligibility in the second-tier screening, and 354 reports were removed since met the exclusion criteria, namely (i) lack of yield data per unit area of annual crop in the sole cropping system (control); (ii) lack of yield data per unit area of annual crop in the agroforestry system; (iii) absence of information about the experiment design and/or data replication; (iv) lack of information about data variance; (v) absence of information about geographic area or experiments outside the Mediterranean climatic zones; (vi) different agronomic practices between agroforestry and sole cropping systems; (vii) experiments from greenhouses, pots, and lab or controlled environments; and (viii) studies only presenting modeled results, farmer interviews, and systematic reviews.

New studies ($n = 19$) were identified from other sources (references of included studies), and 14 were assessed;

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

Database	Searching string
SCOPUS	<p>("agroforest*" OR {mixed farming} OR {mixed-farming} OR {forest farming} OR silvoarable OR "silviarable" OR "silvopast*" OR "silvipast*" OR "agrosilvi*" OR "Agrosilvo*" OR {alley crop*} OR {hillside system} OR {shade crop*} OR {crop-over-tree} OR {crop over tree} OR {tree intercrop*} OR {tree strip crop*} OR {tree-strip-crop*} OR "dehesa" OR {farm woodland*} OR {forest grazing} OR {grazed forest*} OR {orchard grazing} OR montado OR {orchard intercrop*} OR {hedgerow intercrop*} OR {agroforestry parkland*} OR {wood* pasture*} OR {fodder tree*} OR pannage)</p> <p>AND</p> <p>("Mediterran*" OR Portugal OR Spain OR Gibraltar OR France OR Monaco OR Italy OR Malta OR Slovenia OR Croatia OR Bosnia OR Montenegro OR Albania OR Greece OR Turkey OR Cyprus OR Lebanon OR Israel OR Palestine OR Gaza OR Jordan OR Egypt OR Libya OR Tunisia OR Algeria OR Morocco)</p> <p>AND</p> <p>("LER" OR "yield" OR "relative yield" OR "product*" OR {Land Equivalent Ratio} OR {land-use efficiency} OR {crop efficiency})</p>
WoS	<p>(AB=("agroforest*" OR "mixed farming" OR "forest farming" OR "silvoarable" OR "silviarable" OR "silvopast*" OR "silvipast*" OR "agrosilvi*" OR "Agrosilvo*" OR "alley crop*" OR "hillside system" OR "shade crop*" OR "crop-over-tree" OR "tree intercrop*" OR "tree strip crop*" OR "dehesa" OR "farm woodland*" OR "forest grazing" OR "grazed forest*" OR "orchard grazing" OR montado OR "orchard intercrop*" OR "hedgerow intercrop*" OR "agroforestry parkland*" OR "wooded pasture*" OR "wood pasture*" OR "fodder tree*" OR pannage) OR TI=("agroforest*" OR "mixed farming" OR "forest farming" OR "silvoarable" OR "silviarable" OR "silvopast*" OR "silvipast*" OR "agrosilvi*" OR "Agrosilvo*" OR "alley crop*" OR "hillside system" OR "shade crop*" OR "crop-over-tree" OR "tree intercrop*" OR "tree strip crop*" OR "dehesa" OR "farm woodland*" OR "forest grazing" OR "grazed forest*" OR "orchard grazing" OR montado OR "orchard intercrop*" OR "hedgerow intercrop*" OR "agroforestry parkland*" OR "wooded pasture*" OR "wood pasture*" OR "fodder tree*" OR pannage) OR AK=("agroforest*" OR "mixed farming" OR "forest farming" OR "silvoarable" OR "silviarable" OR "silvopast*" OR "silvipast*" OR "agrosilvi*" OR "Agrosilvo*" OR "alley crop*" OR "hillside system" OR "shade crop*" OR "crop-over-tree" OR "tree intercrop*" OR "tree strip crop*" OR "dehesa" OR "farm woodland*" OR "forest grazing" OR "grazed forest*" OR "orchard grazing" OR montado OR "orchard intercrop*" OR "hedgerow intercrop*" OR "agroforestry parkland*" OR "wooded pasture*" OR "wood pasture*" OR "fodder tree*" OR pannage))</p> <p>AND</p> <p>(AB=("Mediterran*" OR Portugal OR Spain OR Gibraltar OR France OR Monaco OR Italy OR Malta OR Slovenia OR Croatia OR Bosnia OR Montenegro OR Albania OR Greece OR Turkey OR Cyprus OR Lebanon OR Israel OR Palestine OR Gaza OR Jordan OR Egypt OR Libya OR Tunisia OR Algeria OR Morocco) OR TI=("Mediterran*" OR Portugal OR Spain OR Gibraltar OR France OR Monaco OR Italy OR Malta OR Slovenia OR Croatia OR Bosnia OR Montenegro OR Albania OR Greece OR Turkey OR Cyprus OR Lebanon OR Israel OR Palestine OR Gaza OR Jordan OR Egypt OR Libya OR Tunisia OR Algeria OR Morocco) OR AK=("Mediterran*" OR Portugal OR Spain OR Gibraltar OR France OR Monaco OR Italy OR Malta OR Slovenia OR Croatia OR Bosnia OR Montenegro OR Albania OR Greece OR Turkey OR Cyprus OR Lebanon OR Israel OR Palestine OR Gaza OR Jordan OR Egypt OR Libya OR Tunisia OR Algeria OR Morocco))</p> <p>AND</p> <p>(AB=("LER" OR "yield" OR "relative yield" OR "product*" OR "Land Equivalent Ratio" OR "land-use efficiency" OR "crop efficiency") OR TI=("LER" OR "yield" OR "product*" OR "Land Equivalent Ratio" OR "land-use efficiency" OR "crop efficiency") OR AK=("LER" OR "yield" OR "product*" OR "Land Equivalent Ratio" OR "land-use efficiency" OR "crop efficiency"))</p>

unfortunately, none of these resulted eligible. The final number of studies that fulfilled the inclusion criteria and selected for the meta-analysis was twenty-two, covering thirty-six study sites (Table SM-2). Thirty-five were located in Southern Europe and one in North Africa (Fig. 3).

2.2 Data collection

Data were collected from original, replicated field experiments carried out within the geographic boundaries of this study (Bsk, Csa and Csb Mediterranean climatic zones; Peel et al. 2007) that included crop yields of both agroforestry system and sole crop (control). For studies that did not report the yields at a control site, the furthest distance from trees [30 m as in Moreno et al. (2007a) and in Husain et al. (2009), at 2.5 times the crown radius as in Gea-Izquierdo et al. (2009) and beyond the tree canopy influence as in L6pez-Carrasco et al. (2014)] was used as the control since, according to the authors, the shading effect on crop yield was irrelevant.

Numerical data from plots, figures, and maps were extracted through the WebPlotDigitalizer (Rohatgi 2017).

If precipitation was not available in a study throughout the experimental growing season(s), the geographic coordinates of the site (or otherwise the nearest location) were used to gather information using the Climate Information tool of AQUASTAT (FAO's Global Information System on Water and Agriculture n.d.). When the crop growing cycle was not reported in a study, the growing season length was assumed to be the same for the crop group (grain cereal, grain legume, sown forage grass, sown forage legume, sown forage mixture, and natural vegetation) tested in similar environmental conditions. The final number of studies selected for data collection had 161 pair comparisons (agroforestry vs sole crop) from diverse agroforestry systems (Table 2, Table SM-2).

2.3 Response variable

The response variable of the present study was the response ratio (RR), namely the crop mean yield in the agroforestry system relative to the sole crop mean yield:

$$RR_{ij} = \frac{\mu_{aj}}{\mu_{cj}}$$

where RR_{ij} is the response ratio of annual crop i in the study j ; μ_{aj} is the mean dry matter yield of annual crop i in agroforestry system (Mg ha^{-1}) in the study j ; and μ_{cj} is the mean dry matter yield of annual crop i in the sole crop condition (Mg ha^{-1}) in the study j .

Since RR was not normal according to the Anderson-Darling test for normality, the natural logarithm transformation of RR [$\log(\text{RR})$] was carried out to normalize the response variable:

$$\log(\text{RR}) = \ln\left(\frac{\mu_{aj}}{\mu_{cj}}\right) = \ln(\mu_{aj}) - \ln(\mu_{cj})$$

Positive values of $\log(\text{RR})$ indicate a higher value in the agroforestry system, while negative values indicate a higher value in the sole crop system.

To account for different sample size, the $\log(\text{RR})$ was weighted according to Lee et al. (2019):

$$W\log(\text{RR})_i = \frac{1}{N_i} \sum \log(\text{RR})_{ij} \times W(\text{RR})_{ij}$$

where N_i is the number of observations for the explanatory variable i (ID study, location, study year, system type, tree species, crop species, and agronomic treatment), the $\log(\text{RR})_{ij}$ is the log response ratio of the explanatory variable i in study j , and $W(\text{RR})_{ij}$ is the weighted response ratio of the explanatory variable i in study j that was calculated as the inverse of the reported standard deviations (Borenstein et al. 2009).

Explanatory variables (Table SM-2) were collected as follows: (i) the ID study is the identification number of the selected study from the identified documents; (ii) the location is the country where the study was carried out; (iii) the study year refers to the number of experimental years in a study; (iv) the system type refers to the agroforestry system employed in a study, such as alley cropping or Dehesa and Montado. Dehesa and Montado, being the same system carried out in Spain and Portugal, respectively, were differentiated as silvo-arable when sown species (i.e., forages) were tested, and silvo-pastoral when unsown species (i.e., natural vegetation) were collected; (v) the tree species refer to the trees used in a given agroforestry system; (vi) the tree cover was ranked according to the tree density per unit area, irrespective of type, age, crown radius, and height of trees, as follows: low (from 1 to 99 trees ha^{-1}), medium (from 100 to 199 trees ha^{-1}), and high (≥ 200 trees ha^{-1}); (vii) crop species refer to the field crop tested beneath the trees and in open field. Unsown legumes, grasses, and forbs are classified as natural vegetation, while sown forage legumes, sown grasses, and their mixtures as forages; (viii) agronomic practices, that in the same study were compared with a paired untreated control, refer to crop variety, tree pruning, permanence of crop species on field (crop age), crop harvest time, fertilization, irrigation, and imposed warming and drought (Hidalgo-Galvez et al. 2022). In this latter, authors installed an Open Top Chamber above the canopy

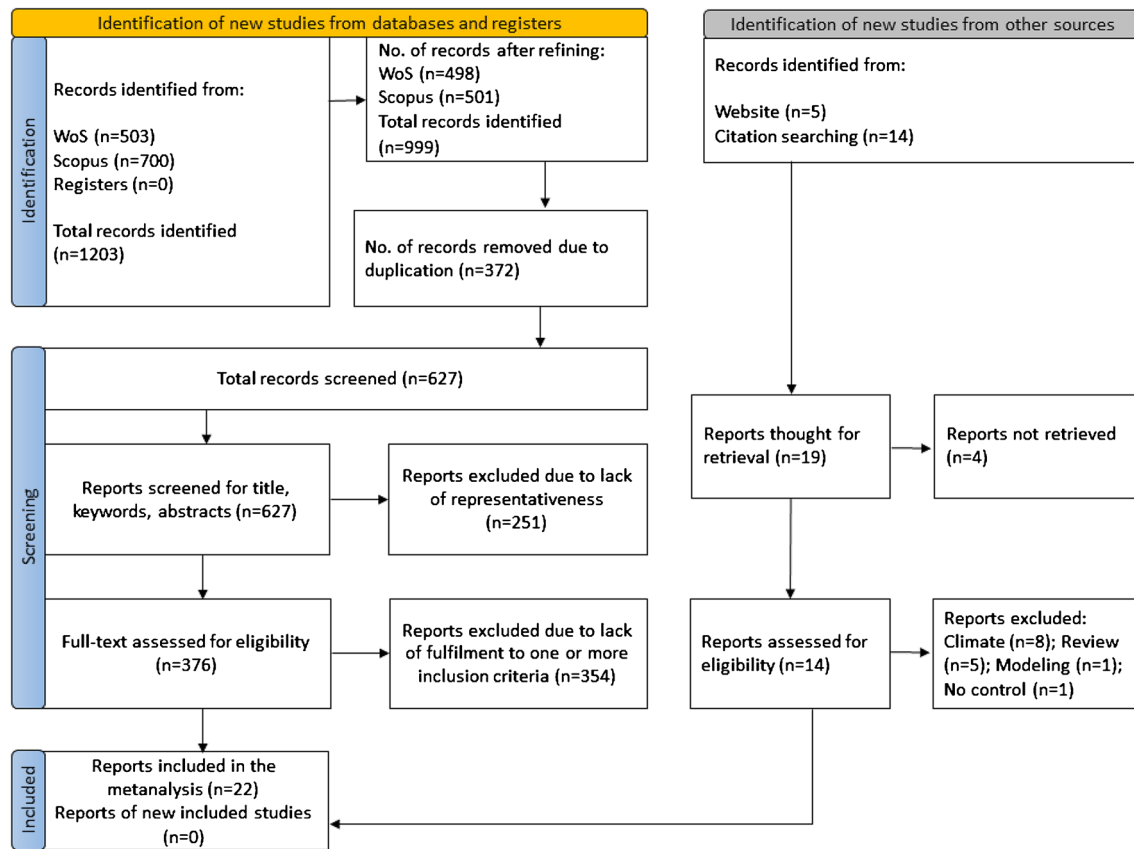


Fig. 2 Flow diagram according to the “Preferred Reporting Items for Systematic Reviews and Meta-Analyses” (Page et al. 2021)

to simulate the warming effect (increase of 2–3 °C of air temperature), while the drought was implemented using a rain-exclusion shelter in the plots.

For ease of interpretation, the $W\log(RR)$ values were exponentially back transformed and expressed as the percentage of yield change in response to agroforestry, compared to the control (sole crop):

$$\text{Change with agroforestry (\%)} = [(exp^{W\log(RR)} - 1)] \times 100$$

Positive values indicate a higher yield in the agroforestry system, while negative values indicate a higher yield in the sole crop system.

2.4 Statistical analysis

The means and standard errors (SEs) of each comparison were extracted from the selected studies, and the standard deviations (SDs) were calculated as follows:

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

where n is the sample size. If data were given with a mean and a confidence interval (CI), the SDs for each group were

obtained by dividing the length of the confidence interval by 3.92 ($\alpha = 0.05$), and then multiplying by the square root of the sample size. In studies without data variance ($n = 4$), the SDs were assumed as 1/10 of the means (Shi et al. 2017).

The means and 95% CIs of the $W\log(RR)$ were calculated by a bootstrap resampling procedure. For studies with a sample size lower than three, the $W\log(RR)$ means were reported without estimated CIs. A treatment effect was considered significant if the 95% CIs for means did not overlap with zero.

In addition, the effect of the explanatory variables on the $W\log(RR)$ was analyzed by eight different linear mixed models using the SAS PROC MIXED procedure (Statistical Software ver. 9.4, SAS Institute Inc., USA, Cary, NC). The restricted maximum likelihood (REML) was used to estimate the heterogeneity variance, as this method is known to be unbiased (Langan et al. 2019). Models 1, 2, 3, 4, and 5 included, as random effects, the study ID, the study year, and the location, whereas models 6, 7, and 8 considered as random factors the ID study, the ID study and the year, and the ID study and the location, respectively (Table 3). The fixed factors were the system type (alley cropping, silvo-arable, silvo-pastoral), the tree cover (low, medium, high), the tree species (ash tree, chestnut, cork oak, holm oak, olive, poplar, walnut), the crop species (alfalfa, barley, durum wheat, faba bean, forage, oat, pasture,

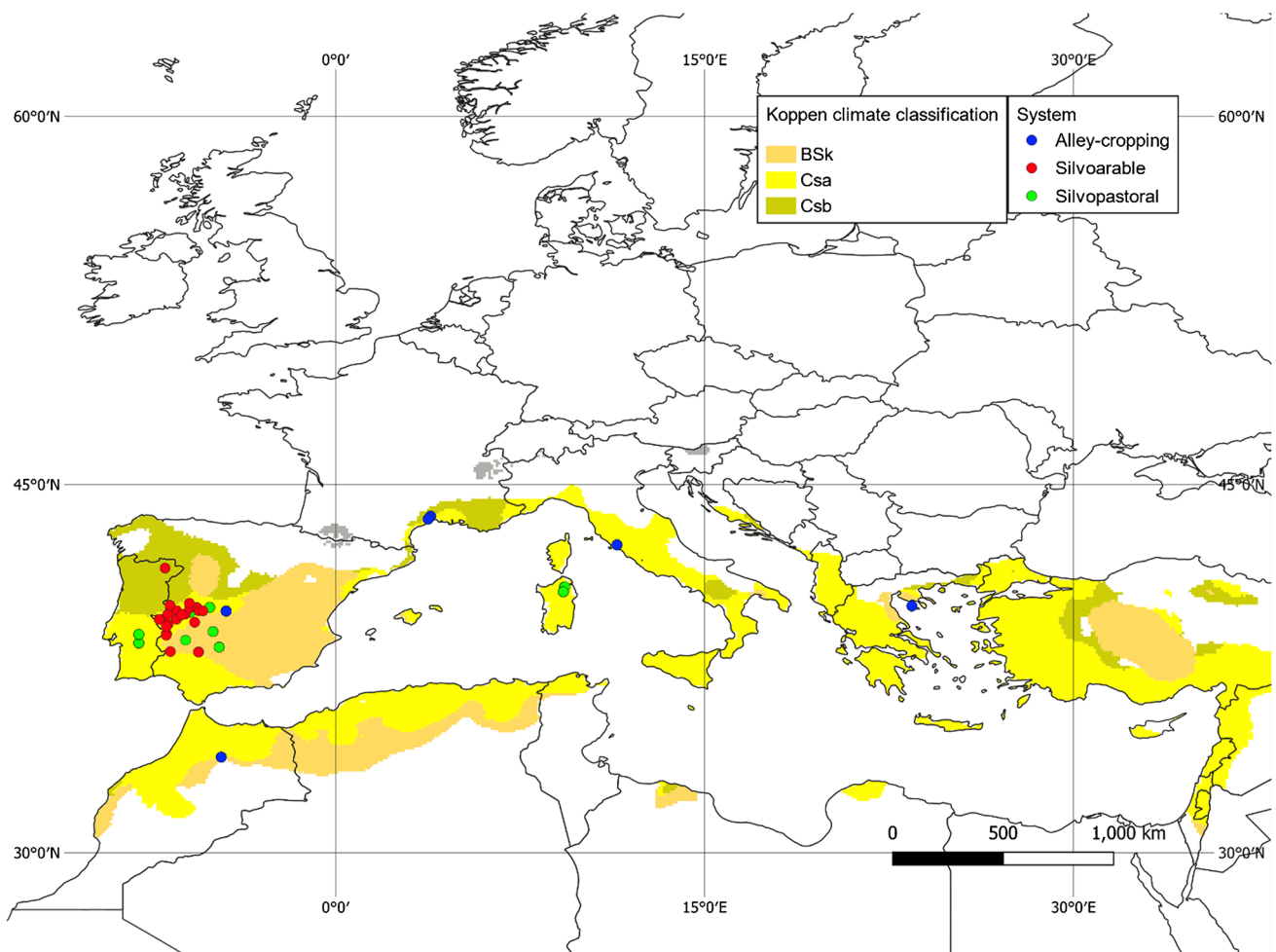


Fig. 3 Distribution of experimental field trials and agroforestry systems (alley-cropping, silvo-arable, and silvo-pastoral) in the Mediterranean basin (modified from Peel et al. 2007). White areas are climatic zones outside the boundaries of this study

pea, winter wheat), and the management (yield age classes, imposed warming and drought, fertilization, harvest time, irrigation, pruning, variety). Annual rainfall and crop growing cycle were included in model 5 as covariates of crop species to improve model accuracy. When fixed factors resulted significant in a model, the jackknife analysis was carried out to assess the sensitivity of estimates of $Wlog(RR)$ to each study of the dataset. One study from the dataset was removed each time, and models were run with the remaining data. The Akaike information criterion (AIC) was used as estimator of the quality of the statistical models.

A random-effect model was employed for the analysis of study heterogeneity. The effect size index was the standardized difference in means. The test of the null hypothesis that all studies in the analysis share a common effect size was analyzed by the Q test for heterogeneity, while the proportion of the variance in observed effects over the true effects was addressed by the I^2 statistic (Higgins et al. 2002). The

absolute amount of dispersion of the effect size was assessed by prediction intervals (Borenstein 2022).

The existence of publication bias was assessed by funnel plots of the standard error by standardized difference in means, and of the precision ($1/SE$) by standardized difference in means. Furthermore, the Duval and Tweedie's Trim and Fill method and the Egger's test of the intercept procedure were used. Computations were carried out using the software Comprehensive Meta-Analysis Version 4 (Biostat Inc., Englewood, NJ, USA).

3 Results

3.1 Study heterogeneity and publication bias

The average change with agroforestry (%) in the analyzed studies was -22.12% , which ranged from -79.56 to $+$

Table 2 Study ID, number of observations (Obs.), experimental year (Yr), agroforestry system type, tree species, field crop species, and management practice

ID	Obs.	Yr	Country	System	Tree	Tree density* (age**)	Crop	Management	Reference
#29	34	3	Spain	Alley	Walnut	333 (9–10)	Barley, winter wheat	Variety	Arenas-Corraliza et al. (2018)
#141	8	2	Portugal	Montado	Holm oak	40 (na)	Pasture	Fertilization	Cubera et al. (2009)
#160	16	3	France	Alley	Walnut	100 (19–21)	Durum wheat, barley, pea	Pruning	Dufour et al. (2020)
#161	2	2	France	Alley	Walnut	100 (12–13)	Durum wheat	None	Dufour et al. (2013)
#210	3	3	Spain	Dehesa	Holm oak	10 (na)	Pasture	None	Gea-Izquierdo et al. (2009)
#247	7	7	Spain	Dehesa	Holm oak	na (na)	Forage, pasture	Crop age	Hernández-Esteban et al. (2019)
#251	4	3	Spain	Dehesa	Holm oak	15 (na)	Pasture	Imposed warming and drought	Hidalgo-Galvez et al. (2022)
#260	2	1	Portugal	Montado	Holm oak	103 (na)	Pasture	Harvest time	Hussain et al. (2009)
#263	2	1	France	Alley	Poplar, Ash tree	128 (16), 385 (21)	Durum wheat	Pruning	Inurreta-Aguirre et al. (2018)
#264	2	1	Spain	Alley	Walnut	96 (23)	Durum wheat, barley	Pruning	Inurreta-Aguirre et al. (2022)
#315	3	3	Spain	Dehesa	Holm oak	17 (na)	Pasture	None	Lopez-Carrasco et al. (2014)
#335	10	2	Italy	Alley	Olive	200 (70)	Alfalfa	Harvest time	Mantino et al. (2021)
#336	3	3	Greece	Alley	Olive	100 (80)	Barley	None	Mantzanas et al. (2021)
#348	1	1	Portugal	Montado	Chestnut	69 (40)	Forage	None	Martins et al. (2011)
#379	15	1	Spain	Dehesa	Holm oak	25 (~ 105)	Pasture	Fertilization, irrigation	Moreno (2008)
#382	16	1	Spain	Dehesa	Holm oak	7–28 (~ 100)	Oat	Fertilization	Moreno et al. (2007a)
#427	6	3	France	Alley	Olive	278 (13–15)	Durum wheat	Pruning	Panozzo et al. (2022)
#473	2	3	Italy	Dehesa	Cork oak	~115–182 (na)	Pasture	None	Pulina et al. (2021)
#534	4	1	Italy	Dehesa	Cork oak	450 (na)	Forage, pasture	Variety	Sanna et al. (2018)
#555	6	2	Portugal	Montado	Holm oak	12 (na)	Pasture	Harvest time	Serrano et al. (2021a)
#558	3	5	Portugal	Montado	Holm oak	12 (na)	Pasture	None	Serrano et al. (2021b)
#591	12	2	Morocco	Alley	Olive	204 (65)	Durum wheat, faba bean	Irrigation	Temani et al. (2021)

*Tree density in number of trees per hectare and, in parenthesis, tree age in years

60.97% in the study #260 and #379, respectively (Figure SM1). Means were reported without CIs in studies #161, #260, #263, #264, #348, and #473 since the sample size was lower than three.

In the test for heterogeneity, one study was removed (#348), since it included only one observation ($n = 1$). Therefore, the analysis was based on 21 studies (Table SM-3). The mean effect size of the standardized difference in means was -1.004 with a 95% confidence interval (CI) from -1.515 to -0.492 . The Z value and the Q value were significant. The corresponding I^2 was 72%, and the 95% prediction interval ranged from -3.034 to 1.027 .

The publication bias was assessed by depicting funnel plots of the standardized difference in means by standard error and by precision ($1/SE$) of observed study

(Figure SM2a-b). The Egger's test at 95% confidence level (intercept -2.146 and 95% CI -3.759 to -0.533) was significant for the one-tailed P value (0.0059) and for the two-tailed P value (0.0118). On the contrary, the Trim and Fill method under the fixed-effect model (point estimate -0.593 and a 95% CI for the combined studies -0.831 to -0.355), and under the random effects model (point estimate -1.003 and 95% CI for the combined studies -1.515 to -0.491), suggested no imputed missing studies to remove the unbiased effect (Figure SM2c-d).

3.2 Change with agroforestry

Fixed-effect terms in the eight fitted linear mixed models and significance at 95% confidence level are presented in Table 4.

The system-type effect in model 1 was not significant ($P = 0.641$, Table SM-3). The average change with system type in agroforestry was -18.91% , ranging from -12.89% in silvo-arable to -28.53% in alley cropping (Fig. 4).

The tree species effect in model 2 was significant ($P = 0.030$, Table SM-4). In multiple comparisons (difference of least squares means), Wlog(RR) mean in ash tree was significantly lower than chestnut, holm oak, poplar, and walnut. This latter showed a significantly higher Wlog(RR) than cork oak and olive. Holm oak Wlog(RR) mean was higher than olive but lower than poplar. The average change with tree species in agroforestry was -26.07% , which ranged from -75.78% in ash tree to $+3.30\%$ in walnut (Fig. 5).

The tree cover effect in model 3 was significant ($P = 0.017$, Table SM-5). In multiple comparisons, Wlog(RR) mean was significantly lower in high tree cover than low and medium ones. These two latter did not differ. The average change with tree cover in agroforestry was -23.95% , ranging from -33.47% in the high to -8.24% in the low tree cover (Fig. 6).

The crop species effect in model 4 was significant ($P = 0.015$, Table SM-6). The Wlog(RR) mean was significantly higher in barley than faba bean, and in durum wheat than faba bean. This latter had a significantly lower Wlog(RR) mean compared to forage, pasture, oat, pea, and winter wheat. Model 5 included “rainfall” and “crop growing cycle” as covariates of crop species. However, both covariates were not significant, and this model did not show appreciable improvements compared to the previous one (Table SM-7). The average change with crop species in agroforestry was -24.26% , ranging from -80.78% in the faba bean to $+13.11\%$ in the winter wheat (Fig. 7).

The management effect in model 6 was not significant ($P = 0.837$, Table SM-8), and the average change with management in agroforestry was -24.42% , ranging from -52.84% in the imposed warming and drought treatment to $+16.13\%$ in the variety treatment (Fig. 8).

When analyzed separately, pruning and fertilization were the only treatment that converged. In model 7, pruning and crop species were not significant, and the interaction of

pruning \times crop species was slightly above the confidence level ($P = 0.065$, Table SM-9). In model 8, the fixed-effect fertilization was significant ($P = 0.006$, Table SM-10), while crop species and the interaction were not. The unfertilized treatment showed a significantly higher Wlog(RR) mean than the fertilized treatment, likely due to the significantly higher mean of natural vegetation under no fertilization than the fertilization treatment. On the contrary, oat fertilized and unfertilized did not statistically differ.

3.3 Sensitivity analysis

The sensitivity analysis was carried out for models whose fixed effects were significant (Table SM-12-14). Generally, the analysis did not show influential data coming from a single study, except for the model 3 (tree cover) when the study #427 was excluded ($P = 0.102$).

The AIC in model 2 was 199.9; the model improved by excluding the study #260, #335, #379, #427, and #591.

In model 3, the AIC was 206.5. The model improved by excluding the study #29, #247, #251, #260, #263, #348, #382, #427, and #591.

In model 4, the AIC was 199.4. The AIC improved by excluding the study #260, #335, #379, #427, and #591.

Excluding the other studies did not improve the performance of the three statistical models.

4 Discussion

4.1 Study heterogeneity, publication bias, and sensitivity analysis

The interaction between trees and associated crops is a complex phenomenon that involves facilitative and competitive relationships (Moreno et al. 2007b). Hence, agricultural practices to maximize synergies between trees and crops must be ensured. Due to the highly diverse agroforestry systems, climate, soil type, tree cover, crop and tree species, and management practices analyzed in the twenty-two studies (Table 2 and Table SM-2), a substantial variability

Table 3 Random and fixed effect terms in the seven fitted linear mixed models and number of observations (Obs.)

Model	Random terms	Fixed terms	Obs.
#1	ID, location, year	System type	161
#2	ID, location, year	Tree species	161
#3	ID, location, year	Tree cover	161
#4	ID, location, year	Crop species	161
#5	ID, location, year	Crop species cov. rainfall and growing cycle	161
#6	ID	Management	106
#7	ID, year	Crop species, pruning, crop species \times pruning	22
#8	ID, location	Crop species, fertilization, crop species \times fertilization	32

in the yield response was found. In accordance with the Q statistic, the null hypothesis that all studies in the analysis share a common effect size was rejected. The proportion of the study variance in observed effects reflecting the variance in true effects rather than sampling error was quite large ($I^2 = 72\%$), which is common for agronomic meta-analysis (Garba et al. 2022), and reflects the multiple differences in agroforestry systems above mentioned. In order to understand how much the effect size varies within a meta-analysis, Borenstein (2022) proposed to use the prediction intervals. If we assume that the true effects are normally distributed, the prediction interval in the present study ranged from -3.034 to 1.027 , suggesting that true effect size in 95% of all comparable populations falls within this interval (Borenstein et al. 2017; Borenstein 2020; DerSimonian and Laird 2015; Higgins 2008; Higgins and Thompson 2002; Higgins et al. 2003; Higgins and Thomas 2019; IntHout et al. 2016).

The Egger's test was significant, suggesting the existence of publication bias. However, the visual inspection of the funnel plot revealed no pattern of bias since the studies appeared to be dispersed equally on either side of the overall effect (Figure SM2a-b). In the presence of bias, the bottom of the plot would tend to show a higher concentration of studies on one side of the mean than the other. The absence of bias was confirmed by the Trim and Fill method, where both observed and imputed point estimates were unchanged, and there were no imputed missing studies to remove the unbiased effect (Figure SM2c-d).

Likewise, the sensitivity analysis did not show a significant change in the overall outcome due to the omission of any study. Except for the model 3 when the study #427 was excluded, the fitted linear models employed indicated that the estimates from this meta-analysis remained below the

Table 4 Fixed effect terms in the eight fitted linear mixed models and significance at 95% confidence level

Model	Fixed effect terms	F value	P value
#1	System type	0.37	0.693
#2	Tree species	2.41	0.030
#3	Tree cover	4.18	0.017
#4	Crop species	2.42	0.014
#5	Crop species	2.22	0.044
	cov. Crop cycle	0.22	0.640
	cov. Rainfall	0.00	0.963
#6	Management	0.49	0.837
#7	Crop species	1.09	0.366
	Pruning	3.25	0.094
	Crop species \times pruning	3.38	0.065
#8	Crop species	0.09	0.762
	Fertilization	8.81	0.006
	Crop species \times fertilization	1.64	0.211

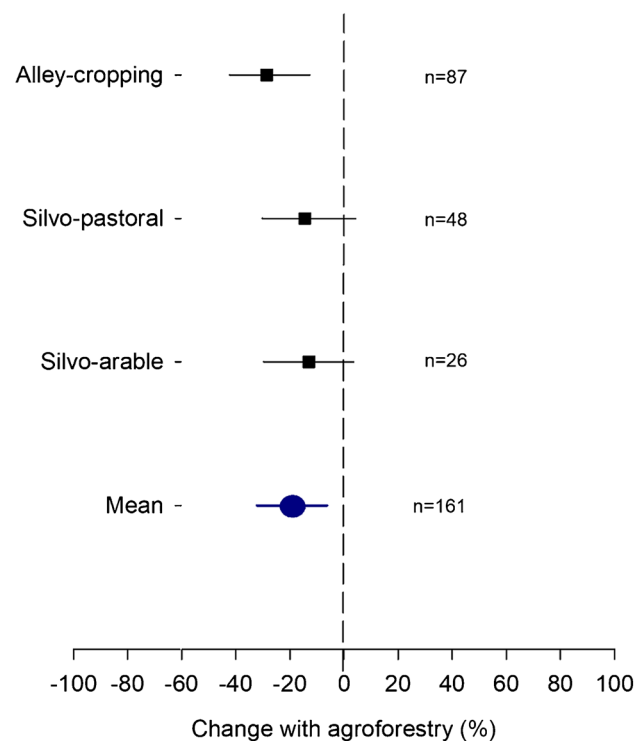


Fig. 4 Change with agroforestry (%) of system type and 95% confidence intervals, and number of observation (n) from the twenty-two reviewed studies. The blue circle represents the mean effect and 95% confidence intervals

significance level; therefore, the models can be considered robust (Philibert et al. 2012). Nonetheless, we found room for improvements of model performances when some studies were removed. In particular, the AIC improved by excluding studies #260, #427, and #591 from the three models. Surprisingly, these three studies showed the most negative percentage of change with agroforestry (Figure SM1).

The study of Hussain et al. (2009) (i.e., #260) investigated the biomass yield and light interception of natural vegetation in a Montado system for 1 year (low tree cover), in the proximity of the tree trunk (at least 2 m) and at least 30 m from the closest tree as a control. Crops in agroforestry were likely too close to the tree trunk for a reliable outcome, as distance from trees has been indicated a key driver of crop productivity in agroforestry (Van Vooren et al. 2016; Ivezić et al. 2021). Panozzo et al. (2020) (i.e., #427) investigated the pruning effect in an olive alley cropping with different genotypes of durum wheat in France for 3 years. The experiment was conducted in two different olive orchards, one that was pruned yearly and one that was never pruned. In addition to the possible differences in soil conditions and different responses of durum wheat genotypes, orchards had different olive varieties and age of the trees, which might have added further within-study variability. Finally, Temani et al. (2021) (i.e., #591) investigated faba bean and durum wheat

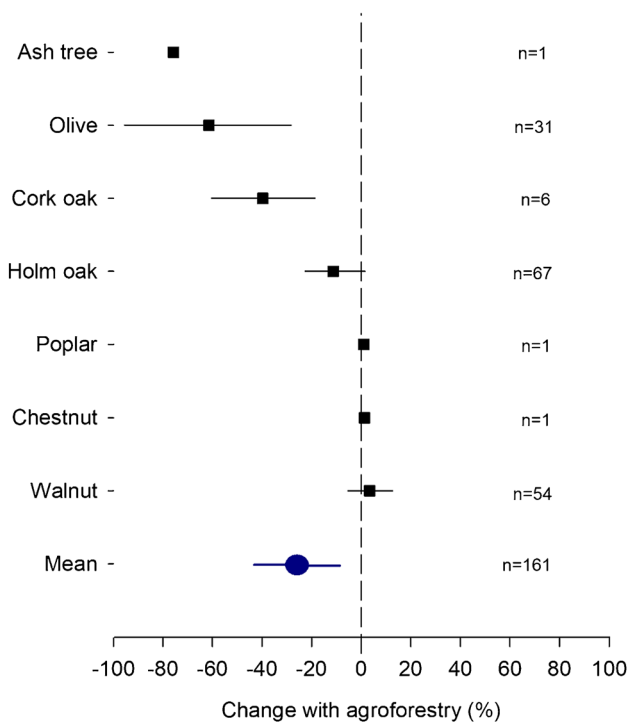


Fig. 5 Change with agroforestry (%) of tree species and 95% confidence intervals, and number of observation (*n*) from the twenty-two reviewed study. The blue circle represents the mean effect and 95% confidence intervals

under three levels of irrigation in an olive alley cropping in Morocco for 2 years. Authors stated that increasing water availability with irrigation, maintaining the same amount of nutrients, may have unbalanced crop nutrient requirement and a possible shift in limiting factor from water to nitrogen. In particular, faba bean showed very poor grain yield, which could be accounted for the low level of nutrients applied at sowing, 9 kg N ha⁻¹ and 23 kg P ha⁻¹, in both years and irrigation regimes. Furthermore, there was no reference for specific rhizobium strain for this legume species, which is known to significantly enhance the root nodulation, growth, and dry matter yield (Allito et al. 2021).

4.2 Agroforestry system and tree cover

Our results related to system type and to tree cover are in line with the findings of Ivezić et al. (2021), who indicated competition between trees and crops less relevant in extensive systems compared to more intensive alley cropping, and that crop yield declines with increasing the tree density. Montado and Dehesa (silvo-arable and/or silvo-pastoral, depending on sown or unsown crop species, respectively) systems, being characterized by low density and scattered trees, sometimes ancient trees of high natural value, are less flexible to management intervention as compared to young

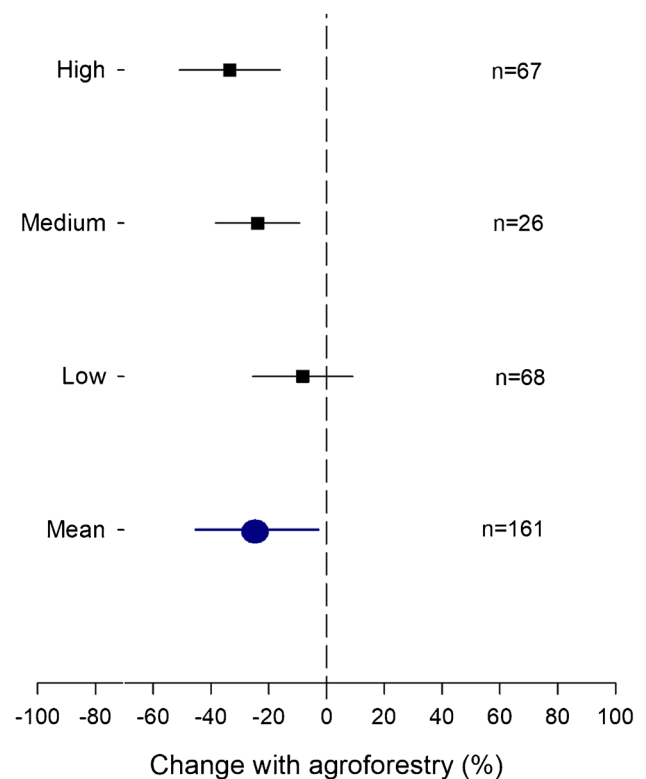


Fig. 6 Change with agroforestry (%) of tree cover and 95% confidence intervals, and number of observation (*n*) from the twenty-two reviewed studies. The blue circle represents the mean effect and 95% confidence intervals

alley cropping. For this latter, strategic management options should be carefully considered, either when plantations are planned for agroforestry systems or when already established ones are adapted to. This includes the tree spatial orientation to maximize light interception in the alley (Dufour et al. 2013), tree pruning (Cubera et al. 2009; Mantino et al. 2021) and pollarding (Dufour et al. 2020), and crop distance from trees to minimize shading effect (Moreno et al. 2007a; López-Carrasco et al. 2014).

Crop performance assessments in alley-cropping systems in Europe have been generally conducted by testing very narrow spacings between rows of trees, typically lower than 15 m. Recently, wide tree spacing has been tested successfully (e.g., from 26 to 54 m) to limit competition between trees and crops in temperate agroforestry (Pardon et al. 2018; Veldkamp et al. 2023). Unfortunately, studies at wider tree row spacing were not available at the latitudes investigated in this meta-analysis.

We ranked tree density on low, medium, and high cover, and found an inverse gradient in the response variable with tree cover, which agrees with other meta-analysis carried out in agroforestry and hedgerow systems in more temperate environments (Van Vooren et al. 2016; Ivezić et al. 2021).

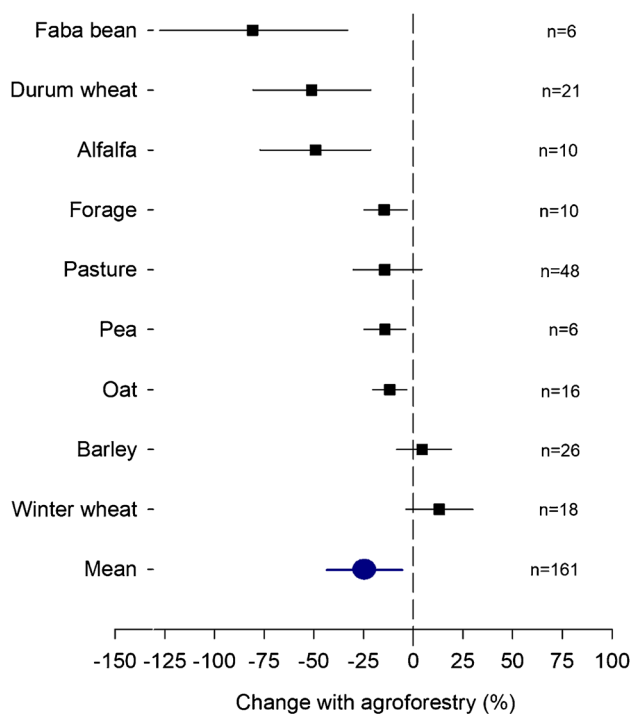


Fig. 7 Change with agroforestry (%) of crop species and 95% confidence intervals, and number of observation (n) from the twenty-two reviewed studies. The blue circle represents the mean effect and 95% confidence intervals

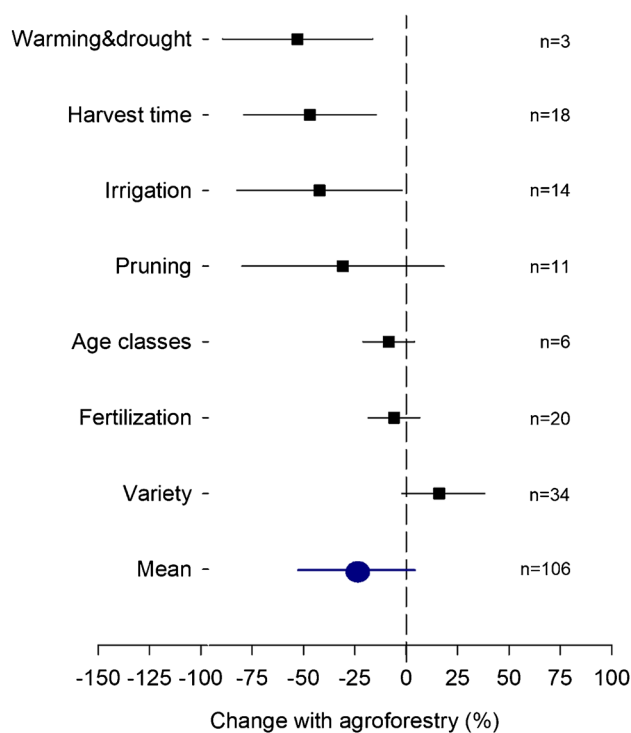


Fig. 8 Change with agroforestry (%) of agronomic management, and 95% confidence intervals, and number of observation (n) from the twenty-two reviewed studies. The blue circle represents the mean effect and 95% confidence intervals

Hedgerows, windbreaks, and field shelterbelts might deserve attention, as it has been demonstrated that these systems can increase crop yield and quality worldwide (Kort 1988; Baldwin 1988); however, these agroforestry systems were not available in our dataset. In Germany, for instance, Kanzler et al. (2019) observed a 16% grain yield increase of winter wheat in a short-rotation poplar hedgerow (48-m alley), which was related to the significantly lower atmospheric evaporative demand and wind speed in agroforestry than open field. Hence, Mediterranean experimental trials focusing on these systems are strongly encouraged in order to enlarge the data available for future meta-analysis.

4.3 Tree, crop, and management

The impact of tree species on the response ratio was significant and can be ascribed to the different tree functional group, development and system type as also shown by Rivest et al. (2013) and by Ivezić et al. (2021). There was also a significantly different impact of crop species in agroforestry on the response ratio, while management did not have an impact on the response ratio. Regarding tree species, we found an almost null effect with walnut agroforestry (Arenas-Corraliza et al. 2018; Dufour et al. 2013; Inurreta-Aguirre et al. 2022). This deciduous tree is of particular interest as leaves appear fairly late in the cropping season, and many genotypes have been developed for delayed budbreak in spring (Soleimani et al. 2019); therefore, it is extremely relevant for winter crops. Although walnut/barley and walnut/winter wheat alley cropping in Spain (9-year-old walnut hybrid, 6 × 5 m) highlighted a strong influence of climatic conditions on crop yield, the percentage of change with agroforestry indicated that barley and winter wheat showed slightly positive yield response. Compared to winter wheat, barley was better adapted to intercropping with walnut in drier years, with hot and dry events in spring. Being an earlier maturing and drought-resistant crop, it was favored by tree sheltering, while winter wheat yield response mostly depended by the variety (Arenas-Corraliza et al. 2018). In the non-pollarded walnut trees, with 80% of the average global radiation, barley mean yields were mostly unaffected as compared to durum wheat (68% of the sole crop) (Dufour et al. 2020). In another site, barley and durum wheat associated with walnut (23-year-old walnut hybrid, 13-m-wide alleys, 96 tree ha⁻¹) reduced grain yield as compared to the sole cropping despite a lower air temperature during the day and the higher soil moisture in the agroforestry system. The reduction was mainly related to a low and uneven incident solar radiation (Inurreta-Aguirre et al. 2022). Even when the walnut plantation was younger (17-year-old) at the same site, the shape of the tree crown, the width of the crop alley, and the orientation of the tree rows modified the intensity of the shade,

impacting the mean grain weight of wheat to a different extent (Dufour et al. 2013).

Intercropped with other tree types, the percentage of change of durum wheat in agroforestry ranged from slightly positive values with poplar under favorable climatic conditions to negative ones when intercropped with ash tree in the same environment (Inurreta-Aguirre et al. 2018). Highly negative values were observed in association with olive in France (Panozzo et al. 2020), highlighting the importance of tree/crop association. Also, biomass accumulation in alfalfa was negatively affected by the olive tree presence at different crop harvest times, suggesting that competition for light seems to be more important than competition for water between alfalfa and olive trees (Mantino et al. 2021). In fact, olive, being an evergreen tree, shades continuously the associated crops, and it was the second most impacting tree species in agroforestry.

It is worth mentioning that net photosynthesis in C3 plants saturates around 50–60% of maximum sunlight (Carrier et al. 2019), which is below the average shading found in many agroforestry systems. Arenas-Corraliza et al. (2018) argued that plants under continuous shade reduce leaf area and leaf area index, and advance phenological stages, which impacts the overall carbon assimilation and yield. This sub-optimal growth under shade could in part explain the lower response changing system type and tree-crop interaction as compared to full sun conditions. In accordance with a recent meta-analysis on the susceptibility of different temperate crops to increasing shading levels (Laub et al. 2022), we found grain legumes (i.e., faba bean and winter field pea) to be very susceptible to shade. Faba bean, which was the crop with the most negative percentage of change with agroforestry, reduced grain yield either in rainfed and under irrigated olive alley cropping, suggesting that water was not the limiting factor (Temani et al. 2021). Winter field pea intercropped with non-pollarded walnut reduced the thousand seed weight rather than the number of pods as tree budburst coincided with the grain-filling period in France (Dufour et al. 2020). On the other hand, the olive competed with faba bean during critical stages before flowering in Morocco, causing a significant reduction in grain number per unit area (Temani et al. 2021).

The ash tree appeared the most competing tree mainly due to a significant radiation intercepted (62.9%, measured as the gap fraction from hemispherical photographs before budbreak) by the large trunk and the dense branches (21-year-old, 15-m tall, 2 m distant in the row) even before budbreak in March (Inurreta-Aguirre et al. 2018). Nevertheless, results should be extrapolated with caution since only one site for 1 year was available for ash tree, as well as for poplar. Also, chestnut (40-year-old, 12 × 12 m) was tested only in one Montado site in Portugal (Martins et al. 2011). Although the

experiment was run for 3 years, data were reported across years and treatments. Authors argued on a strong influence of the year as a source of variation (37.9%), while the effect of sown pasture position (beneath tree crowns or open areas) was rather marginal (7.9%).

Cork oak and holm oak are evergreen trees which provide shade all year through, with either positive and negative outcome. These tree species were usually associated with pasture and forage species in extensive silvo-arable and silvo-pastoral systems. In general, forages (sown grasses, sown legumes, and their mixture) have been indicated as species with a less than proportional loss of yield at low levels of shade (Laub et al. 2022). Our results confirm the shading resilience of forages, as we found either an improved forage production by a direct effect of shading by holm oak intercropped in multiple Dehesa sites (Moreno 2008), to a more than proportional yield reduction when the incoming solar radiation in the cork oak agroforestry (at a very high density, 450 tree ha⁻¹) was 15–30% that of full sunlight (Sanna et al. 2018). Similar trends were observed for pasture species, although variation in the estimate was higher and could be linked to the larger heterogeneity of studies due to different plant community, tree density, season, and level of pasture degradation, among others (Moreno 2008; Cubera et al. 2009; Gea-Izquierdo et al. 2009; Hussain et al. 2009; López-Carrasco et al. 2014; Sanna et al. 2018; Hernández-Esteban et al. 2019; Serrano et al. 2021a; Serrano et al. 2021b; Hidalgo-Galvez et al. 2022; Pulina et al. 2021).

The management practices investigated in this meta-analysis did not show significant differences, but tended towards negative values, particularly under imposed warming and drought, different crop harvest time, and irrigation regimes; the percentage of change in agroforestry was almost unchanged with crop age classes, fertilization, and pruning or slightly improved in the variety treatment. Reviewed studies provided some strategies to improve the performances of understory crops in agroforestry.

For example, Cubera et al. (2009) found a negative effect of shade on rainfed pasture production in a Montado holm oak agroforestry (35–45 tree ha⁻¹); nevertheless, water supplied by irrigation increased pasture biomass suggesting that this tree species does not compete for soil-water resources when water is not a limiting factor. Indeed, other studies found near-neutral net effects of evergreen oak trees on pasture production, which was associated to the likely root niche separation between trees and the herbaceous layer (Rivest et al. 2013).

Serrano et al. (2021b) emphasized that the low incidence of legume species (only 4–7% of coverage area) under holm oak agroforestry was the main bioindicator of pasture degradation, and nitrogen application and reseeded of legumes were recommended to restore the pasture

floristic balance. In fact, sowing seed mixtures with a high content of self-reseeding legume species were keys for pasture floristic composition, productivity, and persistence in holm oak multisite Dehesa systems (Hernández-Esteban et al. 2019). Manipulated higher temperatures and drier conditions were studied in a Dehesa system (Hidalgo-Galvez et al. 2022). Low density and scattered holm oak canopy (tree density 14.5 ± 1.3 trees ha^{-1}) buffered thermal stress as compared to the open field; however, combined with drought caused a significant shift in the functional structure of plant communities, both in the open field and beneath trees.

In a low-input holm oak agroforestry system (unfertilized plots), oat productivity was enhanced by the higher soil fertility beneath the tree canopy in different sites with trees ranging from 80 to 120-year-old, 7–12 m of canopy width and tree density from 10 to 30 trees ha^{-1} (Moreno et al. 2007a). Oat production decreased near trees in fertilized plots, and fertilization enlarged the gap between sole crop and agroforestry, from nearly similar values when unfertilized to 32% in highly fertilized plots.

López-Carrasco et al. (2014) advocated that pasture in good weather conditions (> 450-mm annual rainfall with at least 100 mm spring rainfall) was relatively homogeneous in species richness or biomass in different orientations beneath the canopy of scattered holm oak woodland (tree density 17 trees ha^{-1}). On the contrary, when water was scarce (< 350-mm annual rainfall), species richness among orientations varied, with higher influence in the warmest orientation (southwest) of the larger trees. Also, Moreno (2008) stated that the facilitative effect of trees (i.e., positive effect of holm oak shade and improved soil fertility in multiple Dehesa sites with tree density between 21 and 29 tree ha^{-1}) was offset by the competitive use of soil water, as results depended on rainfall amount and distribution in a particular year, and on the species composition in a specific site (e.g., annuals vs perennials, and legumes vs grasses). Although the effective rainfall greatly changed from year to year and from site to site in the reviewed studies (from 32 to 1054 mm, with a pooled mean of 436 mm), which is in line with the typical pattern in Mediterranean environments (Alexopoulou et al. 2015), rainfall effect did not improve the performance in the model 5. Also, the crop-growing cycle (from 61 days in alfalfa in very early cuts in April to 240 days in durum wheat) was not significant.

The spatial difference in root profiles between trees and crops has been recently addressed as a key driver of competition, mainly when tree roots are shallow and take up soil moisture at high rates (Rivest et al. 2013). Inurreta-Aguirre et al. (2022) suggested that root pruning in walnut might be effective to reduce competition for water, but not in sites with deep soil, high water-holding capacity, and rainfall evenly distributed throughout the season. It could have a

facilitative effect in drier areas; however, the literature lacks experimental trials to support this hypothesis.

4.4 Limitations of the study

In this work, a standardized process for study collection based on the PRISMA method was adopted. Moreover, two different approaches were used, the 95% confidence interval analysis and eight linear mixed models to analyze the explanatory variables, the test for heterogeneity, publication bias, and the sensitivity analysis to identify the influence of a particular study. We used original research papers with field trials in our selection, and this probably did not capture all the available information on the agroforestry systems in the Mediterranean countries, as relevant conclusions might be further offered by the grey literature and papers other than experimental ones. However, we relied on peer-reviewed studies with replicated field trials to not incur in flawed approaches or low-quality data. Nineteen new studies were retrieved from other sources, but none of these was eligible. Although there is a limited number of observations in our dataset ($n = 161$), we included also 1-year studies, which is usually a shortcoming for agronomic experiments; nonetheless, it was possible to assess the variance of the dataset, and the sensitivity analysis did not detect influence from any single study (except for the study #427 in model 3), thus confirming the reliability of the selected approach.

This paper focused on the crop yield of herbaceous species in agroforestry as compared with the sole crop. Although results suggest a negative effect of tree on crop yield, it must be pointed out that the alternative products provided by trees and livestock were not included, as well as the ecosystem services (i.e., carbon storage, prevention of deforestation, conservation of biodiversity, capture of nutrients, soil erosion prevention) and the multifunctionality this system can support. The basic idea was to assess the LER as a response variable; unfortunately, only a few studies calculated this index by collecting both crop and tree products. Our findings can therefore mislead the real potentiality of agroforestry systems and consequently the information to farmers, practitioners, and decision-makers. In fact, most studies in temperate conditions provide LER values of agroforestry systems ranging between 0.95 and 2.0 (Graves et al 2007; Sereke et al 2015; Pent 2020), thanks to the higher land use efficiency. Hence, it is highly recommended to focus on this index in future works or to couple productive and ecological indexes that consider the system as a whole. Also, wider tree spacing successfully tested in temperate alley cropping (Pardon et al. 2018; Veldkamp et al. 2023), as well as hedgerows, windbreaks, and field shelterbelt strategies might offer new perspectives on the effectiveness of the agroforestry

systems. Unfortunately, these arrangements were not available at the latitudes investigated in this meta-analysis to date.

5 Conclusions

This meta-analysis allowed to draw the following key findings: (1) system type tended to gradually ameliorate the weighted response ratio from alley cropping to silvo-arable and silvo-pastoral; (2) tree cover significantly improved the weighted response ratio at low and medium as compared with high tree cover; (3) tree species significantly impacted the weighted response ratio, suggesting tree traits (morphology, phenology, physiology) and diversity (taxonomic and functional) should be carefully evaluated; (4) crop species significantly impacted the weighted response ratio, hence knowledge on crop response to shade, particularly at specific crop phenological stages, spatial root profile and other morphological and physiological traits should be improved; and (5) management tended to gradually reduce the weighted response ratio in agroforestry, except for variety treatment, indicating that care must be taken to make decisions about the usefulness of the practice and that their application must be tailored to specific growing conditions.

Most of the reviewed studies agree on the negative effect of tree shading on crop yield and the need to investigate traits or genotypes to breed shade-tolerant crops fine-tuned for agroforestry. This can be confirmed by the system type and the tree cover. Alley cropping, an intensive agroforestry system, and high tree cover had the highest impact on the response ratio. Also, tree management practices to improve the incident solar radiation to the associated crop were extensively discussed. The tree species was also a significant effect to consider: evergreen species are usually more impacting than deciduous ones, but care must be also taken with tree traits and phenology (growth speed, canopy density, branchiness, date of bud-break, and root distribution), as well as the tree age and size, density, diversity (taxonomic and functional), and orientation, among others.

Despite the reduction in crop yield in agroforestry compared to sole crops, trees may lead to a diversification and increase in overall productivity, therefore reducing farmers' vulnerability to markets. Moreover, trees can mitigate the effect of extreme climate events due to hydraulic lift, as shelter from heat waves and preventing lodging from strong winds, provided that both crop and tree cycles are staggered, root systems explore different soil layers, and there are no effects from a phytosanitary point of view.

In general, barley and oat seem suitable cereals for agroforestry systems mainly due to their short cycle,

drought tolerance, and low-input demand. Forage and pasture are extensively used in agroforestry and have been indicated as species with a less than proportional loss of yield at low levels of shade. However, it is essential to manage through sowing forage mixtures and fertilization plan to balance floristic composition, persistence, and productivity. Grain legumes were very susceptible to agroforestry due to shading, while wheat response mostly depended on the cultivar, seasonal climatic conditions, and tree-type association.

Although management practices were not significant in models, they showed a trend. Variety, in particular, seems to ameliorate the yield responses in agroforestry, while the application of other practices must be tailored to specific growing conditions to prove their usefulness.

It is worth mentioning that the reviewed experiments did not include improved species or varieties for agroforestry; hence, efforts should be made to investigate shade-tolerant crop species and other companion planting options and designs in the Mediterranean regions. There is also a need to run long-term studies to assess the whole lifespan of these systems along with the overall benefit agroforestry can provide at the field and landscape level (i.e., land use efficiency, value creation and economic balance, multifunctionality, biodiversity, and ecosystem services).

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

Code availability SAS Statistical Software (ver. 9.4, SAS Institute Inc., USA, Cary, NC). Codes are not publicly available but may be obtained from the corresponding author on reasonable request.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable

Conflict of interest The authors declare no competing interests.

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