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Winners and losers: post-fire European forest taxa abundance meta-analysis

Gemma Gerber[1*], Martin Jung[1] and Piero Visconti[1]

Abstract

Background Climate change is intensifying wildfire regimes across European forests, creating urgent management challenges. Fire acts as a powerful selective filter with highly variable, context-dependent effects. Yet taxonomically comprehensive syntheses quantifying fire impacts on abundance across European forests remain limited. Regional synthesis is needed for informing management and conservation planning, because European forests have distinctive ecological characteristics and management histories compared to more extensively studied fire-prone ecosystems.

Results We conducted a PRISMA meta-analysis of 29 studies ($n = 2192$ effect sizes) to assess the impact of fire on European forest taxa' abundances and whether these effects can be explained by taxonomic group, fire characteristics (type, severity, time since fire), and environmental context (ecoregion, biome). Abundance served as the response metric, ensuring comparability across studies and taxa. Taxonomic identity emerged as the strongest predictor of post-fire responses. Fire-sensitive taxa (e.g., *Gastropoda*, *Passeriformes*) declined in abundance after fire, *Bryophyta* even at low fire severity, while fire-opportunistic taxa (e.g., *Hemiptera*, *Lepidoptera*) showed increases, particularly after high-severity fires and 1–5 years post-fire. Mediterranean forests showed less negative overall responses than temperate and boreal forests, yet fire-sensitive taxa declined severely even there. However, only 13 of Europe's forest ecoregions were represented, and biome-level patterns often arose from a single nested ecoregion, limiting spatial generalizability. Substantial residual heterogeneity indicates that unmeasured factors play significant roles, and critical data gaps, especially absent prescribed fire data for fire-sensitive taxa and limited long-term monitoring, constrain management guidance.

Conclusions These findings reveal ecological trade-offs: fire regimes benefiting fire-opportunistic taxa cause severe declines in fire-sensitive taxa. As climate change drives novel fire regimes across Europe, evidence-based fire management requires strategies that incorporate spatial heterogeneity, conserve refugia, and explicitly consider taxonomic trade-offs. Standardized, long-term monitoring across successional stages, fire events, and taxonomic groups is essential, along with consistent reporting of fire characteristics, functional traits, microhabitat complexity, and refugia availability. Combined with improved data sharing, such monitoring will enable adaptive management frameworks that balance wildfire risk reduction with biodiversity conservation in an era of unprecedented fire regime change.

Keywords Biodiversity, Disturbance severity, Fire ecology, Functional guilds, Invertebrates, Plants, Prescribed fire, Vertebrates, Wildfire

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*Correspondence:
Gemma Gerber
gerber@iiasa.ac.at
Full list of author information is available at the end of the article

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Resumen

Antecedentes El cambio climático está intesnificando los regímenes de fuegos de vegetación a través de los bosques de Europa, creando urgentes desafíos de manejo. Los incedios actúan como un filtro selectivo con efectos variables dependientes del contexto en el que ocurren. Aún así, una síntesis taxonómicamente comprensiva que cuantifique los impactos del fuego en la abundancia a lo largo de los bosques europeos aparece como limitada. Una síntesis regional es necesaria para informar sobre el planeamiento del manejo y la conservación, dado que los bosques europeos tienen características ecológicas distintivas e historias de manejo diferentes comparadas con ecosistemas proclives al fuego más estudiados.

Resultados Condujimos un análisis PRISMA-meta de 29 estudios ($n = 2192$ efectos de tamaño), para determinar el impacto del fuego sobre la abundancia de diferentes taxones de bosques europeos y determinar si dichos efectos puede explicarse por grupos taxonómicos, características de los incendios (tipo, severidad, tiempo desde el evento de fuego), y el contexto ambiental (eco-región, bioma). La abundancia sirvió como una respuesta métrica, asegurando la comparación entre estudios y taxones. La identidad taxonómica emergió como predictor más fuerte de las respuestas post fuego. Los taxones sensibles al fuego (i.e., *Gastropoda*, *Passeriformes*), declinaron en su abundancia luego de un incendio y las *Briofitas* también aún a baja severidad del fuego, mientras que los taxones fuego-oportunistas (i. e. *Hemiptera y Lepidoptera*) mostraron aumentos, particularmente luego de fuegos de alta severidad y entre los 1 y 5 años post fuego. Los bosques mediterráneos, si bien mostraron en general respuestas menos negativas que los bosques templados y boreales, también sus taxones sensibles al fuego declinaron severamente. Hay que tener en cuenta que solo 13 ecoregiones de Europa estuvieron representadas en este trabajo, y que los patrones que emergieron a nivel de bioma lo hicieron desde una ecoregión anidada, lo que limita su generalización. Una sustancial heterogeneidad residual indica que factores no mensurados juegan roles significativos, y faltantes de datos que podrían ser críticos, especialmente datos inexistentes de quemas prescriptas sobre taxones sensibles al fuego y la limitante que significa el monitoreo a largo plazo, condicionan las recomendaciones de manejo.

Conclusiones Estos resultados revelan intercambios ecológicos: los regímenes de fuego que benefician a los taxones oportunistas causan severa declinaciones en taxones sensibles al fuego. Dado que el cambio climático conduce a cambios novedosos en los regímenes de fuego de Europa, el manejo del fuego basado en la evidencia requiere de estrategias que incorporen la heterogeneidad espacial y la conservación de refugios que consideren explícitamente los intercambios taxonómicos. Para ello, el monitoreo estandarizado a largo plazo y a través de las diferentes etapas sucesionales, los eventos de fuegos, y los grupos taxonómicos, resultan esenciales, como así también los reportes consistentes de las características de los incendios, las características funcionales, la complejidad de los microhábitats, y disponibilidad de refugios. Combinados con un mejoramiento en el compartir datos, estos monitoreos van a permitir marcos de manejo adapatativo que balanceen la reducción del riesgo de incendios con la conservación de la biodiversidad, en una era de cambios en los regímenes de fuego que no tienen precedentes.

Background

Wildfires are a fundamental ecological process, but climate change and shifting land-use patterns are increasing their frequency and intensity globally (He et al. 2019; Luo et al. 2024). Between 2024 and 2025, wildfires burned approximately 3.7 million km^2 globally (Kelley et al. 2025), releasing massive amounts of carbon and contributing to the climate feedback loop (Lucas-Borja et al. 2025; Zhao et al. 2024). This escalating fire activity poses a significant threat to biodiversity, particularly in ecosystems not historically adapted to frequent fire (Pausas and Lamont 2022; Shivaprasad et al. 2025). Understanding biodiversity responses is central to global conservation, as fire impacts vary widely across taxa and dictate the long-term resilience of ecosystem services (Bieber et al. 2023; Mason et al. 2021).

Europe provides a critical case study for understanding fire impacts across gradients of fire tolerance and persistence adaptation, including both fire-simulated traits and exaptations for survival. The continent's diverse forest types span from fire-prone Mediterranean ecosystems to historically low-fire temperate and boreal forests, with a long history of human intervention creating complex management legacies (Aszalós et al. 2022; Pötzelsberger et al. 2021). Notably, Europe has experienced a net increase in forest area over recent decades, driven by land abandonment, afforestation, and natural regeneration (Cervera et al. 2019; Keenan et al. 2015). However, this expansion has often resulted in structurally simplified, fuel-dense stands that may increase fire hazards and ecological vulnerability under climate change (Naudts et al. 2016).

Climate change is now intensifying fire regimes across this gradient: hotter, drier conditions (Giannaros and Papavasileiou 2023) are increasing wildfire frequency, intensity, and duration (Cunningham et al. 2024; Feng et al. 2025). In 2023 alone, wildfires burned over 500,000 hectares in the European Union (World Bank 2025), followed by 2024, which exhibited strong regional variations driven by climate patterns (Kelley et al. 2025). Climate-driven fire regime projections indicate that both Mediterranean forests and historically low-risk temperate and boreal forests will experience novel fire regimes in the coming decades (Forzieri et al. 2021; Grünig et al. 2023; Miller et al. 2024; Rovithakis et al. 2022; San-Miguel-Ayanz et al. 2022). This escalating regime presents a dual management challenge: mitigating wildfire risk through fuel reduction techniques like prescribed burning to modify fuel structure (Pais et al. 2025), while conserving biodiversity increasingly threatened by both wildfires and management practices themselves (Arrogante-Funes et al. 2024; Kelly et al. 2020). Consequently, integrated or adaptive fire management approaches are increasingly highlighted as essential strategies to balance these competing objectives (Oliveras Menor et al. 2025).

The ecological challenge lies in fire's role as a powerful selective filter with highly variable, context-dependent effects (Pausas and Lamont 2022; Sharma and Kumar 2025; Shivaprasad et al. 2025). While fire can promote biodiversity by triggering germination of fire-dependent plants (Calderisi et al. 2025; García-Duro et al. 2019) or creating habitat heterogeneity (Chard et al. 2022; Driscoll et al. 2024), it can also cause declines in sensitive species through direct mortality (Sgardelis et al. 1995), habitat loss (Ortega et al. 2025), and resource depletion (Shivaprasad et al. 2025). These divergent outcomes are driven by the interaction between taxonomic traits and specific fire regime characteristics, including severity (ecological impact on vegetation and soils), fire type (wildfire vs. prescribed burn), and time since fire.

Severity determines immediate mortality and habitat alteration, particularly as increasing aridity drives larger and more severe fires across Europe (Grünig et al. 2023). Fire type reflects the intensity and management context, where unplanned wildfires typically represent high-intensity, unanticipated events, and prescribed fires are implemented as lower-severity tools for fuel-reduction and habitat management (Hochkirch and Adorf 2007; Zumr et al. 2025). However, the sensitivity of specific taxa complicates this distinction. For example, low-mobility taxa, such as *Gastropoda*, can experience significant declines even after “low-intensity” prescribed burns (Santos et al. 2014). Finally, the time since fire captures the successional dynamics and recovery trajectories of forest structure and biodiversity (Bieber et al. 2023).

The interplay of these factors, further altered by climate change and land management (Bizzarri et al. 2025; Grau-Andrés et al. 2024) creates a fundamental management dilemma: strategies benefiting one taxonomic group may harm another. For instance, open-habitat birds may exploit post-fire resources (Brotons et al. 2008; Versluijs et al. 2020), while forest specialists decline due to habitat degradation (Rey et al. 2019). Long-term European studies confirm these divergent responses, noting that while some species flourish, unburned refugia remain critical for the landscape-level persistence of others (Puig-Gironès et al. 2017, 2022, 2023). Conceptual frameworks for managing divergent ecological responses under novel fire regimes are increasingly needed (Puig-Gironès et al. 2025).

Despite these management dilemmas, comprehensive syntheses quantifying fire effects on species abundance across taxonomic groups in European forests are limited. Previous meta-analyses have focused on global scales (Mason et al. 2021; Moyo 2022) or specific taxonomic groups (Grau-Andrés et al. 2024), potentially masking the divergent responses critical for management decisions. Regional focus is essential because European forests have distinctive ecological characteristics, management histories, and biodiversity patterns compared to more extensively studied fire-prone ecosystems in Australia (Driscoll et al. 2024) or North America (Bieber et al. 2023). Existing knowledge is often fragmented, with many slow-moving or low-dispersal taxa, exemplified by *Gastropoda*, frequently overlooked despite their critical importance for soil health and ecosystem function (Zaitsev et al. 2016). Ultimately, these knowledge gaps limit not only ecological understanding but also the ability to make evidence-based fire management decisions at a continental scale (Oliveras Menor et al. 2025).

We conducted a comprehensive meta-analysis to quantify the impacts of fire on terrestrial animal and plant taxa across major European forest biomes (Mediterranean, temperate, and boreal). We focused on abundance as a direct, ecologically relevant indicator of population response, capable of detecting demographic changes before they manifest as broad diversity shifts (Santini et al. 2017). Our objectives were to (1) quantify overall fire effects on taxa abundance in European forests; (2) determine how fire characteristic heterogeneity (type, severity, time since fire) modulate taxa responses; (3) assess variation in fire responses among major taxonomic groups; and (4) evaluate the influence of environmental heterogeneity (biomes, ecoregions) on post-fire abundance. These objectives help fill key knowledge gaps, such as the lack of regional synthesis, to support more informed fire management in Europe. We hypothesized that taxonomic identity would be the primary determinant of post-fire abundance responses, with fire characteristics and geographic context playing important modulating roles.

Methods

Literature survey and data extraction

We conducted a systematic literature review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Page et al. 2021) (see PRISMA checklist Figure S1) to address: *"How do fires affect plant and animal abundances in European forests compared to unburned conditions?"* We used the PICO (Population, Intervention, Comparison, Outcome) framework (Mattos and Ruellas 2015), to develop the following study eligibility criteria:

1. Population: Reported in situ responses of plants (Plantae) and animals (Animalia) within European forests.
2. Intervention: Exposure to wildfire or prescribed fire.
3. Comparison: Quantitative comparisons between burned (treatment) and unburned (control) areas (Mason et al. 2021). Types of comparisons included: before vs. after a fire within the same patch; unburned vs. burned areas in different patches with similar initial conditions; and unburned vs. single or repeated burns within the same location.
4. Outcome: Measured taxa abundance (mean, standard deviation, sample size) as the primary response variable. Means were required for the calculation of effect sizes (see the "Effect size calculation" section).
5. Ensured comparability between treatment and control sites, such as similar vegetation and land management, e.g., mowing, trimming, and grazing (Mason et al. 2021).
6. Were published in English or languages translatable via standard translation tools (e.g., Spanish, French, German).
7. No publication year limitation.
8. Included grey literature (conference papers and proceedings, theses and dissertations, research and technical reports) to avoid publication bias. Ultimately, 0 grey literature sources were included in the final dataset because they did not meet the eligibility criteria outlined above.

We developed a comprehensive search string targeting fire-related terms; taxonomic groups (plants, animals, invertebrates); outcome measures (abundance, diversity); and study designs (controls, treatments) while excluding microorganisms (see the whole search string in Supplementary Material). We intentionally designed our search string to be highly sensitive to broadly capture any articles related to our study, even if they may not meet tighter search criteria. We searched the Scopus database on 19 June 2024, retrieving 3762 records. We selected Scopus for its comprehensive coverage of ecological and environmental literature and current accessibility. To ensure high sensitivity, we supplemented the Scopus-indexed literature with records identified in previous global and regional meta-analyses ($n = 1439$). We re-screened all supplemental records independently against our eligibility criteria to ensure consistency.

We performed all data cleaning, screening, and analysis in R v4.3.3 (R Core Team 2023). We applied a multi-stage screening protocol to refine the dataset. After removing duplicates ($n = 497$) using litsearchr v0.4.0 (Grames et al. 2019) and retracted articles identified by Zotero ($n = 1$), we applied an automated hierarchical filter to exclude paleo-ecological studies, non-European geographies, and non-forest ecosystems (detailed filtering methodology in Supplementary Material and Tables S1-3). We validated this algorithm using random subset inspections ($n = 20$) and found no false negatives.

We subjected the remaining candidate records ($n = 671$) to a semi-automated manual review of titles, abstracts, and keywords to address complex exclusion criteria that automated screening cannot detect (e.g., studies measuring physiological traits rather than abundance). We excluded records based on geography, lack of modern ecological focus, non-forest ecosystems, lack of fire intervention, failure to measure abundance, or focus on non-target taxa. We specifically excluded fungi because their response timescales and sampling methodologies (e.g., sporocarp vs. mycelium detection) differ fundamentally from plants and animals, warranting a separate synthesis (Franco-Manchón et al. 2019).

Of the remaining studies ($n = 158$), we were able to retrieve and manually screen 48 full-text records. Twenty-nine articles met all criteria (Table S4). The large attrition rate from the initial search ($n = 5201$ to $n = 29$) reflects our high-sensitivity search string, designed to capture all possible fire-related taxa studies, many of which ultimately lacked the necessary abundance measures or unburned comparisons (see Supplementary Material for PRISMA flowchart (Figure S1) and detailed screening methodology).

From each article, we extracted site and fire characteristics (Table S5) known to influence abundance significantly (severity: high/moderate/low; type: prescribed/wildfire; time since fire: < 1 year, 1–5 years, 5–10 years, > 10 years) (Bieber et al. 2023; Mason et al. 2021), and taxa abundances (at species-specific or nearest taxonomic rank) from reported results, supplementary material, or figures digitized using PlotDigitizer (Huwaldt 2020). While fire frequency and seasonality are ecologically critical, they were not included due to insufficient and inconsistent reporting in the primary literature. We converted standard errors (SEs) to standard deviations (SDs) using $SD = SE \times \sqrt{n}$, as needed. Based on the study site coordinates, we assigned World Wildlife Fund (WWF) biome and ecoregion categories (Olson et al. 2001) to each study to facilitate standardized geographic comparisons.

We categorized taxa into 22 functional-taxonomic groups based on ecological similarity, data availability, and taxonomic hierarchy, following previous fire meta-analysis approaches (e.g., Moyo 2022). This approach balances taxonomic rigor with the sample sizes required for robust meta-analysis, prioritizing life-history traits (e.g., mobility, regeneration strategy) that dictate fire response. A full taxa list and detailed justifications are provided in Table S6.

Effect size calculation

We calculated effect sizes using the log response ratio (lnRR) (Hedges et al. 1999) modified by a second-order Taylor expansion to reduce sample size biases (Lajeunesse 2015). Conceptually, lnRR is ecologically meaningful because it quantifies the proportional change in abundance between burned and comparison sites, allowing direct assessment of abundance change across diverse taxa with different baseline abundances and measurement units. For studies reporting mean and SD, we calculated lnRR as:

$$lnRR = \ln\left(\frac{m_1}{m_2}\right) + \frac{1}{2}\left(\frac{CV_1^2}{n_2} - \frac{CV_2^2}{n_1}\right)$$

$$v(lnRR) = \frac{CV_1^2}{n_1} + \frac{CV_2^2}{n_2} + \frac{CV_1^4}{2n_1^2} + \frac{CV_2^4}{2n_2^2}$$

where v is the sampling variance, m_1 and m_2 are the means of groups 1 (treatment) and 2 (control), CV_1 (SD_1/m_1) and CV_2 (SD_2/m_2) are the respective coefficients of variation, and n_1 and n_2 are the sample sizes. As the calculation of lnRR requires no zero events (both control and treatment means > 0) (Xiao et al. 2021), we added an adjustment factor of 0.001 to both groups if either reported a zero mean (Schwarzer 2007; Weber et al. 2020). This "offset" approach follows Weber et al., (2020), who found that targeted adjustments (using a 0.5 factor in their study) perform better than universal corrections. While we acknowledge that this adjustment can introduce bias for low-abundance taxa, it was necessary to prevent systematic exclusion of ecological data with a zero-mean for the control or treatment.

For studies failing to report variability (SD or SE), we applied the "missing cases" method (Nakagawa et al. 2023), estimating lnRR and missing v by assigning a weighted mean CV calculated across the subset of studies that did report SDs:

$$lnRR = \ln\left(\frac{m_1}{m_2}\right) + \frac{1}{2}\left(\frac{\left[\sum_{i=1}^{K}\frac{(n_{1i}CV_{1i})}{\sum_{i=1}^{K}n_{1i}}\right]^2}{n_2} - \frac{\left[\sum_{i=1}^{K}\frac{(n_{2i}CV_{2i})}{\sum_{i=1}^{K}n_{2i}}\right]^2}{n_1}\right)$$

$$v(lnRR) = \frac{\left[\frac{\sum_{i=1}^{K}(n_{1i}CV_{1i})}{\sum_{i=1}^{K}n_{1i}}\right]^2}{n_1} + \frac{\left[\frac{\sum_{i=1}^{K}(n_{2i}CV_{2i})}{\sum_{i=1}^{K}n_{2i}}\right]^2}{n_2} + \frac{\left[\sum_{i=1}^{K}\frac{(n_{1i}CV_{1i})}{\sum_{i=1}^{K}n_{1i}}\right]^4}{2n_1^2} + \frac{\left[\sum_{i=1}^{K}\frac{(n_{2i}CV_{2i})}{\sum_{i=1}^{K}n_{2i}}\right]^4}{2n_2^2}$$

where CV_{1i} and CV_{2i} are the CVs from the *i*th study, and *K* is the number of studies with available SDs for pooling. While this approach assumes a consistent relative CV across the synthesized studies, it prevents the systematic exclusion of less detailed literature. This ensures our synthesis remains representative of the broader literature while maintaining statistical power (Nakagawa et al. 2023).

Meta-analysis

We fit all multilevel meta-analysis models using restricted maximum likelihood (REML) with the function rma.mv() from the metafor (v4.8–0) R package (Viechtbauer 2010).

Base model

We fitted a three-level random-effects base model to quantify the overall effect of fire on taxa abundance. We nested effect sizes within studies (random intercepts: lnRR ~ 1 | Study_ID/EffectSize_ID) to account for non-independence (Giorgis et al. 2021; Nakagawa et al. 2023). We prioritized random intercepts over random slopes to maintain model stability given the sparse data in specific moderator (explanatory variable) levels (see the "Moderator analysis" section).

We partitioned heterogeneity into three levels: sampling error (level 1), within-study variation (level 2, reflecting methodological and ecological differences within studies), and between-study variation (level 3, reflecting broader contextual differences) (Cheung 2014; Harrer et al. 2019). We calculated I^2 statistics for each level to estimate the percentage of total variation attributable to each level. We validated the three-level structure against a two-level model using a likelihood ratio test (LRT) (Cheung 2014; Harrer et al. 2019).

Publication bias and sensitivity analysis

We assessed global publication bias using complementary approaches adapted for multilevel meta-analytic models. Using a suite of complementary approaches provides a more comprehensive and reliable assessment of potential bias, as no single test is definitive for complex meta-analytic structures. We used funnel plots (plotting effect size against precision) for asymmetry indicative of small-study effects (Harrer et al. 2021; Viechtbauer 2010). We conducted a modified Egger's regression (Egger et al. 1997) by adding precision (1/SE) as a predictor in the multilevel model to test whether smaller studies showed systematically different effects. As many publication bias tests assume independent effect sizes, we also aggregated effect sizes to the study level using precision-weighted means and applied standard tests to this aggregated dataset, including Egger's regression test, Begg and Mazumdar's rank correlation test (Begg and Mazumdar 1994), and trim-and-fill analysis to estimate potentially missing studies (Duval and Tweedie 2000).

For sensitivity analyses, we conducted leave-one-out tests (Viechtbauer and Cheung 2010) by systematically removing each study and recalculating the overall effect size to determine whether any single study substantially altered our conclusions. We compared the original and trim-and-fill-adjusted effect sizes to assess the impact of potential publication bias on our findings. Full publication bias, sensitivity methods, and results are detailed in the Supplementary Material.

Moderator analysis

We independently tested six moderators (explanatory variables) of fire effects: fire type (wildfire vs. prescribed fire), fire severity (low, moderate, high), time since fire (< 1 year, 1–5 years, 5–10 years, 10 + years), biome, ecoregion, and taxonomic group (22 functional-taxonomic groups). We excluded country as an explanatory variable because national boundaries are administrative and may not capture ecologically meaningful variation.

For each moderator, we fitted two multilevel mixed-effects models with the base random structure: (1) an intercept model for the Q_M omnibus test (a Wald-type chi-square test for heterogeneity among levels) and Pseudo-R^2 (variance explained; (Nakagawa and Schielzeth 2013), and (2) a no-intercept model for level-specific effects vs. zero. We evaluated model fit using the delta Akaike Information Criterion (ΔAIC).

To identify context-dependent taxon responses to fire, we tested pairwise interactions among taxonomic groups, fire characteristics (type, severity, time since fire), and geographic variables (biome, ecoregion). We tested all possible interaction combinations (Tables S12–15) and focused on taxonomic group here, as combining taxonomic group with environmental or temporal variables reveals context-dependent differences in vulnerability (e.g., by habitat or fire characteristics).

To ensure stable parameter estimation, we first filtered the data to retain combinations with $n \geq 3$ effect sizes. We chose this threshold to ensure sufficient data for variance and confidence interval computation (Borenstein et al. 2009). Given the dataset structure (2192 effect sizes from 29 studies), filtering by effect count rather than study count allowed us to retain ecological resolution for taxonomic groups that were well-sampled within specific studies but represented in fewer independent publications (Koricheva and Gurevitch 2014).

As the filtering altered the dataset, we compared each interaction model to a dedicated internal base model (with no interactions) fitted to the same filtered data. This ensured that model fit statistics (ΔAIC) and variance explained (Pseudo-R^2) were calculated relative to a consistent data baseline. For each interaction, we fitted two multilevel mixed-effects models with nested random effects to filtered subsets: (1) an intercept model on filtered data for the Q_M omnibus test and Pseudo-R^2, and (2) a no-intercept interaction model testing combination-specific effects vs. zero.

For interpretability, we back-transformed lnRR to percentage change in abundance following fire as: $\text{Change}(\%) = \left(e^{lnRR} - 1\right) \times 100$. We note that substantial percentage changes (> 1000%) may reflect very low baseline (control) abundances, high variability, or data limitations. Therefore, we report lnRR as the primary metric for interpretation, with percentage changes as supplementary context (Tables S12–15).

Results

Literature survey results

Our final database consisted of 2192 effect sizes from 29 studies published between 1998 and 2024, spanning 10 European countries (Fig. 1; Figure S2). Geographic representation was concentrated in Southern and Central Europe, with the largest contributions from Spain (28.5%), Czechia (28.4%), Sweden (14.1%), and Switzerland (10.2%) All four major European forest biomes were represented, with the majority of observations from temperate broadleaf and mixed forests (36.6%) and Mediterranean forests, woodlands, and scrubs (35.3%), with comparatively lower representation from Boreal forests (12.3%) and Temperate Coniferous forests (15.8%; Fig. 1).

Within these four biomes, the dataset covered 13 ecoregions, dominated by Central European mixed forests (28.4%) and Northeastern Spain and Southern France

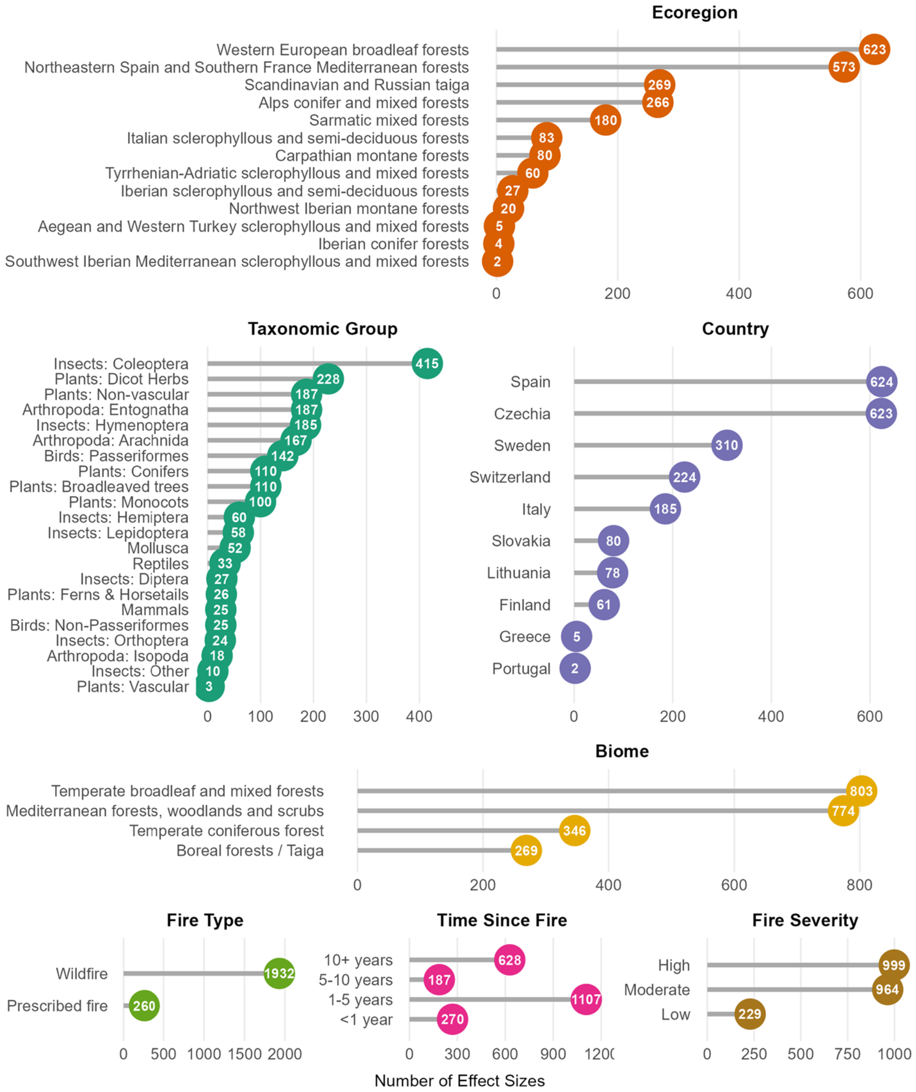

Fig. 1 Effect sizes (*n* = 2192) for each explanatory variable used in our analysis. Ecoregions and biomes per Olson et al. (2001)

Mediterranean forests (26.1%). Spatial coverage was most robust in the Mediterranean biome, with eight included ecoregions, while the Boreal biome was represented solely by the Scandinavian and Russian taiga (Table S7). Data for the Temperate Broadleaf and Coniferous biomes were similarly restricted to two ecoregions each, leaving extensive geographic gaps across areas such as the Icelandic, Ural, and Balkan forest systems (Table S7).

The dataset included 819 unique taxa grouped into 22 broader functional-taxonomic groups (Fig. 1). Taxonomic representation shows a strong imbalance toward invertebrates (54.9%) and plants (37.6%). Insects were especially well represented, with *Coleoptera* (18.9%) and *Hymenoptera* (8.4%) having the largest contributions, and *Arachnida* (7.6%) also prominent among invertebrates. Among vertebrates, *Passeriformes* (6.5%) were dominant, whereas mammals, reptiles, and non-passerine birds each accounted for < 1.5% of total observations. Plants were predominantly represented by Dicot Herbs (10.4%) and non-vascular plants (*Bryophyta* 8.5%), with broadleaved trees and conifers accounting for 5.0% each.

Wildfire events dominated the dataset (88.14%) compared to prescribed fire (11.9%; Fig. 1). Observations were primarily balanced between high (45.6%) and moderate (44.0%) severity, with low-severity events (10.4%) reported less frequently. Temporally, half of the observations (50.5%) reflect responses 1–5 years post-fire, while long-term data (> 10 years) accounted for 28.6% and immediate responses (< 1 year) accounted for 12.3%.

Overall model results and heterogeneity

The intercept-only three-level base model indicated that the average effect of fire on abundance was not statistically different from zero (lnRR = 0.2, $p = 0.56$; Table S8). In other words, across taxa and contexts, the mean response does not show a clear directional shift in abundance. However, high heterogeneity in the intercept-only base model (total $I^2 = 99.3\%$; Q test $p < 0.001$; Figure S3; Table S8) suggested substantial variation in how taxa abundances respond to fire. Most heterogeneity was attributed to differences within studies ($I^2 = 93.5\%$), reflecting variation among taxa responses to fire within individual studies, and less to between-study heterogeneity ($I^2 = 5.8\%$). Supporting the multilevel approach, the three-level model fit the data better than a simpler two-level model ($LRT = 60.8$; $p < 0.001$). Together, these results indicate that abundance responses to fire are highly context-dependent, motivating moderator analyses to identify factors explaining this variation.

Individual moderator analysis revealed substantial heterogeneity in abundance responses to fire, with clear differences in the explanatory power of each (Table 1; Table S9). Taxonomic group was the strongest statistically significant moderator ($Q_M = 172.4$, $p < 0.001$), produced the largest improvement in model fit relative to the base model (ΔAIC ≈ -238.7), and explained the greatest share of heterogeneity (Pseudo-$R^2 = 5.2\%$; Table 1).

Time since fire also significantly moderated fire effects ($p < 0.001$), but accounted for only a small additional fraction of heterogeneity (Pseudo-$R^2 = 0.6\%$) and improved fit less than taxonomic group (ΔAIC $= -30.3$; Table 1). Fire type, fire severity, biome, and ecoregion did not explain detectable variation in effect sizes ($p > 0.05$), explained comparatively less heterogeneity (Pseudo $-R^2 < 0.3\%$), and were poorer model fits relative to the base model (ΔAIC > -8.2; Table 1).

All taxonomic group interactions, however, substantially improved model fit relative to intercept-only models on the filtered data (ΔAIC $= -294.6$ to -404.4; Table 1; Table S9) and explained additional heterogeneity (Pseudo-$R^2 = 3.2$–9.7%). Interactions with biome (Pseudo-$R^2 = 9.7\%$) and time since fire (7.2%) explained the most variance, nearly doubling the explanatory power of taxonomic group alone (5.2%). The contrast between non-significant main effects and improved interaction model fit for biome, severity, and ecoregion indicates that these factors do not uniformly shift post-fire abundance but instead modulate responses in taxon-specific ways.

Publication bias and sensitivity analysis

We assessed potential publication bias and sensitivity using multiple approaches (Table S10). The modified Egger's test for multilevel models suggested no clear relationship between effect size and precision ($p = 0.19$; Table S10). Similarly, both the standard Egger's regression and Begg and Mazumdar's rank correlation tests on aggregated data were statistically non-significant ($p > 0.05$; Table S10). Visual inspection of funnel and precision plots (Figures S4–S6) did not reveal clear asymmetry.

Trim-and-fill analysis identified six potentially missing studies, suggesting possible underrepresentation of positive effects (Table S10). While the adjusted effect size (lnRR = 0.7) was larger than the original estimate

Table 1 Comparison of main effects and interaction models assessing European forest fauna response to fire from 29 studies. All models fitted using REML. *Levels* (number of levels/interaction combinations); *n* (number of effect sizes); Q_M (omnibus Q-statistic for model significance; (Viechtbauer 2010); *df* (degrees of freedom for Q_M); *p* (*p*-value for Q_M test); *Pseudo-R^2* (%) (proportion of heterogeneity explained vs. base model); Δ*AIC* (AIC difference from base model; negative indicates better fit). For interaction models, all analyses were conducted on filtered datasets (combinations with ≥ 3 effect sizes)

Moderator/interaction	Levels	*n*	QM (df)	*p*	Pseudo-R^2 (%)	Base AIC	ΔAIC
Taxonomic group	22	2192	172.4 (21)	< 0.001***	5.2	13,436.0	− 238.7
Time since fire	4	2192	18.9 (3)	< 0.001***	0.6	13,436.0	− 30.3
Fire type	2	2192	3.7 (1)	0.07	0.9	13,436.0	− 8.2
Biome	4	2192	3.6 (3)	0.36	0.3	13,436.0	− 18.5
Fire severity	3	2192	0.5 (2)	0.79	0	13,436.0	− 10.2
Ecoregion	13	2192	5.1 (12)	0.94	0	13,436.0	− 58.5
Taxonomic group * biome	44	2182	217.4 (43)	< 0.001***	9.7	13,383.8	− 354.3
Taxonomic group * ecoregion	54	2180	212.8 (53)	< 0.001***	5.2	13,373.4	− 397.4
Taxonomic group * time since fire	58	2176	223.9 (57)	< 0.001***	7.2	13,340.8	− 404.4
Taxonomic group * fire type	33	2192	190.4 (32)	< 0.001***	5.7	13,436.0	− 294.6
Taxonomic group * fire severity	45	2178	194.8 (44)	< 0.001***	3.2	13,363.5	− 341.3

Statistical significance indicated at $p < 0.05$(*); $p < 0.01$(**); $p < 0.001$(***)

(lnRR = 0.2), we interpret this discrepancy with caution. Given the high total heterogeneity in our base model ($I^2 = 99.3\%$), particularly the dominant within-study variation ($I^2 = 93.5\%$), trim-and-fill may struggle to differentiate between publication bias and true ecological diversity in responses. Therefore, we treat this as a sensitivity test for potential small-study effects rather than definitive evidence of publication bias. Finally, the leave-one-out analysis showed that no single study unduly influenced the results; removal of any individual study did not alter the statistical significance of the overall effect ($p > 0.23$; Figure S7, Table S11).

Taken together, these analyses indicate that our findings are robust to the influence of individual studies and show no consistent evidence for systematic publication bias. While the high heterogeneity and trim-and-fill analysis suggest that the "global" average is sensitive to potential missing data, the consistency across all other tests supports the reliability of the observed taxonomic and environmental patterns as drivers of fire abundance responses in our dataset.

Effects of specific levels

Ecological responses to fire were highly variable and strongly driven by taxonomic identity (Table 1). Some plant groups exhibited positive abundance responses to fire (Fig. 2). Ferns and Horsetails showed the largest abundance increase post-fire (lnRR = 5.5, $p < 0.001$), followed by Dicot Herbs (lnRR = 0.0, $p < 0.001$; Fig. 2). In contrast, no statistically significant effects were detected for other plant groups ($p > 0.05$; Fig. 2).

Among invertebrates, *Hemiptera* (true bugs) were the only group to show increased abundances after fire (lnRR = 2.8, $p < 0.001$; Fig. 2). Conversely, *Gastropoda* (molluscs) were highly fire-sensitive, experiencing severe abundance declines (lnRR = −3.7, $p < 0.001$; Fig. 2). No other invertebrate group showed statistically significant abundance changes post-fire in the main effects model ($p > 0.05$; Fig. 2).

Passeriformes, aggregated from 22 families including *Paridae*, *Muscicapidae*, and *Fringillidae*, showed abundance declines after fire (lnRR = −2.1; $p < 0.01$; Fig. 2). Non-passerine birds, mammals, and reptiles showed no statistically significant abundance responses to fire ($p < 0.05$; Fig. 2).

Time since fire was the only significant moderator among fire regime characteristics (Table 1). Overall taxa abundance was statistically significantly higher in the 5–10-year post-fire interval (lnRR = 1.5, $p < 0.01$; Fig. 2). Fire type (prescribed vs. wildfire), fire severity (low, moderate, high), biome, and ecoregion did not significantly explain variation in taxonomic group abundance ($p > 0.05$; Fig. 2).

Interaction analyses revealed that fire traits drive divergent taxonomic abundance responses masked in the main effects (Fig. 2). Invertebrate insect responses were strongly fire-context-dependent. *Hemiptera* abundances generally increased following wildfire (lnRR = 4.0, $p < 0.001$), 1–5 years post-fire (lnRR = 3.3, $p < 0.001$), and high-severity fire (lnRR = 3.1, $p < 0.01$; Fig. 3). Data were missing for low-severity fire and the 5–10 years post-fire window. *Lepidoptera* abundances, despite showing no overall response to fire (Fig. 2) increased after prescribed fire (lnRR = 5.9, $p < 0.05$), high-severity fire (lnRR = 7.6, $p < 0.05$), and 1–5 years post-fire (lnRR = 7.2, $p < 0.05$; Fig. 3). *Lepidoptera* abundance data were missing for low-severity fire and the 5–10 and 10 + years post-fire windows. *Coleoptera* abundances also increased after wildfire (lnRR = 1.5, $p < 0.01$) and 1–5 years post-fire (lnRR = 1.2, $p < 0.05$; Fig. 3).

In contrast, invertebrate *Gastropoda* showed near total abundance losses (> 97% decrease) after wildfire, 1–5 years post-fire, and high-severity fire (lnRR = −3.3 to − 3.7, $p < 0.001$; Fig. 3). *Gastropoda* lacked data for low and moderate fire severity, prescribed fire, < 1 year, 5–10 years, and 10 + years post-fire windows. The remaining invertebrate groups showed no statistically significant post-fire abundance changes, and were characterized by substantial data gaps, specifically for prescribed fire, low-severity, and multiple post-fire windows (e.g., *Orthoptera* was missing all windows except 1–5 years).

Within vertebrate groups, *Passeriformes* abundances declined following wildfire, 1–5 years post-fire, and high-severity fire (lnRR = −1.8 to − 2.04, $p < 0.05$; Fig. 3). Data for *Passeriformes* were missing for moderate fire severity and for post-fire windows of < 1 year and 5–10 years. Other vertebrate groups showed no statistically significant abundance responses across interactions (Fig. 3), though data gaps were notable for high-severity and prescribed fires.

Plants showed mixed post-fire responses (Fig. 3). Dicot Herbs, and Ferns and Horsetails abundances increased after wildfire and moderate severity fire (lnRR > 3.0, $p < 0.05$), with Ferns and Horsetails also responding positively after low severity fire (lnRR = 6.1, $p < 0.01$; Fig. 3). Data for high fire severity were missing for both groups. Ferns and Horsetail abundances increased across all post-fire windows, peaking at 1–5 years (lnRR = 6.4, $p < 0.01$), while Dicot Herbs showed strongest responses 5–10 years post-fire (lnRR = 4.6, $p < 0.001$; Fig. 3).

Broadleaved trees (5 families, including *Betulaceae*, *Fagaceae*, and *Salicaceae*) showed abundance increases < 1 year after fire (lnRR = 4.2, $p < 0.05$), while Monocots (4 families, including *Poaceae*, *Cyperaceae*, and *Asparagaceae*) increased 5–10 years post-fire

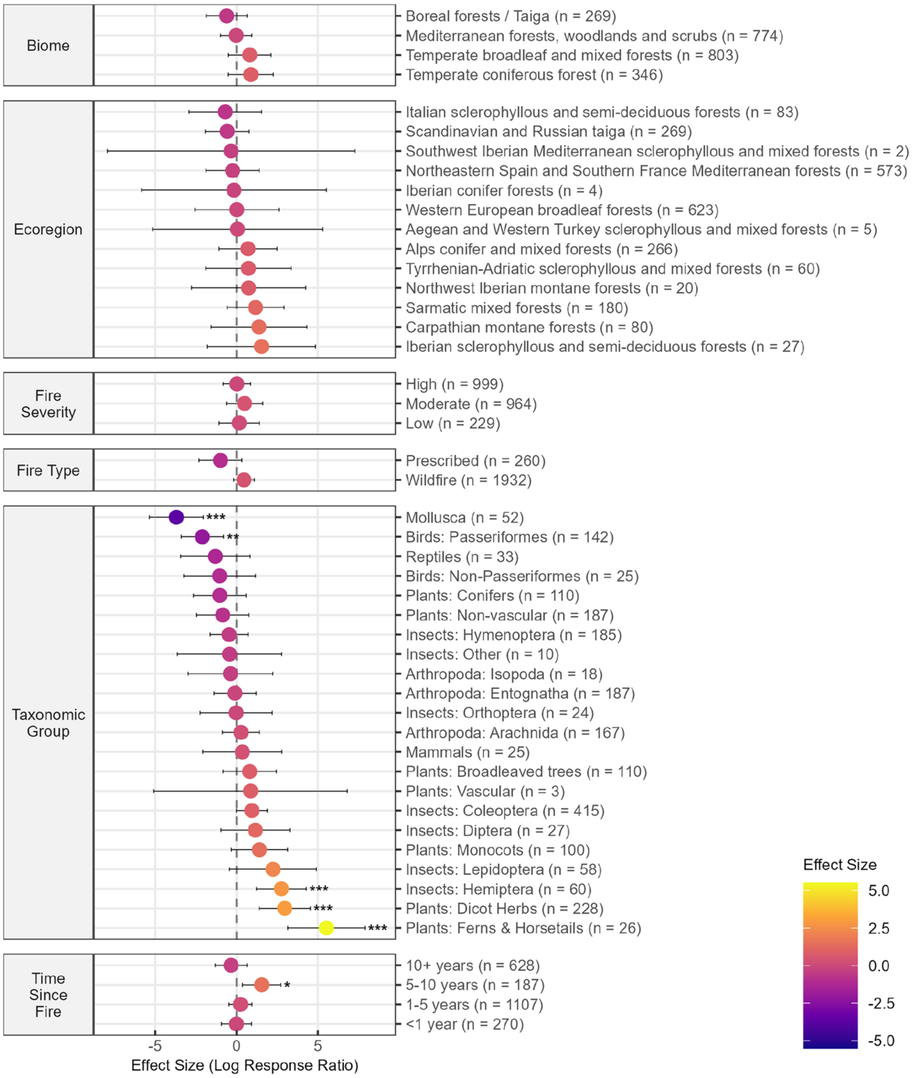

Fig. 2 Effect sizes (log response ratios lnRR ± 95% CI) showing the effect of fire on abundances compared to zero. Error bars represent 95% confidence intervals. Positive values (yellow) indicate increased abundance following fire, negative values (blue) indicate decreased abundance, n is the number of effect sizes per level; statistical significance indicated by asterisks ($p < 0.05$*, $p < 0.01$**, $p < 0.001$***)

(lnRR = 3.1, $p < 0.05$; Fig. 3). Monocots lacked data on high-severity fire and prescribed fire. Non-vascular plant (*Bryophyta*) abundances declined after low-severity fire (lnRR = −5.1, $p < 0.05$), but were missing data for high fire severity, < 1-year post-fire, and prescribed fire.

Biome- and ecoregion-level analyses revealed that taxonomic group responses to fire varied across spatial scale (Fig. 4), with biome-level analyses providing a broad overview of post-fire abundance patterns, and ecoregion-level analyses allowing examination of within-biome responses. Biome-level statistically significant responses were frequently accompanied by non-significant ecoregion-level trends in the same direction (Fig. 4), suggesting that individual ecoregions often lacked sufficient sample sizes to detect effects independently. Where a taxon was represented by a single ecoregion within a biome (Fig. 4), its generalizability across the biome should be interpreted with caution.

Among animals, *Gastropoda* and *Passeriformes* abundances declined in the biome Mediterranean Forests, Woodlands, and Scrubs (lnRR < 1.7, $p < 0.05$; Fig. 4). *Gastropoda* data were available from one ecoregion (Northeastern Spain and Southern France Mediterranean Forests). *Passeriformes* were represented in two Mediterranean ecoregions (Italian Sclerophyllous and Semi-deciduous Forests; Northeastern Spain and Southern France Mediterranean Forests), showing non-significant declines in abundance after fire in both ecoregions (Fig. 4).

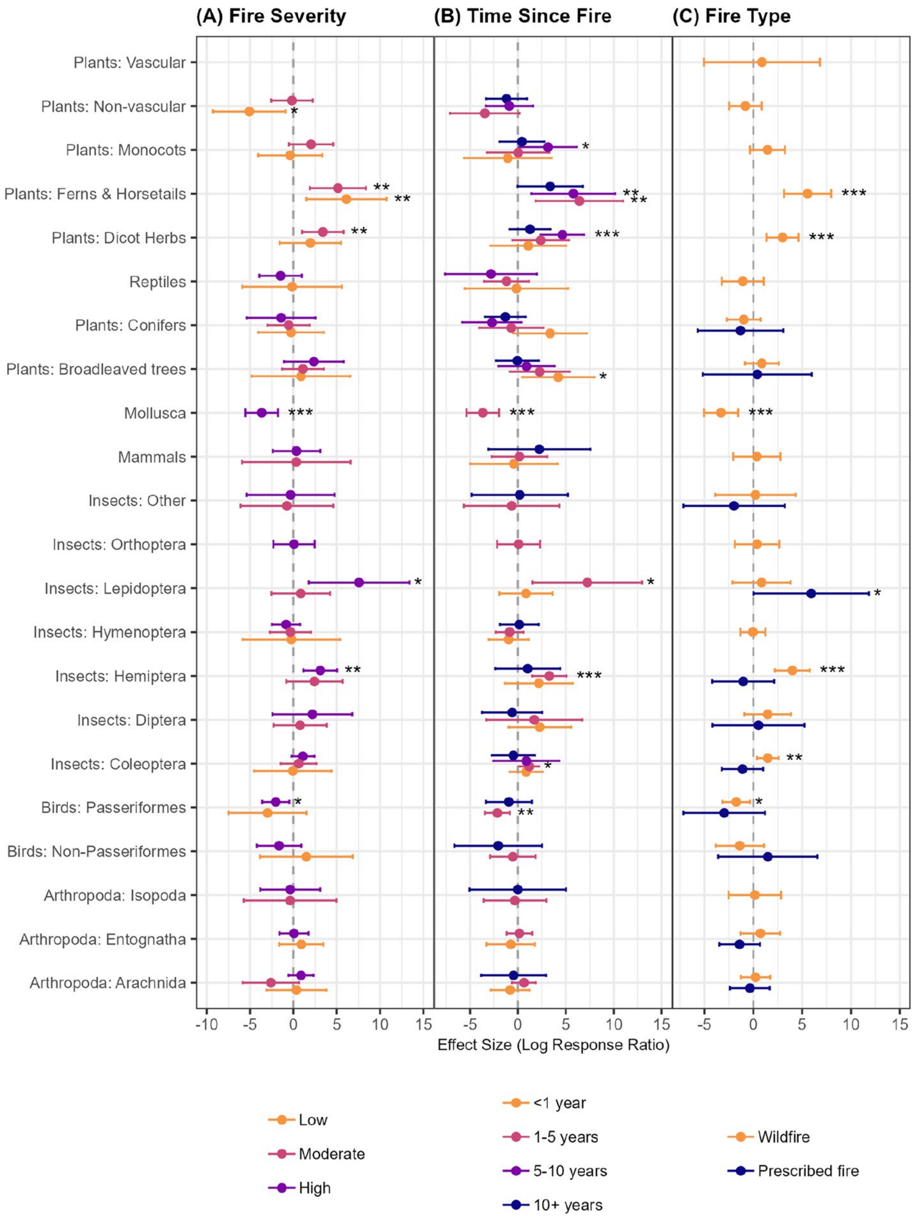

Fig. 3 Interactive effects of taxonomic group with fire severity (**A**), time since fire (**B**), and fire type (**C**) on abundance response (log response ratios lnRR ± 95% CI) to fire compared to zero. Statistical significance indicated by asterisks (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$). Interaction analysis could not be conducted for some combinations due to insufficient data ($n < 3$)

Insects showed increased post-fire abundances in the Mediterranean biome, particularly *Hemiptera* and *Coleoptera* (lnRR > 1.5, $p < 0.05$; Fig. 4). *Hemiptera* data were from one ecoregion (Northeastern Spain and Southern France Mediterranean Forests). Within the Mediterranean biome, post-fire *Coleoptera* abundances increased in all three ecoregions in which it was represented (lnRR 0.7–1.7, $p > 0.05$; Fig. 4). Post-fire *Coleoptera* abundances also increased in the Temperate Broadleaf and Mixed Forests biome (lnRR = 3.6, $p < 0.001$), where data were from ecoregion Sarmatic Mixed Forests (Fig. 4).

Lepidoptera abundances showed no statistically significant post-fire biome-level responses (Mediterranean and Boreal Forests), but a statistically significant increase within the ecoregion Scandinavian and Russian Taiga (Boreal biome, lnRR = 6.4, $p < 0.05$; Fig. 4). We note that biome Boreal forests and Taiga showed few statistically significant taxonomic responses (Fig. 4), suggesting that sample sizes from the single representative ecoregion (Scandinavian and Russian Taiga) were insufficient to detect biome-specific patterns.

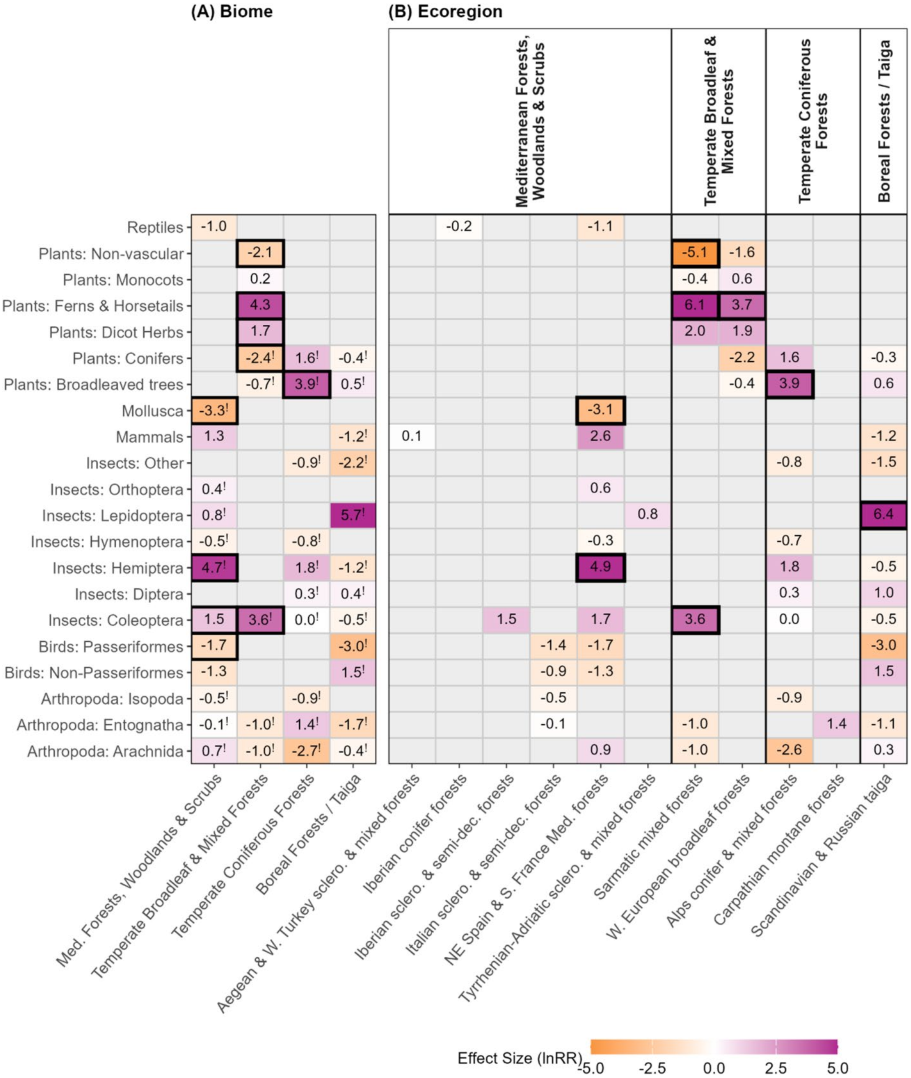

Fig. 4 Interactive effects of taxonomic group with Biome (**A**) and Ecoregion (**B**) on abundance response (log response ratio lnRR ± 95% CI) to fire compared to zero. Each cell shows the effect size (lnRR), colored by magnitude and direction (orange indicates decline, purple indicates increase). Cells outlined in black indicate statistical significance ($p < 0.05$). Grey cells indicate combinations excluded due to insufficient data ($n < 3$). The exclamation mark "!" indicates biome-level estimates derived from a single ecoregion

Among plants, statistically significant post-fire abundance responses were concentrated in the Temperate Broadleaf and Mixed Forests biome, with increases shown by Ferns and Horsetails, and Dicot Herbs ($\ln RR = 1.7–4.3$, $p < 0.05$), and decreases by non-vascular plants and conifers ($\ln RR = -2.1$ to -2.4, $p < 0.05$; Fig. 4). At the ecoregion level, Ferns and Horsetails abundance increased post-fire in both Sarmatic Mixed Forests and Western European Broadleaf Forests ($\ln RR = 3.7–6.1$, $p < 0.05$), whereas Dicot Herbs did not in either ecoregion (Fig. 4). Non-vascular plants showed statistically significant post-fire abundance declines in ecoregion Sarmatic Mixed Forests ($\ln RR = -5.1$, $p < 0.05$), but not in Western European Broadleaf Forests (Fig. 4). In Temperate Broadleaf and Mixed Forests, conifer abundance declined after fire at the biome-level ($\ln RR = -2.4$, $p < 0.01$), but not at the ecoregion-level (Western European Broadleaf Forests; Fig. 4). In the Temperate Coniferous Forests biome, broadleaved trees were the only group to show abundance increases after fire ($\ln RR = 3.9$, $p < 0.01$), and only in one ecoregion (Alps Conifer and Mixed Forests).

Discussion

Our meta-analysis, to our knowledge the first to synthesize fire effects on taxonomic abundance across European forests, reveals a profound divergence in post-fire outcomes. While the global mean effect was non-significant, fire acts as a highly selective ecological filter (Driscoll et al. 2024; Giorgis et al. 2021; González et al. 2022; Mason et al. 2021), where outcomes are determined by the interplay of taxonomic traits (Bieber et al. 2023; Moyo 2022; Santos et al. 2014), fire characteristics (Grau-Andrés et al. 2024), and environmental context (Giorgis et al. 2021; Moyo 2022). Without a comprehensive understanding of these opposing responses, management actions intended to promote recovery or reduce fuel loads could inadvertently harm sensitive biodiversity.

Taxonomic identity as primary determinant of post-fire abundance responses

Taxonomic identity was the strongest predictor of post-fire abundance responses, though substantial residual heterogeneity indicates that most variation remains unexplained by the factors examined (Table 1). The divergent responses between fire-sensitive and fire-opportunistic groups underpin the management trade-offs discussed below.

Fire-sensitive taxa: Gastropoda, Passeriformes, and Bryophyta

The most significant finding for conservation is the severe decline in abundance after fire for several key forest-dwelling groups. *Gastropoda* abundances declined across all examined fire contexts (Fig. 3), reflecting their dependence on humid microhabitats and organic substrates (Hylander 2011; Santos et al. 2014). Fire removes the moisture-retaining litter layer and bryophyte cover essential for gastropod survival (Brugués et al. 2025; Hylander 2011), while *Gastropoda* limited mobility prevents rapid recolonization from unburned refugia (Hylander 2011; Santos et al. 2014). Severity-dependent *Gastropoda* abundance responses (Fig. 3) suggest that increasing wildfire severity under climate change could disproportionately threaten these taxa (Brugués et al. 2025; Decker et al. 2023), with potential cascading effects on decomposition and trophic dynamics given their roles as prey for birds and mammals and contributors to nutrient cycling (De Oliveira et al. 2010; Rosin et al. 2011).

Passeriformes (aggregated from 22 families, including *Paridae*, *Muscicapidae*, and *Fringillidae*) showed statistically significant abundance declines after wildfires and high-severity fires, consistent with fire-induced simplification of vegetation structure, which reduces foraging substrates and nesting sites (Herrando et al. 2003; Versluijs et al. 2020). These patterns are consistent with the long-term dynamics documented by (Puig-Gironès et al. 2017; Puig-Gironès et al. 2022; Puig-Gironès et al. 2023), who demonstrated the impact of fire on forest birds, and the importance of unburned refugia and temporal dynamics in post-fire bird community recovery. However, the absence of abundance data for the < 1-year post-fire period means that the observed decline in the 1–5-year window likely underestimates the initial impact, rather than representing a temporal lag in habitat recovery (Herrando et al. 2003; Ukmar et al. 2007).

Non-vascular *Bryophyta* (47 species across 24 families) abundances declined after low-severity fire (Fig. 3). This reflects their dependence on stable microclimatic conditions and limited capacity to recover quickly from minor heat exposure and desiccation (Cooper et al. 2025). Abundance declines at low but not moderate severity (Fig. 3) is counterintuitive and may be driven by greater spatial heterogeneity in moderate-severity wildfires, which often leave unburned "micro-refugia" within the burn perimeter (Hylander 2011; Jones and Tingley 2022). In contrast, low-severity prescribed burns are often designed for uniform surface-fuel consumption, which can more thoroughly remove ground-layer vegetation (Fernández-Guisuraga and Fernandes 2024). Critically, we note that the low-severity estimate is based on a smaller subset of observations ($n = 12$) from a single study, compared to the more robust moderate-severity dataset ($n = 174$ from 2 studies). Consequently, the low severity decline should be interpreted as an indicator of potential vulnerability rather than a definitive trend. Regardless, this finding is policy-relevant, challenging assumptions that low-intensity prescribed burns are universally benign fuel management practices for ground-layer biodiversity (Gamba et al. 2025).

Fire-opportunistic taxa: Hemiptera, Lepidoptera, Coleoptera, and plant groups

Several groups showed increases in abundance after fire, capitalizing on post-fire environments. *Hemiptera* (true bugs) showed the strongest overall positive insect response, thriving after wildfires, at high severity, and 1–5 years post-fire (Fig. 3), consistent with previous meta-analyses (Bieber et al. 2023). The mechanisms driving post-fire *Hemiptera* abundance increases remain understudied in European contexts (Zumr et al. 2025), but likely involve rapid host plant regeneration and increased insolation (Plumanns-Pouton et al. 2025), and fire-induced predator reduction (Puga et al. 2024). However, ant predators may also increase post-fire (Bishop et al. 2021), and it can be hypothesized that this can lead to additional complex, species-specific interactions driving *Hemiptera* abundances post-fire.

Lepidoptera (butterflies and moths) showed short-term abundance increases in specific contexts: prescribed fire, high-severity fire, and 1–5 years post-fire (Fig. 3), consistent with rapid colonization of post-fire herbaceous layers tracking floral resources (Mason et al. 2021; Zumr et al.

2025). Fire increases insolation and flowering pioneer plant availability in the short term (Mason et al. 2021; Passovoy and Fulé, 2006; Swengel and Swengel 2007), which provides ephemeral but vital habitat patches for *Lepidoptera* (Zumr et al. 2025). The large magnitude of some positive effects (Tables S12-14) may reflect genuine rapid colonization dynamics, though wide confidence intervals indicate data limitations. Additionally, long-term studies suggest that even low-intensity fires may reduce flowering over decadal timescales (Dixon et al. 2023), suggesting that sustained positive effects of fire on *Lepidoptera* should not be assumed.

Coleoptera (aggregated from 35 families including *Carabidae*, *Staphylinidae*, *Curculionidae*, *Cerambycidae*) abundances increased after wildfires, and 1–5 years post-fire (Fig. 3). These responses likely reflect the exploitation of newly available resources (Zumr et al. 2025), saproxylic beetles (*Cerambycidae*, *Buprestidae*, *Scolytinae*) benefitting from fire-weakened or dying trees (Moretti et al. 2006; Zumr et al. 2025), while post-fire microhabitat changes in patch moisture (Toivanen 2014) and vegetation structure (Santos et al. 2014) may favor ground-dwelling beetles.

Vascular plant group abundances showed strong temporal variation after fire. Broadleaved trees showed rapid, strong increases in abundance < 1-year post-fire (Fig. 3), which may be explained by resprouting from dormant buds on root systems and stumps (Camarero et al. 2024). However, while post-fire germination and resprouting of broadleaved tree seedlings is frequently high immediately after fire, they rapidly decline as density-dependent mortality reduces cohort size before reproductive maturity (Schüle et al. 2023). In conifer-dominated forests (e.g., Temperate Coniferous Forests and Alps Conifers and Mixed Forest) fire-induced canopy gaps create high-light environments that favor the colonization of pioneer broadleaves such as European aspen (*Populus tremula* L.) and goat willow (*Salix caprea* L.) (Lanta et al. 2025; Mantero et al. 2024). This creates a temporary competitive shift from shade-tolerant conifers to light-demanding broadleaves (Yao et al. 2025). However, the significant biome-level broadleaved tree increase in Temperate Coniferous Forests was restricted to the Alps Conifer and Mixed Forest ecoregion (Fig. 4), limiting generalizability across the biome.

Dicot Herb abundances increased after wildfires and at moderate severity, peaking during 5–10 years post-fire (Fig. 3). Monocot abundances increased 5–10 years post-fire, suggesting they capitalize on intermediate conditions after pioneer establishment but before canopy closure (Tangney et al. 2022). Ferns and Horsetails showed large post-fire abundance increases (Fig. 3), consistent with pioneer species having spore dispersal, facilitating rapid colonization (Thomas and Cleal 2022). The timing of post-fire surveys relative to these successional dynamics critically affects abundance estimates and may partially explain the large magnitude of some positive effects.

Taxa with complex or non-significant responses

In this study, several taxonomic groups, including Arachnida (48 taxa, including spiders and mites), *Hymenoptera*, *Entognatha*, *Isopoda*, Mammals, and Reptiles, showed non-significant abundance responses to fire (Figs. 2, 3). Rather than true ecological resilience, these results likely reflect aggregation masking, in which pooling taxa with divergent life-history traits into coarse groups obscures opposing responses. Our *Hymenoptera* results (Figs. 2, 3) provide a clear example of this artifact, as the group is aggregated from forest-dwelling ants (*Formicidae*) and wild bees (*Andrenidae*, *Apidae*, *Halictidae*, *Colletidae*; Table S6). Ants typically decline post-fire due to nest litter loss (Puga et al. 2024), while wild bees that thrive on enhanced post-fire floral resources and nesting sites (Moretti et al. 2006; Zumr et al. 2025).

Similarly, the neutral response of *Arachnida* (Figs. 2, 3) may reflect a balance between increased mortality in vegetation-associated spiders and the persistence of ground-dwelling species in rocky refugia (Puga et al. 2024). Among vertebrates, non-significant trends in Reptiles (Figs. 2, 3) likely mask species-specific shifts driven by altered thermal environments (Ferreira et al. 2016; Ferreira et al. 2017). These patterns underscore that in high-level meta-analyses, a non-significant group effect size can be a statistical byproduct of taxonomic coarseness rather than an absence of fire impact.

Conifers showed no significant overall response to fire (Fig. 2), yet declined significantly in Temperate Broadleaf and Mixed forests (Fig. 4). This divergence likely reflects biome-specific species composition: declines in mixed forests are likely driven by fire-intolerant species such as Norway spruce (*Picea abies* (L.) H. Karst.) and European silver fir (*Abies alba* Mill.), which possess thin bark, shallow roots, and ladder fuels (Bizzarri et al. 2025; Bledý et al. 2024; Caudullo et al. 2016). Although not tested here, this vulnerability may be compounded by insect (*Coleoptera*)–fire interactions. For example, bark beetle (*Ips* spp.) outbreaks can increase subsequent fire severity through fuel accumulation from standing dead trees (Beetz et al. 2025). Conversely, fire-weakened trees provide vulnerable hosts that can drive increases in bark beetle abundances (Andrus et al. 2025). The lack of abundance change for more fire-tolerant European larch (*Larix decidua* Mill.) and Scots pine (*Pinus sylvestris* L.) in Temperate Coniferous Forests likely mask negative responses at the aggregate level (Holík et al. 2025; Niccoli et al. 2025).

Modulating factors and management trade-offs

While taxonomic identity was the strongest predictor of post-fire abundance (the "Taxonomic identity as primary determinant of post-fire abundance responses" section), fire regime characteristics and spatial context further modulated outcomes. Fire regime characteristics, including intensity, severity, and timing, fundamentally drive post-fire outcomes. Our results highlight the critical distinction between fire intensity (energy released during combustion) and fire severity (ecological impact on vegetation, soils, and ecosystem structure) (Hardy 2005; Rossi et al. 2020). Although related, their relationship is context-dependent, influenced by fuel structure, vegetation type, soil moisture, and seasonal timing (Pais et al. 2025).

In this study, wildfires (typically high intensity, larger extent) and prescribed fires (typically low intensity, interpreted as low severity Hochkirch and Adorf 2007; Zumr et al. 2025)) produced distinct taxonomic signatures (Fig. 3). Wildfires drove declines in the abundance of *Passeriformes* and *Gastropoda*, but increases in *Hemiptera*, *Coleoptera*, and pioneer plants. At the same time, prescribed fires were associated with *Lepidoptera* abundance increases and no declines in other taxa (Fig. 3). However, ecological impact cannot be predicted from intensity alone; declines in *Bryophyta* abundance after low-severity fire (Fig. 3; the "Fire-sensitive taxa: Gastropoda, Passeriformes, and Bryophyta" section) demonstrate that even low-intensity burns can negatively affect ground-layer taxa (Fernández-Guisuraga and Fernandes 2024; Pais et al. 2025; Viegas et al. 2024). Furthermore, prescribed burning inherently increases fire frequency and shortens fire-free intervals, which can cause resprouting failure in trees (Fairman et al. 2016), insufficient intervals for flowering and reproduction (Enright et al. 2015), and progressive structural decline (Anderson et al. 2025). Our meta-analysis could not directly assess cumulative frequency or seasonality effects due to inconsistent reporting across studies, but these factors likely modulate long-term outcomes and warrant explicit investigation.

Temporal patterns revealed trade-offs across taxa, though direct comparison is constrained by uneven data availability (Fig. 3; the "Method considerations and future research" section). Vascular pioneer plants (e.g., Ferns and Horsetails) showed positive post-fire abundance responses peaking at 5–10 years, while *Passeriformes* showed negative responses at 1–5 years post-fire (Fig. 3). This temporal mismatch suggests that structural complexity and microhabitat conditions (litter depth, bryophyte cover, humidity gradients, snag availability) may recover more slowly than plant cover (Herrando et al. 2003; Malmström et al. 2009). Conversely, insect (*Hemiptera*, *Lepidoptera*) abundances increased most within 1–5 years post-fire (Fig. 3). This creates a management dilemma where fire return intervals that optimize early-successional plant and insect diversity may perpetuate habitat deficits for taxa requiring late-successional conditions. Addressing this dilemma requires management approaches that create spatial heterogeneity mimicking natural patch dynamics (Holík et al. 2025). For example, creating mosaics of burned and unburned patches via targeted prescribed fire, while leaving adjacent structurally complex forest undisturbed (Niccoli et al. 2025), can support fire-tolerant species while providing essential refugia for fire-sensitive fauna (Pradervand et al. 2025).

Biome and ecoregion context further modulated post-fire responses. Generally, animal abundance was less negatively affected, and insect responses were more strongly positive, in the Mediterranean Forests, Woodlands, and Scrubs biome compared to Temperate and Boreal biomes (Fig. 4). This potentially reflects longer evolutionary exposure to fire (Calderisi et al. 2025; Schwörer et al. 2024), the testing of which is beyond the scope of this study. However, fire-sensitive taxa such as *Gastropoda* still declined severely within the Mediterranean (Fig. 4), and evolutionary fire-tolerance was not directly tested. Critically, our analysis shows that many biome-level responses were derived from a single ecoregion (Fig. 4), limiting generalizability (discussed further in the "Method considerations and future research" section).

Method considerations and future research

Our focus on abundance as the primary response metric was deliberate, given its sensitivity as an early indicator of ecological change (Santini et al. 2017) and cross-study compatibility. However, the extreme magnitude of some increases (Tables S12–14), particularly for *Lepidoptera*, Ferns and Horsetails, and broadleaved trees, warrants careful interpretation, as these may reflect genuine responses, transient pulses, edge effects, or methodological artifacts. Future meta-analyses integrating multiple biodiversity metrics (e.g., species richness, functional diversity, community composition) will provide a more comprehensive understanding.

Our analysis revealed critical data limitations that constrain management guidance. The absence of data for the critical < 1-year post-fire window for many groups, combined with underrepresentation of long-term post-fire trajectories (> 10 years), limits the assessment of both immediate impacts and full recovery dynamics. This uneven sampling prevents direct comparison of recovery rates and underscores the need for standardized, long-term monitoring. Furthermore, the complete absence of prescribed fire data for several fire-sensitive groups represents a key knowledge gap, preventing robust assessment of whether prescribed burns offer lower-impact alternatives for vulnerable taxa (Brugués et al. 2025).

High residual heterogeneity (Table 1) suggests that unmeasured factors play significant roles but are inconsistently reported in studies. These include burn frequency (Brugués et al. 2025), fire seasonality (Jorge et al. 2022), environmental context including vegetation cover (Brugués et al. 2025), microhabitat complexity (Han et al. 2025), microclimate and soil moisture (Puga et al. 2024), and taxa functional roles and traits including feeding specialization (Santos et al. 2014), body size (Puga et al. 2024), and mobility (Santos et al. 2014). Furthermore, aggregating taxa at coarse levels is problematic because it obscures declines in fire-sensitive taxa within broadly positive or neutral groups, a pattern evident in our *Hymenoptera* and Conifer results. This underscores the need for species-level analyses alongside higher-order syntheses (Bieber et al. 2023; Puga et al. 2024; Schüle et al. 2023).

While our synthesis represents a fairly comprehensive spatial assessment of European post-fire taxa abundance, spatial representation was uneven across forest biomes, with most observations from Temperate Broadleaf and mixed forests (36.6%) and Mediterranean forests (35.3%), and comparatively lower coverage of Boreal (12.3%) and Temperate Coniferous forests (15.8%; Fig. 1). Within these four biomes, only 13 of Europe's many forest ecoregions were represented, dominated by Central European mixed forests (28%) and Northeastern Spain and Southern France Mediterranean forests (26.1%), leaving extensive gaps across areas such as Icelandic, Ural, and Balkan forest systems (Table S7). This uneven coverage has direct consequences for spatial inference. Biome-level patterns frequently arose from a single nested ecoregion, such that the ecoregion result was effectively equated to the biome result (Fig. 4). The Boreal biome reflects data exclusively from the Scandinavian and Russian Taiga, and the Temperate Broadleaf and Coniferous biomes were each restricted to two ecoregions (Table S7). Conversely, multi-ecoregion aggregation can mask local signals: *Lepidoptera* showed no significant biome-level response in the Boreal yet increased significantly within the Scandinavian and Russian Taiga (Fig. 4). These patterns underscore that findings should be interpreted at the ecoregion scale and validated locally rather than derived from biome-level averages.

To address the identified data deficiencies, we recommend an integrative, coordinated approach to biodiversity monitoring and reporting in fire-affected ecosystems, including the following: (1) long-term, multi-taxa monitoring across successional stages and fire events, prioritizing underrepresented taxa and regions; (2) standardized reporting of fire intensity versus severity, microhabitat characteristics, refugia availability, functional traits; (3) include experimental prescribed fire studies in meta analyses, to explicitly measuring effects on fire-sensitive taxa to fill the critical knowledge gaps in effects on fire-sensitive taxa; and (4) finer taxonomic resolution to understand which species drive group patterns. Collaborative data sharing, coordinated monitoring, and improved measurements linking fire intensity to ecological severity are urgently needed to support evidence-based fire management in an era of accelerating climate change and altered fire regimes.

Management implications

Our meta-analysis demonstrates fundamental ecological trade-offs in post-fire European forests that are relevant to two management challenges: (1) biodiversity conservation amid increasing wildfire risk and (2) ecological sustainability of fuel load reduction strategies.

With climate change projected to increase wildfire frequency and severity, bolstering ecosystem resilience is critical. The taxonomic divergence documented here provides an evidence-based foundation for post-wildfire conservation planning. Fire-sensitive taxa declined across most contexts examined (the "Fire-sensitive taxa: Gastropoda, Passeriformes, and Bryophyta" section), and coarse taxonomic aggregation can mask these declines within broadly neutral groups (the "Taxa with complex or non-significant responses" section), underscoring the need for finer resolution, taxon-specific assessments. Given the vulnerability of certain taxa to even low-severity fire, post-fire management should prioritize conservation of fire refugia (areas unburned or burning at lower severity) (Andrus et al. 2021; Meddens et al. 2018). For low-mobility taxa, such as *Gastropoda*, unburned patches serve as essential source populations for landscape recolonization (Kolden et al. 2017). Proactively identifying potential refugia (e.g., moist valley bottoms, north-facing slopes, low fuel load areas) before fires occur, then prioritizing post-fire protection from disturbance, are key management priorities (Cervelli et al. 2022).

Our findings warrant careful interpretation regarding prescribed fire. Notably, no taxonomic group in our dataset showed a statistically significant negative response to prescribed fire, and some (*Lepidoptera*) show an increase, at least in the short term (Fig. 3). However, the complete absence of prescribed fire data for fire-sensitive taxa such as *Gastropoda* prevents conclusions that prescribed burns are benign for all taxa. Our caution stems not from demonstrated negative effects, but from unknown effects on vulnerable groups. Where data exist, effects appear neutral or positive, suggesting that carefully managed prescribed burns may benefit fire-responsive taxa while potentially reducing the risk of more severe wildfire impacts on sensitive habitats (Pastro et al. 2011). Nevertheless, prescribed fire as a fuel-reduction tool warrants careful evaluation in temperate and boreal forests, where many species lack fire-tolerance traits. Trophic linkages compound this uncertainty: *Gastropoda* serve as prey for birds and mammals (Rosin et al. 2011), and their decline could cascade to *Passeriformes*, potentially affecting broader ecosystem functioning.

Where fire-sensitive taxa are a conservation priority, alternative or complementary fuel reduction methods such as mechanical removal may reduce impacts on sensitive ground layers, though these carry their own trade-offs (Stephens et al. 2021; Stevens et al. 2016). Hylander (2011) found that clear-cutting caused lower Gastropoda mortality than burning, illustrating that context-specific method selection matters. No single management tool is universally appropriate; fuel reduction strategies should be tailored to local ecological contexts with explicit consideration of taxonomic trade-offs. Adaptive management frameworks incorporating monitoring of fire-sensitive taxa and predefined impact thresholds can help ensure that prescribed fire programmes remain responsive to ecological outcomes.

Conclusions

This meta-analysis provides a comprehensive, taxonomically broad synthesis of fire effects on abundance across European forests, revealing that taxonomic identity is the primary determinant of post-fire responses, though substantial heterogeneity remains. Fire acts as a selective ecological filter, creating stark divergences in taxa responses. Fire-sensitive taxa (*Gastropoda*, *Passeriformes*, bryophytes) abundance declined after fire, while fire-opportunistic taxa (*Hemiptera*, *Lepidoptera*, *Coleoptera*, vascular plants) abundances increased. This fundamental ecological trade-off challenges simplistic assumptions about fire management and demonstrates that no single strategy can simultaneously benefit all forest biodiversity.

These findings are relevant as climate change drives novel fire regimes across European forests. The absence of an overall effect across combined taxa underscores that fire impacts depend on taxonomic identity, fire characteristics, and environmental context. Biome-level patterns often arose from single nested ecoregions, and only 13 of Europe's forest ecoregions were represented, suggesting that spatial generalizability remains limited and that management recommendations should be validated at the ecoregion scale. Declines in *Bryophyta* abundance even at low fire severity challenge assumptions that low-intensity prescribed burns are universally benign, while the complete absence of prescribed fire data for many fire-sensitive taxa prevents a robust assessment of whether managed burns offer lower-impact alternatives. At the same time, no taxonomic group showed significant negative responses to prescribed fire where data exist, and some groups showed clear benefits, indicating that carefully managed prescribed burns may play a role in management strategies that include refugia conservation.

For fire management and conservation, our synthesis demonstrates that evidence-based decision-making requires explicit recognition of unavoidable taxonomic trade-offs. Approaches that incorporate spatial heterogeneity, proactively conserve refugia before fires occur, and target the protection of fire-sensitive taxa are essential. Critical data gaps, particularly the absence of early post-fire (< 1 year) monitoring, prescribed fire studies for sensitive taxa, and assessment of cumulative fire frequency and seasonal effects, constrain management guidance. Standardized, long-term, multi-taxa monitoring across successional stages, combined with experimental prescribed fire studies explicitly measuring effects on fire-sensitive taxa, are urgently needed to support adaptive management in an era of accelerating fire regime change across Europe.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-026-00471-x.

Additional file 1: Supplementary.

Authors' contributions

All authors contributed to the manuscript, have approved this manuscript for submission, confirm that the content has not been published or submitted elsewhere, and have no competing interests to declare.

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Data availability

The datasets generated and analysed during the current study (version 3) are available in the open-access Zenodo repository, https://doi.org/10.5281/zenodo.15800906.

Declarations

Competing interests

The authors declare that they have no competing interests.

Author details

[1]International Institute for Applied Systems Analysis, Biodiversity, Ecology, and Conservation Research Group, Schlossplatz 1, Laxenburg 2361, Austria.

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