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Fire Ecology

REVIEW

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Post-fire treatments in Mediterranean forests: a review for enhancing restoration strategies

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Abstract

Background Forests act as carbon sinks and are crucial for mitigating climate change. However, the increasing magnitude, duration, and intensity of fires threaten these ecosystems and their capacity to provide essential services, especially in the Mediterranean region. In this context, forest restoration is essential to reversing ecosystem degradation and preventing the loss of these services. A systematic review of articles on post-fire treatments in the Mediterranean region published between 1991 and 2023 in the Web of Science was conducted to evaluate the most common and effective treatments for enhancing the restoration of forest ecosystems after fires. A total of 515 articles were initially screened for relevance to post-fire treatments, resulting in the selection and evaluation of 108 studies. Ninety percent of the studies focused on natural fires, 75% were conducted in Spain, and 77% were active restorations.

Results *Pinus halepensis*, *P. pinaster*, and *P. brutia* were the most frequently burned species in the restoration studies analyzed. Most of the restoration efforts focused on promoting species regeneration and protecting soil from erosion, mainly through applying mulch. In fact, 74% of the studies considered restoring the burned area using the same species affected by the fire. The indicators used to evaluate the outcomes of the restoration activity revealed considerable heterogeneity, with nearly three-quarters of the studies focusing on physical and forest stand structure indicators. One of the main research gaps identified was the lack of long-term studies assessing the effectiveness of implemented strategies, as well as the need for more comprehensive approaches integrating both active and passive restoration initiatives. However, the temporal trend of publications related to this subject does not reflect the increase in fires observed in recent years in these areas.

Conclusion This review provides insights into post-fire restoration activities in the Mediterranean region over the past three decades and establishes a foundation for future research in other regions.

Keywords Restoration, Forest disturbances, Erosion, Degradation, Indicator, Systematic review

Resumen

Antecedentes Los bosques actúan como reservorios de carbono, y son cruciales para mitigar el cambio climático. Sin embargo, el incremento en la magnitud, duración, e intensidad de los incendios amenazan esos ecosistemas y sus capacidades para proveer de servicios esenciales, especialmente en la región del Mediterráneo. En este contexto, la restauración de los bosques es esencial para revertir la degradación de esos ecosistemas y prevenir la pérdida de los servicios ecológicos que ellos ofrecen. Una revisión sistemática de artículos sobre tratamientos post fuego publicados

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entre 1991 y 2023 en la Web of Science, fue conducido para evaluar los tratamientos más comunes y efectivos para incrementar la restauración de los bosques luego de incendios. Un total de 515 artículos fueron inicialmente examinados por su relevancia en cuanto a tratamientos en el post fuego, resultando en la selección y evaluación de 108 estudios. El 90% de los estudios se enfocaron en incendios naturales, el 75% fueron conducidos en España, y el 77% correspondieron a restauraciones activas.

Resultados Los pinos (*Pinus halepensis*, *P. pinaster* y *P. brutia)* fueron las especies más frecuentemente afectadas por los incendios en los estudios de restauración analizados. La mayor parte de los esfuerzos en la restauración fueron puestos en promover la regeneración de las especies y la protección del suelo contra la erosión, fundamentalmente aplicando una cubierta de restos orgánicos (i. e. *mulch*). De hecho, el 74% de los estudios consideraron la restauración del área quemada usando las mismas especies que fueron afectadas por los incendios. Los indicadores usados para evaluar los resultados de la actividad de restauración mostraron una considerable heterogeneidad, con cerca de tres cuartas partes de los estudios enfocados en indicadores físicos y estructurales de los rodales. Uno de los mayores déficits de las investigaciones realizadas fue la falta de estudios a largo plazo para determinar la efectividad de las estrategias implementadas, como así también la necesidad de aproximaciones más comprensivas que integren iniciativas de restauraciones tanto activas como pasivas. Desde luego, la tendencia temporal de las publicaciones relacionadas con la restauración no refleja el incremento de los incendios observados en épocas recientes en estas áreas.

Conclusión Esta revisión provee de perspectivas y conocimientos sobre las actividades de restauración en la región del Mediterráneo en las tres décadas pasadas y establece las bases para investigaciones futuras en otras regiones.

Introduction

In recent decades, there has been a notable global rise in both the frequency of wildfires and the extent of burned areas (Flannigan et al. 2009). This trend has also been documented in the Mediterranean region by Bedia et al. (2014), as well as in Spain by authors such as Moreno et al. (1998), Piñol et al. (1998), Pellegrini et al. (2021), and Carrillo-García et al. (2023). In Mediterranean countries, key drivers of this shift in fire patterns include factors such as shrub encroachment, lack of management, rural depopulation, and the reforestation of former agricultural lands with uniform tree stands (Jactel et al. 2012). These changes have led to an accumulation of fuel and continuous biomass structures, both horizontally and vertically, particularly in areas lacking adequate management. In the context of ongoing climate change, the situation is further aggravated by increasingly frequent extreme weather events (Founda and Giannakopoulos 2009; MedECC (Mediterranean Experts on Climate and environmental Change), 2020; Tolika et al. 2009), which amplify the dangers of fuel buildup and can render fires uncontrollable under certain conditions (Cumming 2001).

The impact of wildfires can be particularly severe in Mediterranean forests due to the high occurrence of fire in comparison with other areas and the unique combination of hot, dry summers followed by intense and frequent autumn rains (Lucas-Borja et al. 2018; Shakesby 2011). This seasonal pattern exacerbates changes in soil hydrology caused by the displacement of ash and soil post-fire, increasing the risk of soil fertility loss (Hosseini et al. 2018; Machado et al. 2015; Serpa et al. 2020), water contamination (Bladon et al. 2014; Santín et al. 2015; Smith et al. 2011), and disruptions to riverine ecosystem communities and functions (Erdozain et al. 2024). In addition to these characteristics, the Mediterranean basin also exhibits significant interactions between wildfires and other stressors, such as drought and pest outbreaks, which amplify the damage caused by fire and heighten the vulnerability of the entire forest ecosystem (Doblas-Miranda et al. 2017).

In this context, post-fire management strategies focus on mitigating the short-term impacts (up to 3 years after the fire occurs) of wildfires (Vieira et al. 2016) and can play a crucial role in the long-term recovery of the ecosystem (González-Romero et al. 2022). These strategies are typically classified into three categories: emergency stabilization, rehabilitation, and restoration (Robichaud et al. 2008). Emergency stabilization treatments include actions such as applying mulch to prevent soil erosion (Lucas-Borja et al. 2019), barriers, or chemical treatments (Girona-García et al. 2021). In contrast, rehabilitation and restoration initiatives are longer-term actions that often focus on the biotic components of the ecosystem. Examples include the natural recovery of plant communities, the reintroduction of species for grazing or timber production, or efforts to maintain biodiversity (Beschta et al. 2004; Hessburg and Agee 2003). The Society for Ecological Restoration (SER) defines restoration as the "process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (Society for Ecological Restoration International Science & Policy Working Group, 2004). For burned areas, the concept of rehabilitation may be more appropriate as the focus in

this case is on repairing or recovering ecosystem processes, or the provision of ecosystem services, without necessarily re-establishing the pre-existing ecosystem in terms of species composition, for instance.

In response to environmental degradation caused by human activities, restoration initiatives are developed from various perspectives with the primary goal of mitigating these impacts while promoting biodiversity and the provision of ecosystem services (Gann et al. 2019; McDonald et al. 2016). However, the approach taken depends on factors such as the target ecosystem, the specific restoration objectives, or the resources available. Some studies compared active and passive approaches for restoration actions. On one hand, active restoration involves direct interventions, such as the removal of invasive species, vegetation planting, species reintroduction, burning and/or thinning to achieve a desired structure, or soil amendments (Andersen et al. 2017; Moreira et al. 2012a, b; Rey Benayas et al. 2008, 2009). On the other hand, passive restoration refers to the cessation of land-use practices that contribute to environmental degradation, or when colonization by shrubs and trees and secondary succession take place naturally (Andersen et al. 2017; Morrison and Lindell 2011; Rey Benayas et al. 2009).

Given the growing importance of wildfires worldwide, and particularly in the Mediterranean region, we conducted a systematic review of articles from the Web of Science, published between 1991 and 2023, to analyze post-fire treatments in Mediterranean forests. The main goal of the study was to assess the existing body of knowledge on post-fire treatments and to provide insights for improving forest restoration efforts after fires. Specifically, we aimed to (i) examine the type of restoration implemented in the Mediterranean region post-fire; (ii) analyze the restoration goals outlined; (iii) identify common indicators in the evaluation of the restoration actions implemented; and (iv) identify knowledge gaps in post-fire restoration.

Methodology

Data collection

We conducted a meta-analysis of the existing scientific literature focused on the Mediterranean region in March 2024, using the Web of Science (Core collection of Web of Science). The search employed various keyword combinations, specifically: ((reforest* OR a restoration* OR reveget* OR rehabilit* OR rewilding* OR renaturaliz*) AND (post-fire* OR fire*) AND (Spain* OR Portugal* OR Italy* OR Greece* OR mediterranean*) AND (forest* OR broadleaved* OR conifer*)). The initial search yielded 532 scientific publications, with 512 selected after verifying the inclusion of the abstract and journal information. Using the "Refine Results" option, we excluded books, book chapters, proceedings, and editorial materials. The full set of abstracts was then reviewed and classified to assess their relevance based on the aim of the study, i.e., analyzing the practices employed to achieve post-fire restoration goals. Abstracts (100) in which the relationship to the aim of the study was unclear were evaluated by a second researcher. A final screening was conducted to include only studies that specifically addressed post-fire restoration activities, resulting in a total of 108 relevant papers selected for further analysis and information extraction (Table S3, https://doi.org/10.20350/digitalCSIC/17542). A PRISMA diagram (Page et al. 2021) of the identification and screening process can be found in the Supplementary material (Table S1).

Categorization of papers

The set of 108 selected papers was examined further to extract information about the post-fire activities in restoration projects, including detailed attributes such as country, year and type of fire, recurrence, or species burned (Table 1).

Results

General description of the dataset

The dataset revealed a strong geographic bias (Fig. 1A) in both the number of articles and the recurrence of fire in the studies. The inclusion of the keyword "Mediterranean" in the search resulted in the retrieval of studies from Turkey, France, and Lebanon, despite these countries not being directly specified as a keyword. Nearly 79% of the 108 articles reviewed focused on the Iberian Peninsula, with 68% based in Spain and 11% in Portugal. Other countries represented in the dataset, in decreasing order of appearance, were Greece, Italy, Turkey, France, and Lebanon (10%, 6%, 2%, 2%, and 1%, respectively). The easternmost countries (Turkey and Lebanon) presented only one type of response when analyzing the recurrence of fires. In contrast, the other studied countries displayed varying percentages, ranging from 25% of recurrent fires to 75% of non-recurrent fires in Greece, Spain, and Portugal, to the equal distribution of recurrent and non-recurrent fires in France. In the case of Italy, the percentage of studies where recurrent fires were analyzed was close to 50%.

The analysis of the compiled studies clearly showed that natural fires have been the type most studied in the Mediterranean area in recent years, accounting for 90% of the articles. In contrast, experimental fires made up 2%, while prescribed fires represented 8% (Fig. 1B). Experimental and prescribed fires showed the same distribution of studies in terms of fire intensity (Fig. 1C). In both cases, high- and low-intensity fires each accounted

Table 1 Descriptors, parameters, and levels used to categorize the studies

Descriptors of the study	Level
Country	Country
Type of fire	Wildfire (produced by natural phenomena such as lightning), experimental, prescribed
Intensity	According to the definition in each paper studied. High, moderate to high, moderate, low, irregular
Recurrence	Yes (there has been more than one fire in the area), no (only one fire in the area)
Fire frequency	Number of fires occurring up until the study
Fire date	Years when the fire occurred
Species burned	Type and scientific name of the burned tree species
Type of restoration	Active and passive (defined in the Introduction section)
Objective of the restoration action	According to that proposed by Menéndez-Miguélez et al. (2024, 2025) (Table S2)
Restoration date	Months between the fire and the initiation of activities in the area
Activity in burned vegetation	Type of activity implemented to the vegetation of the burned area. No intervention, cleaning, grazing, partial cut, partial cut plus lopping, salvage logging, burnt treatment
Restoration activity	Activity implemented to restore the burned area. No intervention, fencing, infrastructure, natural regeneration, seeding, planting, mulching, geotextile, chemical soil amendment, organic soil amendment, soil tillage, watering, seed predation experiment
Species	Species planted/seeded or naturally regenerated after the fire event
Indicator	Indicators utilized to evaluate the outcomes of the restoration efforts. Classified into six groups (de Oliveira et al. 2021): physical and structural, composition/biodiversity, environmental services, ecological processes, economic, social*

*de Oliveira et al. (2021) classified the indicators in six groups as follows: "'physical' indicators focus on removing degradation factors and repairing the physical and/or chemical environment. Indicators in 'structural' category are related to forest structure, those in 'composition/biodiversity' category are related to richness or composition and to the presence or absence of distinct functional groups, and those in 'ecological processes' refer to ecosystem functionality (or dynamics)"

for 50% of the studies analyzed. In the case of natural fires, the percentage of high-intensity fires was almost the same as in the above cases (51%), while the rest corresponded, in decreasing order, to fires of moderate to high intensity (25%), moderate (12%), low (8%), low to moderate (2%), and irregular (2%).

The timeline of published studies in the Mediterranean area presented a completely different pattern depending on the country. Spain showed a steady and consistent growth in publications since 1970, the year in which the first article included in this review was published (Fig. 2A). However, the other countries presented occasional spikes in the number of publications in certain years throughout the period, although never reaching even a third of the number of publications dealing with Spain. In 1994, the number of publications increased in France, Italy, and Greece. Similarly, between 2002 and 2004, there was a significant rise in publications in Greece, Portugal, and Italy, with a more modest increase in Turkey (Fig. 2B).

The analysis of the most frequently reported burned tree species revealed distinct species groupings depending on the country (Fig. 3). Only France, Portugal, and Italy reported *Quercus* species among them, with France giving particular importance to *Q. coccifera* L., *Q. pubescens* Mill., and *Q. ilex* L., each accounting for an equal percentage. In Italy, the percentages were as follows: 50% *Quercus* and 50% *Pinus*, with equal representation of *Q. ilex*, *Q. pubescens*, and *P. pinaster* Ait., while the highest percentage of burned species corresponded to *P. sylvestris* L. In Portugal, studies mostly focused on *P. pinaster*, with *Q. suber* L. being less represented. In the case of Spain, the most frequently reported burned tree species were consistently pines, particularly *P. halepensis* Mill. In both Turkey and Lebanon, studies concentrated on a single species, *P. brutia*.

Post-fire interventions in affected areas and vegetation cover

Half of the studies analyzed made no mention of post-fire intervention either in the burned area or the affected (represented by blue dots, Fig. 4). This lack of intervention was particularly notable in studies from France and Lebanon. In Greece, Italy, Portugal, and Turkey, a binary approach was observed, with percentages varying between no intervention and the extraction of burned wood through salvage logging. Spain was the only country where all possible post-fire activities were considered in the analyzed studies, ranging from different treatments for the burned species, additional post-fire treatments, mechanical clearings, to the use of animals for grazing the area (Fig. 4).

Type of restoration and restoration goals

Once the decision to restore the burned areas had been made, three-quarters of the studies (74%) reported the

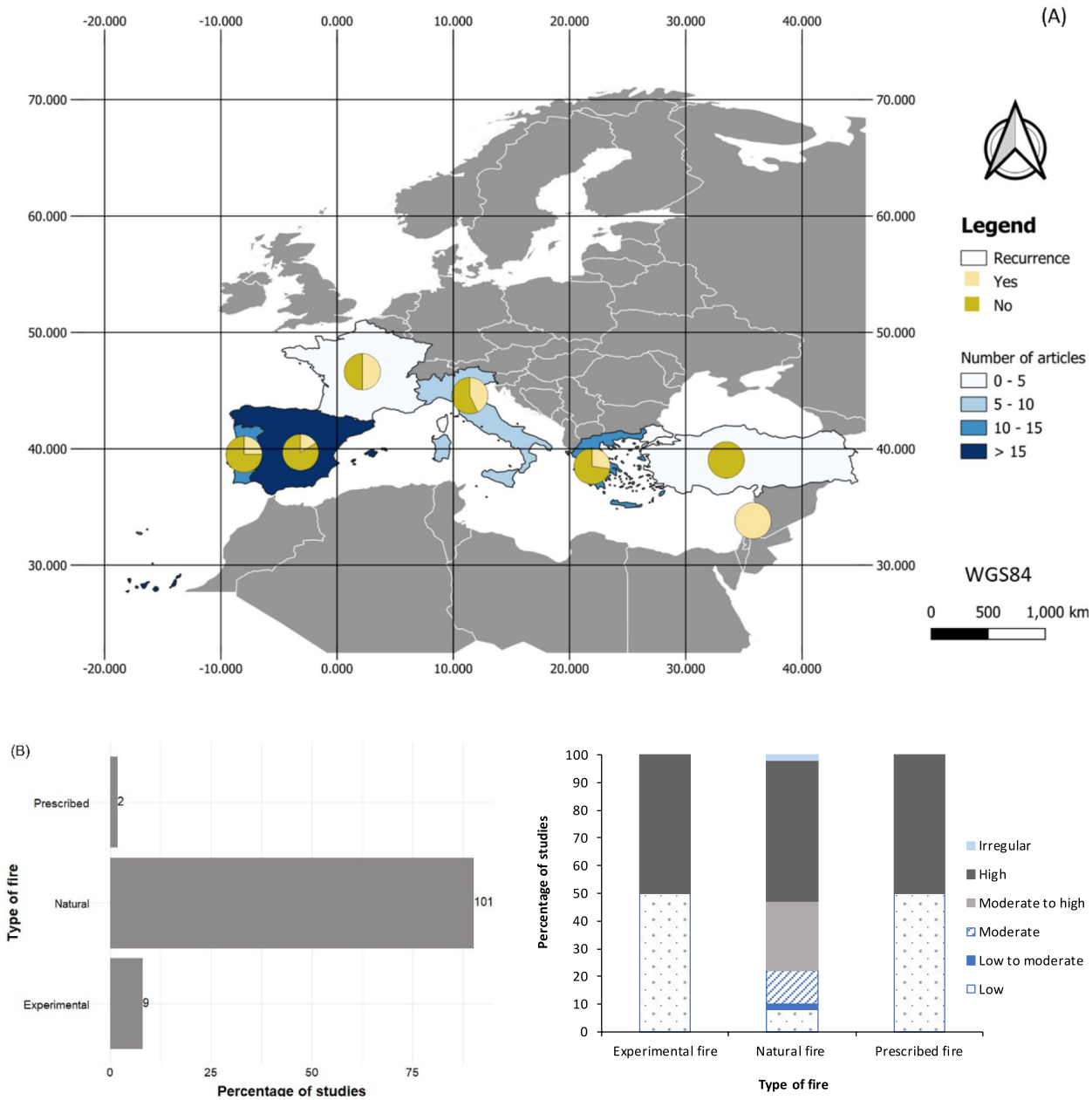


Fig. 1 Global overview of the dataset. **A** Map: displays the number of articles by Mediterranean countries (blue) and highlights whether the studied fires are recurrent (light yellow) or not (dark yellow); **B** fire types: shows the distribution of the different fire types (prescribed, natural, or experimental) across the selected studies. Numbers next to each bar correspond to the exact number of studies for each option; and **C** fire intensity: compares fire intensity across various fire types

implementation of active restoration, while a quarter (25%) reported passive restoration. In the remaining 1% of studies, both approaches were reported to have been implemented, designating different areas for each type of action. Among the 22 possible restoration objectives considered, the studies analyzed in this review revealed that post-fire restoration initiatives primarily focused on *improving* (23% of the studies) and *protecting* (21% of the studies) *soil*, as well as *promoting plant/tree regeneration* (21% of the studies) (Fig. 5). The next most common objectives were *changing species composition* and *increasing ecosystem resilience*, each represented in nearly 7% of the studies. Notably, among the 108 studies compiled, none addressed the other eight proposed restoration objectives after fire occurrence in their areas (*Promote habitats of interest*, *Water quality*, *Increase*

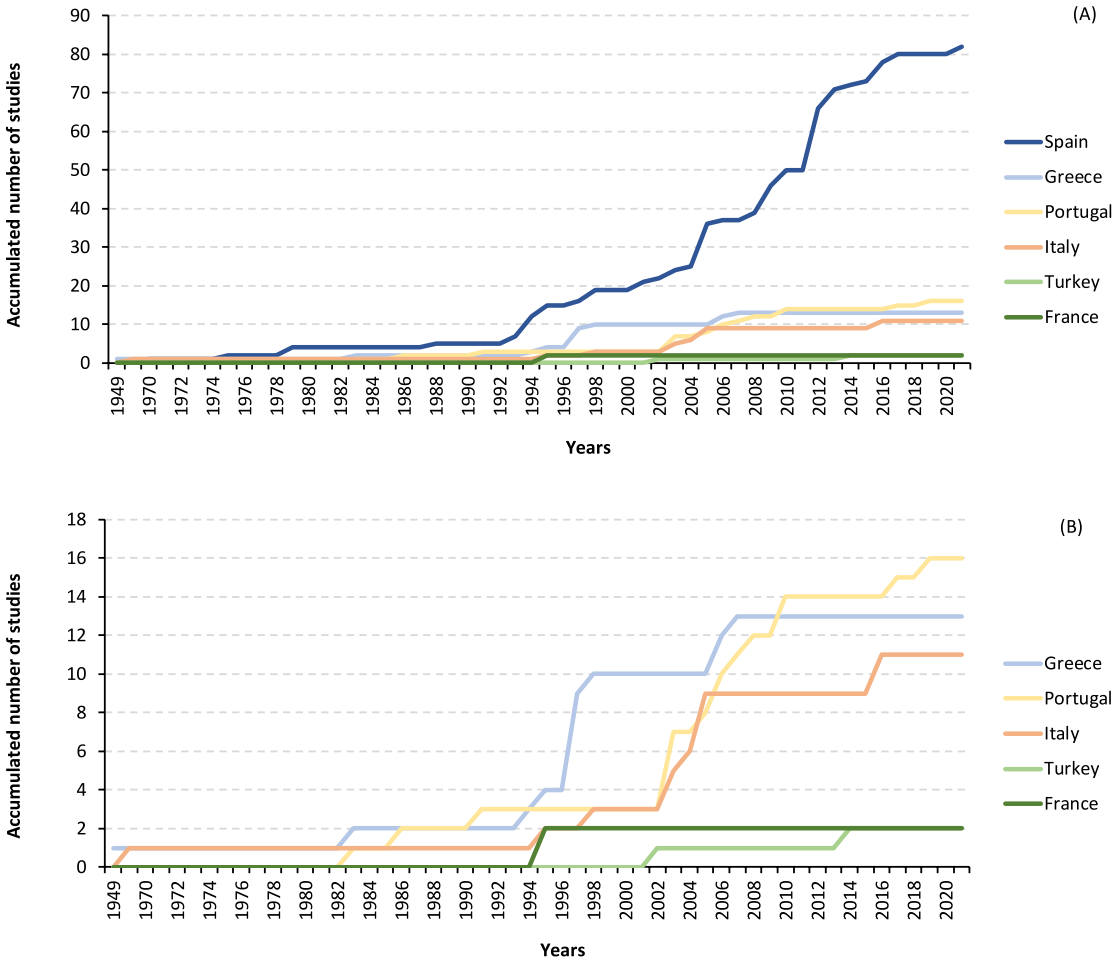


Fig. 2 Timeline of fire occurrences in Mediterranean countries based on the reviewed studies (**A**). Zooming in on the details (**B**), the timeline shows Greece in blue, Portugal in yellow, Italy in orange, Turkey in light green, and France in dark green

landscape connectivity, *CO_2 capture*, *Improve provision of non-timber products*, *Pollution mitigation*, *Local climate regulation*, and *Human health & wellbeing*).

Restoration activities

All countries, except Portugal, which focused primarily on *erosion protection* (28% of studies), concentrated their post-fire restoration efforts on *vegetation-related activities*, with 50% in France, 57% in Greece, 75% in Italy and Turkey, 100% in Lebanon, and 42% in Spain (Fig. 6). These activities included planting, seeding, and promoting natural regeneration. In contrast, *erosion protection* initiatives (28% of studies in Portugal and 24% in Spain) involved actively preventing erosion through the application of mulch or the placement of geotextiles. Among the group of post-fire activities categorized as *infrastructure*, the studies showed decreasing percentages in Greece (36%), Portugal (22%), Italy (13%), and Spain (12%). This category includes actions such as fencing, log barriers, check dams, and contour felled log debris. In France, restoration efforts after a fire were evenly divided between *vegetation-related activities* and *soil-focused actions*. The latter includes activities such as chemical or organic soil amendment, soil tillage, and watering. Under the *other* type of activities (1%), we identified one study located in Spain which focused on a seed predation experiment in the post-fire area. Five of the seven countries studied considered not undertaking any restoration activity to rehabilitate the burned area. These percentages were observed in Turkey (25%), Spain (17%), Italy (13%), Portugal (11%), and Greece (7%).

A more detailed analysis of studies focusing on vegetation-based restoration activities found that only 26% opted to introduce species for restoration which were different from those present prior to the fire, all of these studies corresponding to plantations in Greece (Fig. 7). In contrast, nearly three-quarters (74%) proposed restoration initiatives using the same species that

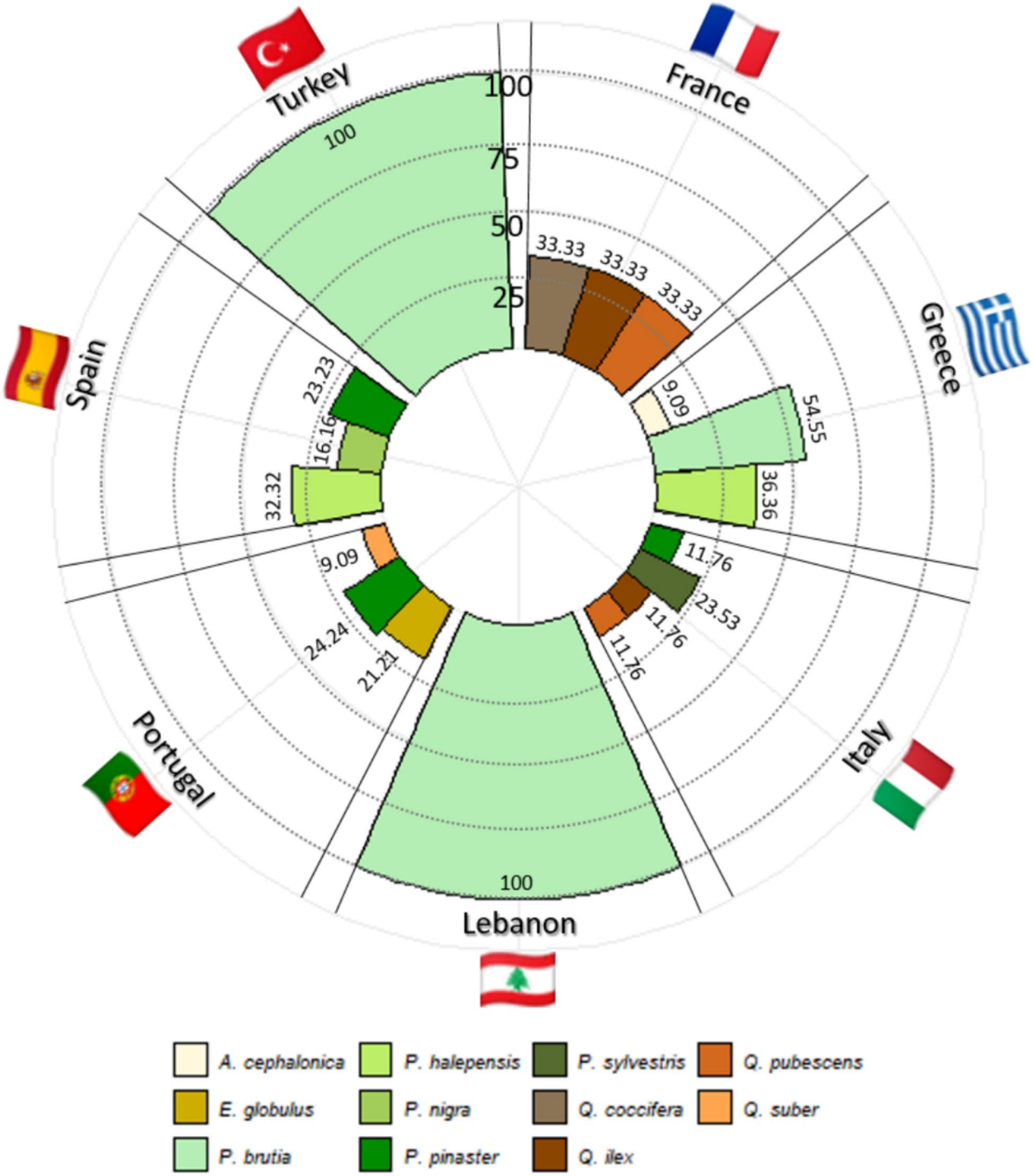


Fig. 3 Distribution of the most frequently reported burned tree species by country in the studies analyzed. Numbers shown represent the percentage (%) of each species in each country

had been affected by fire. Among these studies, all the post-fire activities implemented in France and Lebanon focused solely on natural regeneration. In Portugal, restoration efforts were evenly split, with 50% of activities dedicated to planting trees and 50% to natural regeneration. Meanwhile, Greece, Italy, Spain, and Turkey employed a combination of the three restoration activities, each in varying proportions. In all these countries

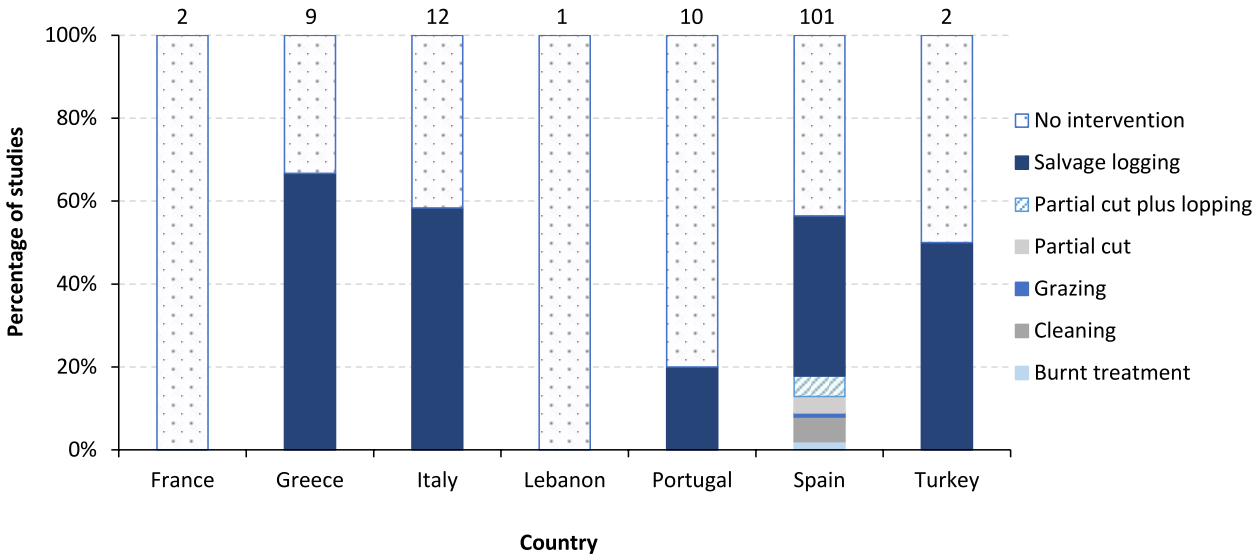


Fig. 4 Distribution of post-fire activities targeting burned areas or vegetation by country. Numbers appearing above each bar correspond to the exact number of cases of each category. The sum of cases (137) exceeds the number of studies analyzed (108) because some studies suggested various post-fire activities

except Turkey, natural regeneration was notably favored over the other two types of restoration activity.

Indicators

This review identified 87 indicators used to evaluate post-fire restoration activities in Mediterranean areas. Nearly all studies (99%) included at least one of these indicators in their assessments. The frequency of each indicator, categorized into six groups proposed by de Oliveira et al. (2021), is presented in Table S1 (Supplementary material). Notably, half of the studies used indicators from only one category.

The analysis revealed significant variation in the indicators used across different countries to assess the success of post-fire restoration (Fig. 8). Studies in France and Lebanon primarily relied on physical and structural indicators (considering the small sample of studies from these countries). Similarly, research conducted in Turkey emphasized these physical and structural indicators, which made up 88% of the metrics used, while incorporating a modest proportion (13%) of composition/diversity indicators to further inform their evaluations. The widest variety of indicator types was observed in post-fire studies conducted in Spain. Notably, none of the studies from any of the countries used social indicators to evaluate restoration success.

Discussion

This review of the literature on post-fire restoration activities implemented in Mediterranean areas revealed variability with regard to how different countries address the loss of ecosystem services following fire disturbances. Although ecosystem services were not a specific focus of this review, they provide a useful framework to interpret the ecological consequences of fire and the management responses identified in the analyzed studies. This variation is evident both immediately after the fire in the actions taken to manage the burned vegetation, and in the overall objectives set for restoration efforts. The results obtained contribute to enhancing current knowledge about post-fire restoration efforts in the Mediterranean region in recent years, with insights into aspects such as the type of fire, the main objectives set, the activities implemented to carry out this restoration, and the type of indicators used to evaluate restoration outcomes. The systematic review of scientific studies has provided partial answers to the objectives outlined in this work. However, one of the main challenges in literature reviews is to accommodate the wide variability of existing studies. On one hand, much of the material falls under non-scientific or gray literature, including publications in outreach and technical journals at the national level, conference presentations, and findings from small-scale field projects, as noted by authors such as Mariotti et al. (2023). Approaches like the one by Erdozain et al. (2024) provide complementary information that enhances our understanding of the true value of European forest restoration efforts. While these approaches alone do not offer a comprehensive overview, together they help advance an integrated understanding of forest restoration in Europe. On the other hand, the combination of

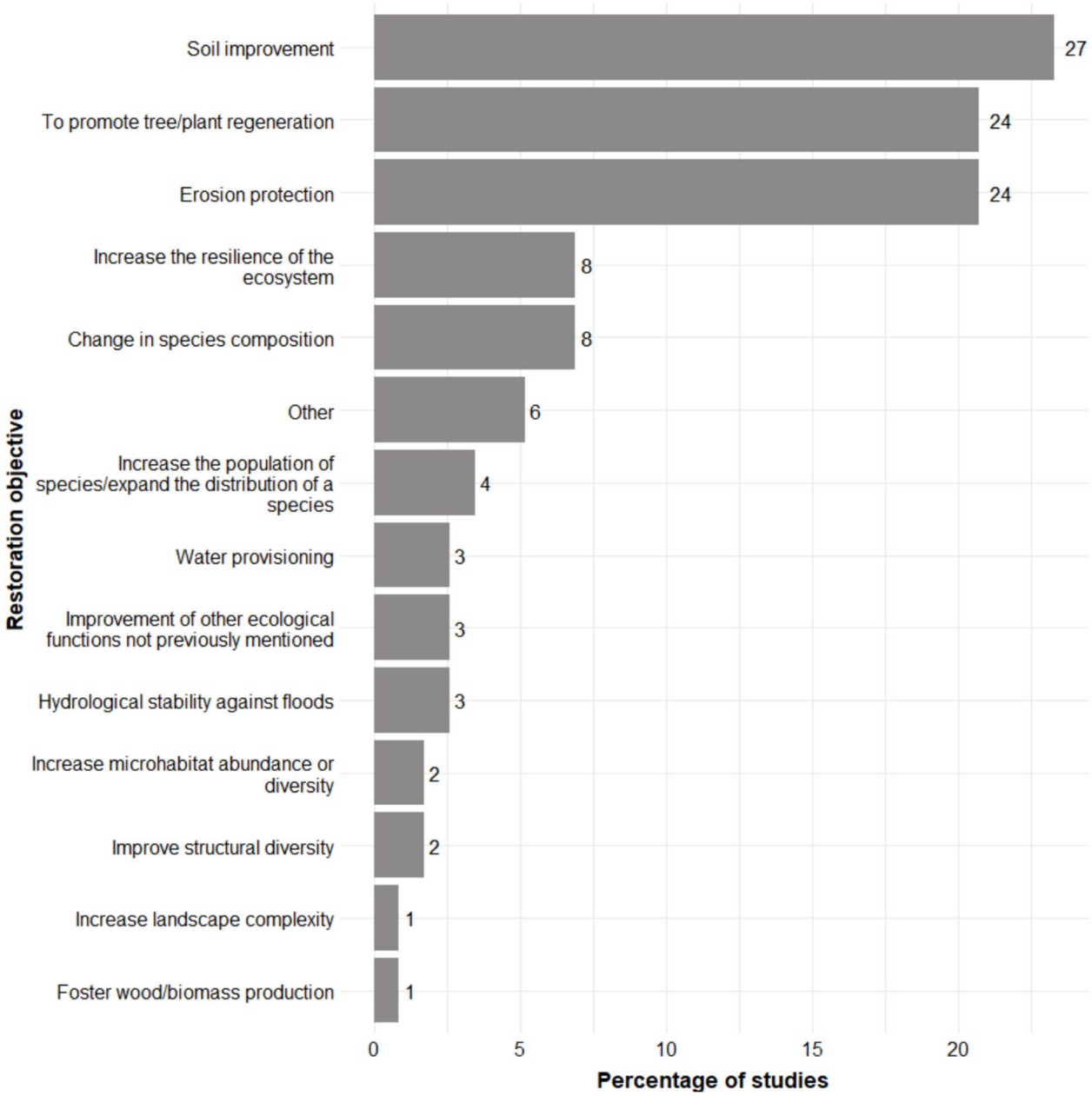


Fig. 5 Distribution of the studies according to the restoration objective. Numbers next to each bar correspond to the exact number of studies for each option

keywords used in the search may have influenced the final list of studies retrieved.

Building on these findings from the literature, it is essential to consider the environmental context in which restoration efforts take place, with special attention to the fire-driven dynamics typical of the Mediterranean region. Mediterranean ecosystems exhibit a landscape dynamic primarily shaped by fires (Bond et al. 2005; Keeley et al. 2011), and fire regimes are currently one of the aspects most impacted by climate change (Dupuy et al. 2020; Jolly et al. 2015). Moreover, the adverse climatic conditions could promote fire regime changes, leading to even more frequent severe fires over a longer fire season (Amatulli et al. 2013; Pérez-Fernández et al. 2016). The timeline of fire occurrences in the Mediterranean countries we analyzed in this review reflects this upward trend over the study period (1949–2021), which likely results from a combination of biophysical drivers—such

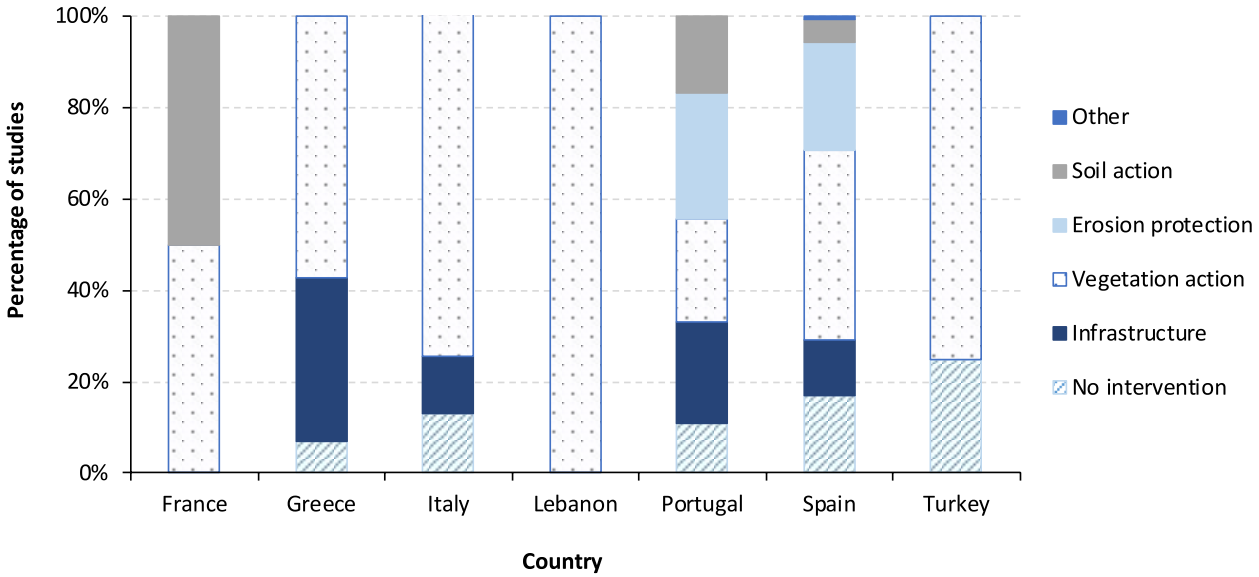


Fig. 6 Distribution of post-fire restoration activities by country

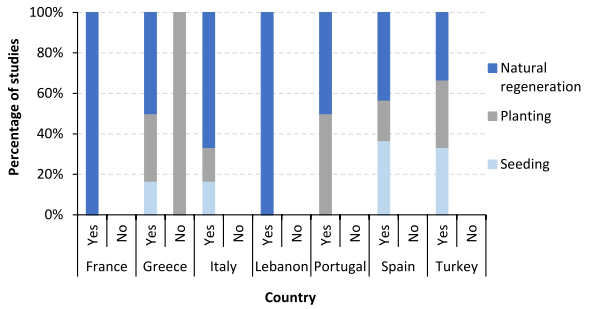


Fig. 7 Distribution of post-fire plant establishment methods by country. The yes/no on the x axis indicates whether the species used was the same as the pre-fire one

as climate and land-use change—and socio-institutional factors, including increased research capacity and greater awareness of fire-related issues. However, the number of fires recorded in the various countries was not always reflected in research papers focused on post-fire restoration studies, and more specifically focused on restoration activities. A clear example of that was all the reforestations implemented in the Landes de Gascogne (France) between 1941 and 1949 after 500,000 ha were destroyed by wildfires (Gadant 1987), with no publications found for this period. Our analysis of the European Forest Fire Information System (EFFIS) data for the period 2006–2024 (last consulted 04-03–2025) identified Portugal as the country with the largest burned area (exceeding 1,800,000 ha), followed closely by Spain (over 1,500,000 ha), and then by Italy, Greece, Turkey, France, and Lebanon in decreasing order of burned area. However, our review found that post-fire restoration studies are primarily being conducted in Spain, with the accumulated number of studies by 2021 quadrupling those in Portugal, Italy, or Greece. France and Turkey displayed a similar trend in the number of post-fire restoration studies. In the case of Lebanon, only one study was identified, with no information provided on the year of the fire, making it impossible to establish a correlation with the burned area. Most of the analyzed countries, with the exception of the eastern ones (Turkey and Lebanon), presented a combination of recurrent and non-recurrent fires in their studies, with a greater or lesser percentage between them. Although the burned area exhibited large interannual oscillations within each country (EFFIS website, last consulted 04-03–2025), the significance of wildfires remained high throughout the study period, as reflected by the main focus of all the studies on natural fires. In fact, the increase in high-intensity fires occurring in recent years was clearly observed for all the types of fire we classified (natural, experimental, and prescribed fires) in this review, based on the data reported in the published studies.

In the Mediterranean region, *P. pinaster* and *P. halepensis*, along with *P. brutia*, are three of the most frequently reported fire-affected forest species (Pausas et al. 2008). These pine species are of significant ecological and economic importance in the Mediterranean region. *P. brutia* is especially important for the eastern Mediterranean rim (Panetsos 1981; Nahal 1984), where it is intensively utilized for timber production, especially in Turkey (Ministry of Environment and Forestry of Turkey 2010), one

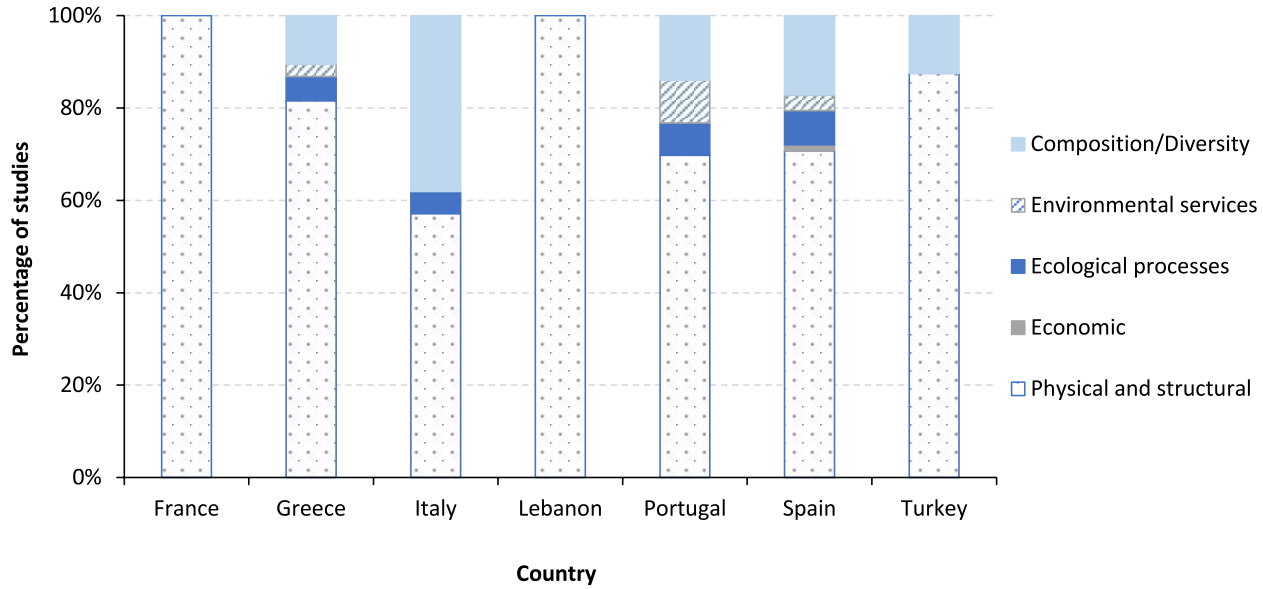


Fig. 8 Distribution of the categories established for the indicators by country

of the leading Mediterranean countries in reforestation (Pausas et al. 2008). *P. pinaster*, a fast-growing species originating from the western Mediterranean basin, has been widely used in reforestations, expanding its distribution area throughout the twentieth century (Castro et al. 2011; Ramón Vallejo et al. 2012; Richardson 2000; Tapias et al. 2004). *P. halepensis* is the most widely distributed and abundant among Mediterranean pines (Lucas-Borja et al. 2020; Richardson 2000; Tapias et al. 2004). These species are highly flammable (Fernandes et al. 2008) and dominate forest ecosystems in many areas, often with a continuous and dense woody understory layer (up to 1.5 m height) (Fernández-García et al. 2019). This creates fuel profiles that facilitate the occurrence of crown fires, leading to high mortality rates (Calvo et al. 2008; Daskalakou and Thanos 2004). However, the advantage of these species is that they are well-adapted to natural regeneration after fire (Ne'eman 1997; Tavşanoğlu and Gürkan 2009; Thanos et al. 2000), with mechanisms for natural reforestation (Sapountzis et al. 2007; Spanos et al. 2001, 2000; Thanos and Marcou 1989), such as high cone production due to their highly serotinous nature (Ramón Vallejo et al. 2012; Tapias et al. 2001) or soil seed banks (Lucas-Borja et al. 2020; Vega et al. 2010). Despite their adaptation to certain fire regimes, serotinous pine forests currently face challenges (Pausas et al. 2008). Given the situation described above, it is not surprising that natural regeneration was found to be the most widely used post-fire revegetation method. This can be largely attributed to its low cost, which makes it a particularly accessible option in many contexts. The identification of distinct species grouping based on country provides valuable insights into the regional ecological variations and fire impacts within the Mediterranean basin. Understanding these patterns is crucial for tailoring post-fire restoration and management strategies to the specific ecological contexts of each country, rather than applying generalized approaches. Furthermore, this result lays the groundwork for future research aimed at exploring how species composition influences ecosystem recovery trajectories and resilience after fire events. By recognizing the predominant burned species in different regions, restoration efforts can be more effectively designed to promote native species regeneration, maintain biodiversity, and enhance ecosystem function. In addition, this identification helps to know the vulnerability and high-risk forest types. This can be extremely helpful for forest planning (zoning) and fire prevention even supporting forest management policies. By knowing this frequently burned species, a transition to more fire-resilient landscapes can be designed and could even be used for prevention and considered in forest fire indices. Ultimately, this knowledge contributes to developing more targeted, efficient, and ecologically appropriate restoration interventions adapted to the unique conditions of each Mediterranean country. However, it is also important to note that the results obtained in this study were entirely dependent on the specific keyword combination used in the Web of Science database. As a result, certain species, ecosystems, or countries may not be represented among the compiled studies. This possible absence does not imply that they are less affected by fire or that post-fire restoration

activities are lacking in those particular contexts. This limitation highlights the need for further data collection and collaboration across regions to build a more comprehensive understanding of post-fire species dynamics.

Post-fire interventions

No clear trend was observed as regards the implementation of actions to the burned vegetation, although half of the studies compiled reported an absence of intervention in the affected vegetation or the burned area. Authors such as Marañón-Jiménez et al. (2013), Marzano et al. (2013), and Marcolin et al. (2019) attributed this lack of action to the beneficial sheltering effect provided by deadwood, which can protect seedlings from high transpiration rates, solar radiation, and elevated temperatures. Similarly, Castro et al. (2012) focused on the impact of salvage logging on the natural recruitment of new oak individuals. In some cases, Puerta-Piñero et al. (2010) and Leverkus and Castro (2017) reported the absence of intervention, emphasizing the role of acorn predation and the identification of seed predators as limiting factors for regeneration. Conversely, other authors considered salvage logging to be a critical post-fire activity for several reasons: its potential to reverse successional processes and alter recovery trajectories (Lingua et al. 2023); the physical barriers posed by felled logs and collapsed branches to post-fire forestry operations (Leverkus et al. 2012); the reduction in habitat suitability for acorn dispersers and consumers due to the collapse of standing snags (Leverkus et al. 2016); the potential for lowering restoration costs and even increasing reforestation success (Leverkus et al. 2012); and the absence of significant long-term effects on soil properties (Puig-Gironès et al. 2023). The lack of consensus regarding the benefits or drawbacks of interventions on burned vegetation appears to stem largely from the complexity of ecosystem dynamics, which require a holistic perspective rather than an assessment based on isolated factors. In this context, Pereira et al. (2018) highlighted that human intervention and the way areas affected by high-severity fires are managed play a crucial role in determining whether such events lead to an increase or a decrease in soil degradation. This view is further supported by Myronidis et al. (2010), who emphasized the importance of integrated approaches when evaluating the success of erosion control measures. A good example of such an approach is the study by Fernández and Vega (2016), who combined restoration activities, immediate post-fire salvage logging, and mulch application to reduce potential soil losses under rainy climatic conditions in NW Spain.

Type of restoration and restoration goals

Meli et al. (2017), in their literature review, noted significant variability in the recovery rates of areas subjected to active and passive restoration. They were unable to conclude that active restoration consistently achieved better or faster recovery than passive approaches, even where studies examined both methods at the same location. Other authors, such as Moreira et al. (2009), argue that passive restoration is an appropriate approach when ecosystem structure or functional damage is limited, and resilience is high. In this study, a clear preference for active over passive restoration was observed when comparing the number of studies focused on each type, with 74% favoring active restoration and 25% passive restoration in post-fire interventions across the evaluated Mediterranean countries. Additionally, studies incorporating a combination of active and passive restoration approaches were also analyzed. For instance, Marcolin et al. (2019) described a mixed approach combining salvage logging in some areas compared with natural regeneration in others. However, an important factor to consider is that the choice between active and passive restoration hinges on the specific species affected by the fire. Certain species that can regenerate from seeds (Pausas 2004) or regrow from tree sprout shrubs or herbaceous plants are more closely associated with passive restoration than active approaches (Moreira et al. 2012a, b).

Restoration activities

The disturbances caused by fire in ecosystems alter biogeochemical cycles and affect water quality, hydrological and geomorphological processes, vegetation, soil, fauna, and even the atmospheric composition (Shakesby and Doerr 2006). This wide range of post-fire impacts is reflected in the diversity of post-fire restoration activities observed in the analyzed studies, with different initiatives focusing on various ecosystem components. Despite the significant damage to soils following fires, none of the studies conducted in Greece, Italy, Lebanon, or Turkey investigated actions directly targeting soil recovery. These can include measures such as soil amendments or tillage, or protective action against erosion through mulch application or geotextile installation. In fact, soil erosion protection measures were exclusively documented in studies carried out in Spain and Portugal. Among these, more studies focused on the application of different types of mulch (e.g., Carmona-Yáñez et al. 2023; Fernández 2021; Santana et al. 2018) than on employing geotextile (Comez-Rey et al. 2013; González-Pelayo et al. 2023; Zema et al. 2020).

Among the post-fire activities classified as infrastructure, only one study conducted in Portugal (Silva et al. 2015) explored the use of fencing to evaluate plant

recovery after a fire. Analysis of the reviewed studies revealed that most post-fire infrastructure activities primarily involve the construction of physical barriers. These barriers are often made using trunks and branches from trees burned in the fire and aim to address several objectives: reducing surface runoff (Albert-Belda et al. 2019), mitigating erosion (González-Romero et al. 2022), controlling sediment transport (Basso et al. 2022; González-Romero et al. 2022), and promoting sediment accumulation to minimize loss of soil organic matter (Elena Gómez-Sánchez et al. 2023; González-Romero et al. 2018; Myronidis et al. 2010).

Finally, the group of studies focused on "vegetation-related activities" proved to be the largest, encompassing all possible post-fire restoration efforts observed across the seven countries included in the literature review, to varying extents. All the evaluated Mediterranean countries featured at least one study addressing natural regeneration following fires. The species studied varied significantly: in Spain, they included *Pinus canariensis* Chr. Sm. ex DC, *P. pinaster* subsp. mesogeensis Ait., *P. halepensis*, and *P. nigra* J.F. Arnold (Arevalo et al. 2014; Arévalo et al. 2001; Fuentes et al. 2018; Leverkus et al. 2016; Taboada et al. 2018, 2017). In Portugal, the focus was on *Quercus coccifera*, *P. pinaster*, and *P. sylvestris* (Meira-Neto et al. 2011; Proença et al. 2010). In Lebanon, studies examined included *P. brutia* (Halabi et al. 2014), while in Greece, they concentrated on *P. halepensis* (Goudelis et al. 2007). In Italy, a broader range of species was studied, including *P. sylvestris*, *P. halepensis*, *P. pinea*, *Q. ilex*, *Q. pubescens*, and *Q. cerris* (Lingua et al. 2023; Marcolin et al. 2019; Marzano et al. 2013; Spatola et al. 2023). In France, the primary focus was on *Q. pubescens* (Larchevêque et al. 2008).

The use of planting or seeding as a vegetation restoration approach for burned areas was not reported in any of the studies from France or Lebanon. In contrast, both methods were considered in varying proportions in the remaining countries, typically to reintroduce the same species that had been lost in the fire. Only studies conducted in Greece and Spain explored the option of reintroducing species different from those affected by the fire. The choice between planting and seeding often depends on cost and ecological impact, and studies comparing the two approaches are relatively rare (Espelta et al. 2003). For instance, Castro et al. (2011) proposed seeding to address post-fire water deficits for seeds, leveraging facilitation processes such as reduced solar radiation and increased soil moisture by leaving branches in situ and dispersing seeds in these areas. However, research by Alloza and Vallejo (2006), Baeza et al. (1991), and Vallejo et al. (2000) highlighted the challenges of transplantation in Mediterranean environments. These include post-transplant shock due to severe drought and water stress, resulting in higher plant mortality rates and difficulty establishing the root system. Additionally, studies have reported lower success rates for *P. nigra* plantations in Mediterranean climates compared to temperate or boreal forests (Archibold et al. 2000; Gemmel et al. 1996; Graham et al. 1989). The findings from the different studies and the differences referred to meant that no clear geographical or species-specific patterns emerged in the reviewed literature to categorize the use of planting or seeding as a restoration strategy for burned areas.

Indicators

Once the restoration initiative has been implemented, evaluating the success or failure of the ecosystem based on any given indicator often presents significant challenges. The review of the compiled post-fire studies revealed considerable heterogeneity in the indicators used for restoration initiatives, as reflected by the findings of Menéndez-Miguélez et al. (2024) in their review of success and failure indicators in European forest restoration. Among the categories of indicators established in this study, we observed that nearly three-quarters (72%) focused on physical and structural indicators, as also reported by Erdozain et al. (2024) for stream ecosystems post-fire. This may be due to the ease of measuring or quantifying aspects such as survival (Ioannidis et al. 2021; Lucas-Borja et al. 2021; Pizarro-Tobías et al. 2015), pH (Barreiro et al. 2016; Fontúrbel et al. 2012; Gómez-Rey and González-Prieto 2014), bulk density (Albert-Belda et al. 2019; González-Romero et al. 2018; Kucuk and Kahveci 2020), or solar radiation (Marcolin et al. 2019). However, it is noteworthy that few studies considered indicators within the economic (1%) (Espelta et al. 2003; Leverkus and Castro 2017; Puerta-Piñero et al. 2012) or social (0%) categories, despite the significant impact that post-fire activities have on the surrounding population and economy. Authors such as Bernhardt et al. (2007), Burton and Ellen Macdonald (2011), and Murcia et al. (2016) highlight the lack of quantification of the number of projects that define measurable objectives with their corresponding indicators, or that directly measure these indicators. However, all the studies compiled in this review assessed, to varying degrees, the success of post-fire restoration using one or more indicators. In many cases, these studies followed a holistic approach, considering multiple aspects of restoration and employing more than one indicator.

Conclusions

The systematic review of the scientific literature reveals that most post-fire restoration studies in the Mediterranean region focus on active restoration approaches,

with Spain standing out as the country with the highest scientific output in this field. However, no clear relationship was found between the number of scientific publications and the magnitude of fires in terms of frequency and affected area in the Mediterranean countries. Importantly, fire frequency data are relative—they depend on the publication date and the baseline year considered by each author—and therefore these values are not directly comparable across studies. This discrepancy could be attributed to several factors: (i) many restoration initiatives are not documented or published as scientific articles; (ii) research, and consequently scientific publications, are not always reactive to fire events due to limitations in time, funding, or available researchers; (iii) countries with frequent and larger fires (e.g., some Eastern Mediterranean countries) may lack the necessary resources or infrastructures for scientific output; and (iv) some countries may produce scientific work primarily in local languages or publish in non-indexed journals, leading to an underrepresentation in international databases.

Despite this uncertainty, the results of the review have provided valuable insights into the progress and limitations of post-fire treatments implemented to date, as well as identifying areas that require further research. One of the key aspects for which information is lacking regards long-term studies evaluating the effectiveness of the strategies applied, highlighting the need for more approaches that combine both active and passive restoration initiatives, tailored to varying ecological and socio-economic aspects.

Another critical issue relates to the economic drivers behind the selection of restoration strategies. The review raises important questions regarding the rationale for implementing certain techniques in some countries but not in others. Are these decisions driven by economic constraints, policy frameworks, or simply by traditional practices? Understanding the economic underpinnings of restoration choices—including whether cost-effectiveness drives the preference for passive over active restoration—represents a crucial avenue for future research.

The indicators used to evaluate the outcomes following the restoration activity revealed considerable heterogeneity, with nearly three-quarters of the studies focusing on physical and structural indicators. This lack of consistency hinders cross-study comparisons and limits the generalization of results. Therefore, there is a pressing need to develop and adopt an agreed multidisciplinary set of indicators—clearly defined and aligned with the overarching objectives of post-fire restoration—to facilitate consistent evaluation across regions and studies.

Overall, this study provides a structured overview of the current state of post-fire restoration research in the Mediterranean and establishes a foundation for future collaborative efforts. The comparative analysis of documented experiences from different countries enables the identification of common challenges and the extraction of transferable lessons. Such a coordinated and regionally adapted approach could lead to the development of more efficient, evidence-based restoration strategies that not only address immediate post-fire impacts but also enhance long-term ecosystem resilience in the face of climate change and increasing fire frequency.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-025-00430-y.

Supplementary Material 1: Figure S1. PRISMA diagram of paper identification and screening process.

Supplementary Material 2: Table S1. Frequency of the indicators identified in the analyzed studies and classified into the six categories proposed by de Oliveira et al. (2021).

Supplementary Material 3: Table S2. Ecological attributes considered and the categorization of the objectives proposed by Menéndez-Miguélez et al. (2024, 2025).

Supplementary Material 4: Table S3. List of the 108 references compiled in the Web of Science for the meta-analysis with the corresponding authors, publication year, title, journal, volume, and doi (https://doi.org/10.20350/digitalCSIC/17542) González-Romero et al. (2021).

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Authors' contributions
M.M.M. (corresponding author): Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. I.C.: Writing – review & editing, Funding acquisition, Conceptualization. M.E.: Writing – review & editing. S.de-M.: Writing – review & editing. I.A.: Writing – review & editing, Conceptualization.

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Data availability
The table listing all references used in the manuscript, it has now been included in the manuscript as new supplementary material (Supplementary material 4, Table S3). It is also available through the institutional open access repository, Digital CSIC (https://doi.org/10.20350/digitalCSIC/17542).

Declarations

Competing interests
The authors declare no competing interests.

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