# A global synthesis of fire effects on ecosystem services of forests and woodlands

Jose V Roces-Díaz[1*], Cristina Santín[2,3], Jordi Martínez-Vilalta[4,5], and Stefan H Doerr[1]

**Fire is a primary disturbance in the world's forested ecosystems and its impacts are projected to increase in many regions due to global climate change. Fire impacts have been studied for decades, but integrative assessments of its effects on multiple ecosystem services (ES) across scales are rare. We conducted a global analysis of persistent (>1 year) fire effects on eight ES reported over the past 30 years, evaluating qualitative and quantitative information from 207 peer-reviewed studies. Significant effects were predominantly positive for "water provision" and negative for "water quality", "climate regulation", and "erosion control"; for "food provision" and "soil fertility", no overall significant effects emerged; and for "recreation" or "pollination", data were insufficient. These effects were generally short-lived (1–2 years) and were more common after wildfires than after prescribed burns. However, available data were primarily derived from only a few countries/biomes and extended only over short time periods, highlighting the need for future research focusing on underrepresented regions and biomes, more extensive timeframes, and multiple ES.**

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Fire is a key ecological disturbance affecting a large fraction of the world's terrestrial ecosystems, spanning a broad range of regions and biomes (Bowman *et al*. 2009; Krawchuk *et al*. 2009). Fire can consume large amounts of biomass, alter soil properties, and substantially impact key ecosystem processes, influencing hydrological (Shakesby and Doerr 2006) and biochemical (Santín *et al*. 2015) cycles. From a biogeographical perspective, fire has also played a key role in plant evolution (Bond *et al*. 2005), for instance by promoting specific functional traits such as resprouting (Keeley *et al*. 2011). Consequently, the relevance of fire to global patterns of biodiversity and vegetation distribution is also widely acknowledged (Pausas and Ribeiro 2017; Kelly *et al*. 2020). The specific effects of a given fire depend on both ecosystem properties (eg fire-adapted versus fire-sensitive ecosystems) and fire characteristics (eg intensity, size, or recurrence; Lavorel *et al*. 1998; Archibald *et al*. 2013). Even during a single fire, impacts can differ both spatially and across different ecosystem components (soil, vegetation, and so forth; Keeley 2009; Mataix-Solera *et al*. 2011). Notably, current fire regimes are being modified by global change drivers (Lavorel *et al*. 1998; Doblas-Miranda *et al*. 2017).

## In a nutshell:

- Fire is a major disturbance in many regions, but its wider effects on ecosystem services (ES) remain poorly evaluated
- We conducted a systematic review of 30 years of literature on environmental effects of forest fires, examining 207 studies that permitted assessment of eight major ES
- Effects were significantly positive for "water provision" and negative for "water quality", "climate regulation", and "erosion control", and non-significant for "food provision" and "soil fertility"
- Negative effects were more dominant after wildfires than after prescribed burns, and effects were generally short lived (1–2 years)
- Key gaps are the lack of data for some regions and biomes (eg tropical forests) and for long-term impacts (>10 years)

Given its often substantial effects on the environment, fire is widely recognized as a key force affecting multiple ecosystem services (ES; Harper *et al*. 2018; Pausas and Keeley 2019; Sil *et al*. 2019), defined in the Millennium Ecosystem Assessment (MA 2005) as "conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life". Indeed, wildfires are often highlighted as one of the major disturbances that negatively impact ES in a range of terrestrial ecosystems, including forests and woodlands (Thom and Seidl 2016). These impacts can affect soil erosion (Shakesby 2011), runoff (Vieira *et al*. 2015), water quality (Harper *et al*. 2018), and soil fertility (Caon *et al*. 2014). However, fire can also enhance some ES (both directly and indirectly), including food provision or biological control of disturbances, due to the key roles played by natural disturbances in ecological processes (Pausas and Keeley 2019). Ensuring effective and desirable fire and land management outcomes requires a deeper understanding of fire impacts on ES, including the effects of both wildfires and prescribed burns (ie controlled fires for management purposes; Davies *et al*. 2016; Pausas and Keeley 2019).

[1]*Department of Geography, Swansea University, Swansea, UK* [*](*j.v.roces@swansea.ac.uk*); [2]*Department of Biosciences, Swansea University, Swansea, UK;* [3]*Biodiversity Research Institute (IMIB; CSIC-UniOvi-PA), Mieres, Spain;* [4]*CREAF, Cerdanyola del Vallès, Spain;* [5]*Universitat Autònoma de Barcelona, Cerdanyola del Vallès, Spain*

The effects of fire have been examined in some specific types of ecosystems and their functioning (eg savannas [Bond *et al*. 2005]; montane areas in the western US [Vukomanovic and Steelman 2019]; boreal regions in North America [Robinne *et al*. 2019]), but the role of fire on ES has not yet been addressed at the global scale. Integrative studies that encompass a wide temporal scale and quantify fire effects on a range of ES, with a broad geographical scope (including the most relevant ecoregions and ecosystem types worldwide) and that account for specific characteristics of these events (eg wildfires versus prescribed fires), are still lacking, even though such work is fundamental to gaining a basic understanding of the environmental effects of this global phenomenon and improving our capacity to forecast ecosystem change.

To address this gap, we conducted a quantitative global synthesis of published effects of fire disturbances on multiple ES in forested and woody-dominated ecosystems. In doing so, we identified not only the main trends from and knowledge gaps in three decades of research on the fire–ES relationship but also essential topics for future research. We hypothesized that the effects of fire vary across different ES, and that impacts are partially driven by the type of disturbance (eg greater impacts after wildfires than after prescribed burns) or by the temporal framework after disturbance (stronger impacts in the short term). Because ecosystems in different geographical areas exhibit distinct natural fire regimes and levels of adaptation to fire (Archibald *et al*. 2013), we also hypothesized that the effects of fire vary in different pyro-geographical and biogeographical areas (eg there are reduced impacts in areas with higher natural fire frequencies than in areas where natural fires are rare).

## Methods

### Ecosystems examined and data compilation

Information was extracted from the English-language, peer-reviewed literature reporting on field-based studies published within the past three decades (January 1989–July 2020). No geographical restrictions were applied. The search parameters that we used are provided in WebTable 1. In selecting studies analyzing fire events, we included papers containing "fire" or other similar terms in the title (eg "wildfire", "burn", and so forth). To focus the search on forest-type ecosystems, we then included studies that contained related terms (eg "forest", "woodland", "tree") in the title, keywords, or abstract. In addition, we included terms describing ecosystems in which trees and other continuous woody-vegetation (eg "shrublands", "scrublands") predominate, due to their relevance in some biomes (eg Mediterranean). Given that fire can alter ecosystem properties at different temporal scales (Wardle *et al*. 2003), we separated effects into short (1–2 years), intermediate (>2–10 years), and long (>10 years) terms after fire. Because we focused on persistent impacts, immediate effects (<1 year post-fire) were not assessed. To encompass as many ES as possible, we used terms related to ES included in the most recent version (v5.1) of the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin 2018) as additional search parameters to structure our search, covering a wide variety of provisioning, regulating, and cultural ES (WebTable 1).

By applying these search parameters, we identified 2614 studies. Titles, abstracts, and (where necessary) experimental designs were examined to select research that fulfilled our criteria (eg studies focused on effects >1 year after fire), resulting in a final selection of 207 studies (WebPanel 1), from which all relevant data were extracted to a database. Information was grouped into 32 variables, including 19 descriptive variables to characterize the context of the studies, seven explanatory variables to test the different hypotheses, and six response variables quantifying fire effects on each ES (WebTable 2). Our seven explanatory variables classified fire events in terms of *four different aspects:* (1) *timeframe after disturbance* (short, intermediate, and long); (2) *type of event* (prescribed burns versus wildfires); (3) *biome* as assigned to one of the 14 World Biomes defined by Olson and Dinerstein (1998) (Figure 1), and then clustered into the following four biome groups: (i) boreal, (ii) temperate, (iii) Mediterranean, or (iv) tropical (these four groups were used in all further statistical analyses, except in the graphical representation of Figure 1, in which the original 14 types were used); and four variables for *fire regime*: (4) regions with high-intensity versus low-intensity fires, (5) regions affected by frequent fires versus regions affected by rare fires, (6) "fire dependent" versus "fire sensitive" areas, and (7) areas where fire is considered a "natural force" versus areas "where it is not". All variables are described in more detail in WebTable 2.

### Data analysis

Data extracted from the 207 studies included eight indicators assessing ES according to the CICES classification, consisting of two indicators for *provisioning* ES (food provision and water provision), five indicators for *regulation and maintenance* ES (mitigation of soil erosion, pollination, water-quality regulation, soil fertility regulation, and climate regulation), and one indicator for *cultural* ES (recreation). Each database entry represented the value of one ES indicator before and at a specific time after a fire event, and thus, a single study may include more than one entry. A positive or negative sign was assigned to each of these values depending on how they affected the ES indicator. For example, we considered the increase of runoff water as positive for water provision, although this increase can bring lower levels of other water fluxes (eg evapotranspiration) and other negative impacts (eg water contamination from eroded ash) (Bodí *et al*. 2014). The total number of entries including all ES was 2474; these were used as the basic units for further analyses.

For each ES, we conducted two analyses based on the comparison of the value of each ES indicator before and after the fire and using the explanatory variables described above. We first developed a semi-quantitative (frequency) analysis for each ES comparing the pre- and post-fire values, and then we fitted different general linear models (GLM) to each target ES. These models included linear regressions (LR) and mixed-effects models (ME), the latter using one variable (the study) or two variables (the study and the ES indicator, crossed) as random factors on the intercept. In all cases, our dependent variable was the logarithm of the ratio between the ES indicator values after (post-) and before (pre-) disturbance (log-ratio), which is a common measurement of effect size in meta-analyses (Hedges *et al.* 1999). Because it is a unitless ratio, this metric allows for combining entries derived from different indicators evaluating the same ES, even if their units differ. These models could only be fitted to cases in which the target ES was assessed before and after the disturbance (76% of all entries). This modeling approach was not performed for two ES (recreation and pollination) because of the low number of entries available for them (only 58 and 29 from five and three different studies, respectively; Figure 2b). The two pyrome variables (pyrome by intensity and pyrome by frequency) were used to test the effects of fire regimes on the different ES. The Akaike information criterion (AIC) was used to compare the fit of and to select among the different models for each ES, including LR and ME with one or two random factors. We used R (v3.5.3; R Development Core Team 2019) for fitting, for assessing the significance of explanatory factors, and for estimating marginal and conditional $R^2$ values (packages *lme4* [Bates *et al.* 2015], *lmerTest* [Kuznetsova *et al.* 2017], and *MunMIn* [Calcagno and de Mazancourt 2010], respectively). Significant differences between levels of a given factor were tested using pairwise contrasts and estimated marginal means (ie the mean response for each factor adjusted for any other variables, using the *emmeans* package; Lenth *et al.* 2018).

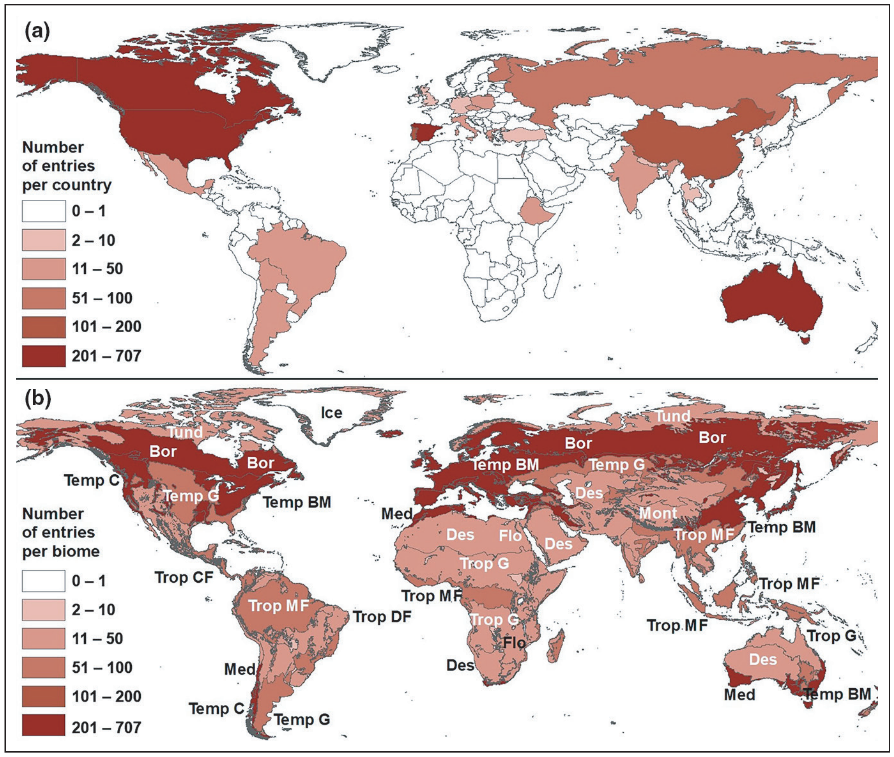


**Figure 1.** Geographical distribution of the database entries compiled by (a) countries and (b) biomes (sensu Olson and Dinerstein 1998). Terrestrial biomes included were boreal forests (Bor); tundra (Tund); montane grasslands and shrublands (Mont); flooded ecosystems (Flo); temperate broadleaf and mixed forests (Tem BM); temperate conifer forests (Temp C); temperate grasslands, savannas, and shrublands (Temp G); Mediterranean forests, woodlands, and scrublands (Med); desert and xeric shrublands (Des); tropical and subtropical moist broadleaf forests (Trop MF); tropical and subtropical coniferous forests (Trop CF); tropical and subtropical dry forests (Trop DF); and tropical and subtropical grasslands and savannas (Trop G). The terrestrial biome "mangroves" was not covered in the literature included in our analysis. Areas covered by ice were not included in our study. Note that for biomes that are widely distributed, most entries may be located in a specific area (eg the majority of studies focusing on the boreal forest were conducted in North America and not Eurasia), and therefore (a) and (b) complement each other.

## Results

### Current status of global fire research on forest and woodland ES

A marked increase of published studies is evident over the past three decades in this research field (WebFigure 1). The studies included here originated from 27 countries (Figure 1a), with the US (29%), Spain (19%), Canada (12%), and Australia (12%) having the highest number of database entries. No entries originated from most countries in the Middle East, Central Europe, Central America, and Africa. Regarding the original classification of World Biomes, our database included entries from 13 of the 14 terrestrial biomes, but >85% of entries originated from four biomes, most in the northern hemisphere (Figure 1b): temperate conifer forests (29%), temperate broadleaf and mixed forests (28%), Mediterranean (20%), and boreal forests (10%).

Studies covered a wide range of forest, woodland, and woody-dominant ecosystems with over 30 dominant plant genera represented (Figure 2a). Almost half of the database entries focused on ecosystems where *Pinus* species were dominant, especially *Pinus ponderosa* and *Pinus contorta* in North America, *Pinus sylvestris* in Eurasia, *Pinus halepensis* in the Mediterranean Basin, and *Pinus pinaster* in Atlantic Europe (WebFigure 2). Oak (*Quercus*) species were frequent in studies in Mediterranean Europe, central Europe, and North America. Finally, *Eucalyptus* species also had many entries, primarily in

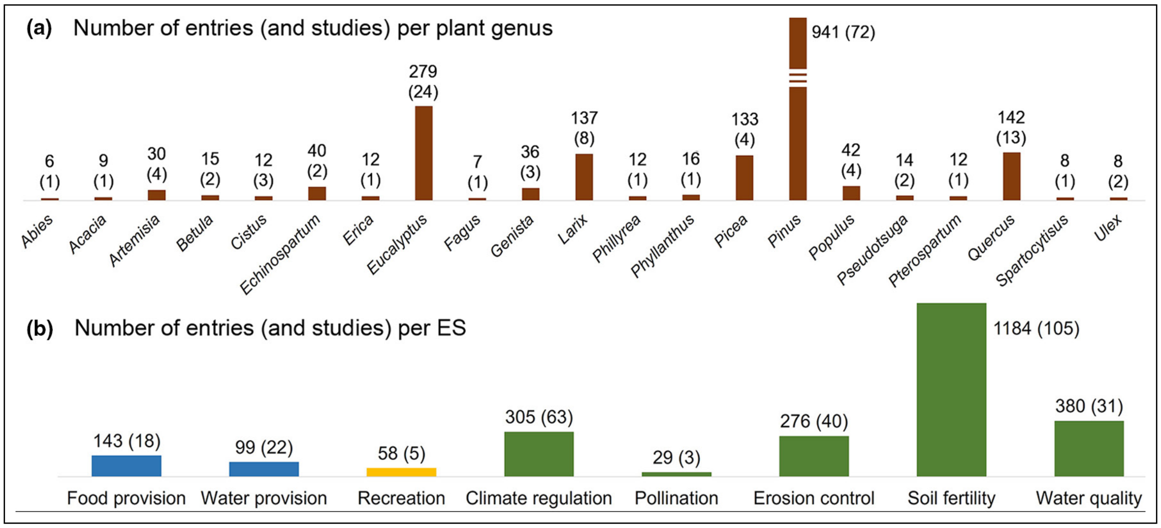


**Figure 2.** Number of entries (and studies) sorted by (a) plant genus and (b) ecosystem service (ES) (see also WebFigures 2 and 3). Each entry represented the value of one ES indicator before and at a specific time after a fire event, and thus, a single study may include more than one entry. In (b), the eight selected ES that serve as indicators (see main text) appear along the x axis: two indicators for provisioning ES (blue), five indicators for regulating and maintenance ES (green), and one indicator for cultural ES (yellow).

studies based in areas where they are naturally distributed (Australia) but also along the Atlantic Coast of southwest Europe (mainly Portugal and Spain).

Although most studies focused on wildfires (77%), a relatively large proportion (23%) assessed prescribed burns. Our database included events with a wide range of sizes (WebFigure 1), from fires smaller than 2 ha to fires larger than 25,000 ha. Most studies did not provide quantitative/detailed information for an accurate characterization of the disturbance regime (such as fire frequency, intensity, or severity). Regulating ES (particularly soil fertility, water quality, erosion control, and climate regulation) were most frequently represented, whereas other ES (such as food or water provision, pollination, or cultural services) were rarely assessed (Figure 2b).

## Impacts of fire on forest and woodland ES

### *Frequency analysis*

Overall, for seven of the eight ES, the number of negative effects was higher than the number of neutral and positive effects (Figure 3; WebFigure 4). Negative impacts were particularly frequent (>50%) for food provision, recreation, climate regulation, and water quality. Water provision showed predominantly positive effects derived from the

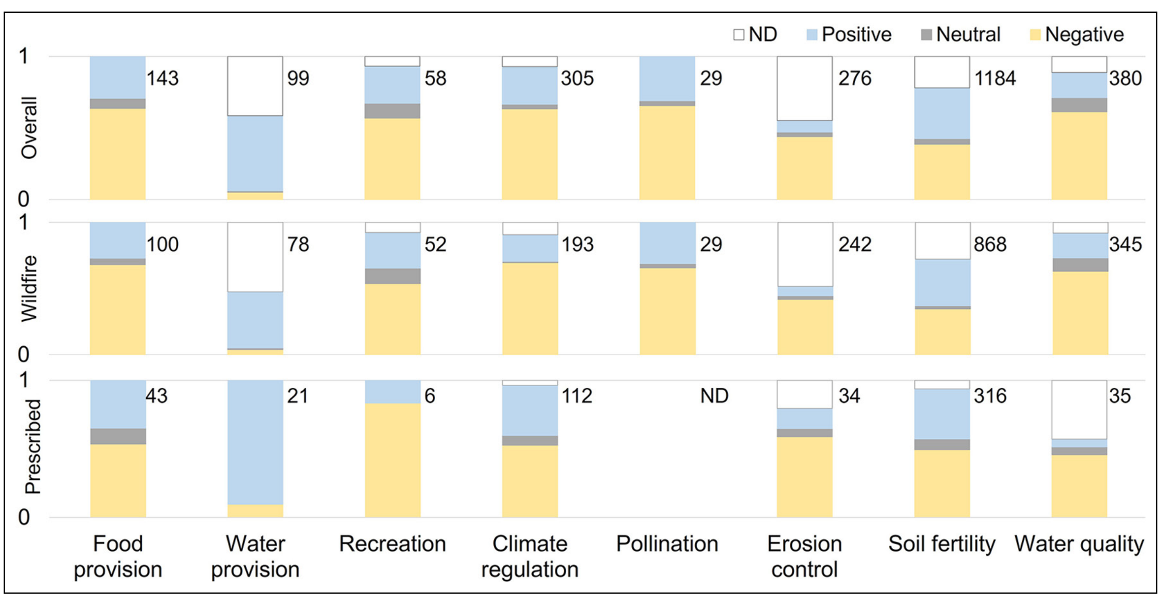


**Figure 3.** Frequency of positive, neutral, and negative effects of fire on the eight selected ES, overall (top row) and separately for wildfires and prescribed burns (middle and bottom rows, respectively). The value to the right of each bar represents the total number of entries (*n*) for each ES within the three categories. ND = no data.

increase of post-fire runoff. For other ES, such as pollination and soil fertility, 30–35% of entries reported positive effects. Regarding the type of event, three ES (food provision, climate regulation, and water-quality regulation) exhibited higher frequencies of negative impacts after wildfires than after prescribed burns; for other ES (eg soil fertility, erosion control), similar or even higher frequencies of negative effects were reported after prescribed burns than after wildfires.

### Model-based analysis

The fitted GLMs identified significant effects of different explanatory variables. WebTable 3 shows all of the 18 models fitted, WebTable 4 presents the results using the two alternative variables for fire regimes, and Figure 4 depicts estimated marginal means (ie the mean response for each factor, adjusted for any other variables, for selected models). A substantial percentage of entries for erosion control (45%) and water provision (41%) did not include a pre-disturbance reference value (ie "no data" in Figure 3; these entries were not included in the models). Water provision showed predominantly positive effects of fire events for almost all factors, whereas water-quality regulation showed the opposite pattern. Wildfires had significantly negative effects on climate regulation, erosion control, and water quality (Figure 4); prescribed fires also had a negative effect, albeit less so, on water quality. The magnitude of the effects tended to decline over longer temporal scales, with the exception of climate regulation. In pyromes with low fire frequency, the positive effect of fire on water provision was not significant, and the negative impacts of fire on climate regulation were not observed. Finally, with regard to biomes, significantly positive effects (Figure 4) on water provision were detected in temperate and Mediterranean systems (the only locations with data) and on soil fertility in temperate ecosystems. Significantly negative effects on climate regulation were found in temperate and boreal biomes and on erosion control in temperate biomes.

## Discussion

This study represents, to the best of our knowledge, the first global synthesis of reported fire effects on a wide range of ES, and is based on an analysis of information extracted from 207 studies published over the past 30 years. The distribution of the obtained information is clearly biased in terms of geographic location and types of ecosystems analyzed. Most studies focus on North America, southwestern Europe, and Australia (Figure 1a). Biomes located in temperate and Mediterranean areas are overrepresented as compared to global patterns of area burned (Andela *et al.* 2017). This is partially the result of our study focusing on ecosystems dominated by tree and woody species and excluding other fire-prone

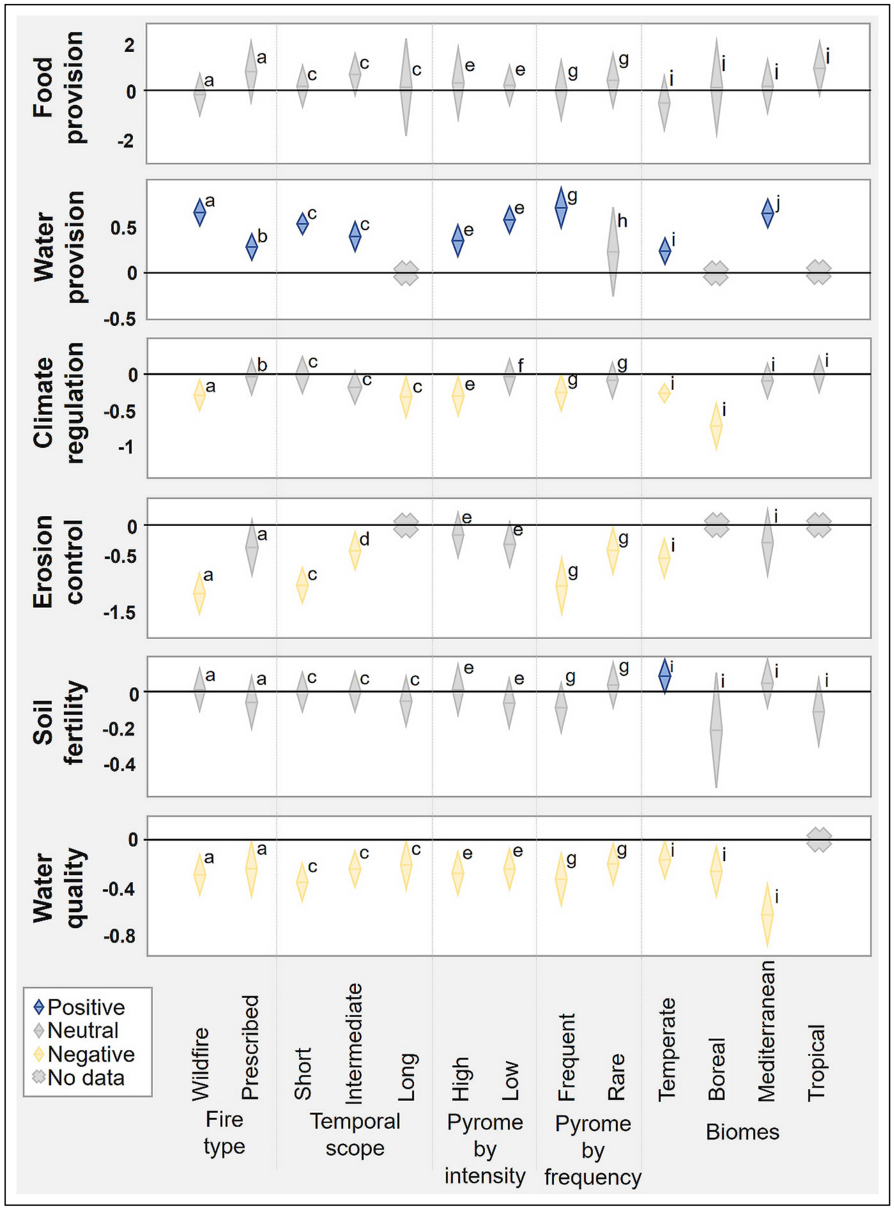


**Figure 4.** Direction and size of effect of fire on ES based on estimated marginal means (emmeans) obtained from the models for each level of the explanatory variables examined. For each ES, estimations show the effects of each level of the explanatory variables (means [horizontal bars within diamond symbols] and 95% confidence intervals [vertical length of diamond symbols]). Equal letters represent non-significant differences among factor levels; different letters for each variable represent significant differences between ES among levels for (a, b) fire type, (c, d) temporal scale, (e, f) pyromes by intensity, (g, h) pyromes by frequency, and (i–k) biomes. Note that two of the eight ES (recreation and pollination) were not included in the model analysis due to the small number of data entries available.

systems such as savannas (Zimmermann *et al.* 2008). Nonetheless, the distribution of the data also reveals a scarcity of published research – in English at least – in other relevant ecosystems, such as tropical and subtropical forests in Africa, South America, or Southeast Asia (Figure 1b), despite fire being an important disturbance in these regions (Krawchuk *et al.* 2009). Our results also revealed an unbalanced distribution of the eight ES assessed. More than 90% of the entries included in the analysis focused on ES relating to soils and the hydrological cycle (eg soil fertility, erosion control, water quality), most likely reflecting the growing interest of the scientific community in fire, water, and soil interactions (eg Shakesby 2011; Caon *et al.* 2014). In contrast, other ES are understudied, especially those in the cultural category, which is consistent with the comparatively low representation of these ES in environmental assessments (Satz *et al.* 2013). Likewise, other important aspects, such as fire effects on pollination or water provision, were examined in only a few studies (Bladon *et al.* 2014; Carbone *et al.* 2019).

Of the recorded effects of fires on ES, 28.5% were reported as being positive, but overall our analysis suggests a predominance of negative effects (46.6%). Negative effects were also dominant (>50%) in a previous analysis of ES in Colorado montane ecosystems (Vukomanovic and Steelman 2019). It is worth considering, however, that negative environmental impacts of fire have been studied for decades by researchers and acknowledged by managers (eg DeBano and Conrad 1978; Hauer and Spencer 1998), and that fire is mainly perceived by society as a major environmental and socioeconomic hazard (Doerr and Santín 2016). It is therefore conceivable that most studies to date have been designed for detecting and highlighting negative fire effects rather than focusing on the positive roles of fire, for example in ecological functioning (Boisramé *et al.* 2017; Jones *et al.* 2019). In addition, there may be a publication bias favoring studies that present substantial rather than limited or neutral effects (Csada *et al.* 1996).

Despite the dominance of negative effects, the proportion of positive fire effects we found is considerable (WebFigure 4). Previous literature shows a range of potential positive effects of fire, including for example those on water yield (Shakesby and Doerr 2006) (but not on water quality), on food provision (improving grazing resources by stimulating germination; Pausas and Keeley 2019), and on pollinator populations (Carbone *et al.* 2019). In addition, it is important to note that indicators that have a negative impact may also have secondary positive effects on other ES; for instance, soil erosion is generally considered as a negative impact, but seen in a different light, erosion is also a natural process that helps to redistribute soil, nutrients, and other material. Moreover, erosion can interact with other ecological processes at the landscape level and affect other ES in positive ways, such as through burial of soil carbon, a positive ES from a climate-regulation perspective (Van Oost *et al.* 2007). Therefore, positive effects of fire on ES and the identification of ES directly derived from fire occurrence (eg reduction in the risk of more severe future wildfires, maintenance of open spaces for grazing, and so forth; Pausas and Keeley 2019) may be partially masked by the type and availability of studies conducted to date. Because of the aforementioned potential bias and data scarcity associated with certain ES, with certain types of fire events, and with certain pyromes/biomes, the predominantly overall negative effect of fire on ES reported here should be interpreted with caution.

Fitted models revealed that effects of wildfires were negative for erosion control, climate regulation, and water quality, and positive for water provision (Figure 4). Regarding the type of event, prescribed burns had a significantly negative effect only on water quality (setting aside the positive role of prescribed burning in reducing future fire risk and potential impacts on ES). Prescribed fire is a widely applied land management tool for fuel reduction and ecosystem rejuvenation, among other purposes (Fernandes *et al.* 2013; van Wilgen 2013). Typically less intense and smaller in extent than wildfires (Fernandes and Botelho 2003), prescribed fires are expected to have reduced impacts on ES (Harper *et al.* 2018). However, previous studies detected no substantial differences between wildfires and prescribed fires for ES such as erosion control (Shakesby *et al.* 2015) or pollination (Carbone *et al.* 2019), and the role of prescribed burns for multipurpose management at multiple scales and temporal frameworks remains unresolved (eg Davies *et al.* 2016). Our database reveals fewer studies assessing prescribed burns than wildfire, and further research comparing multiple impacts on ES from prescribed fire versus wildfire events is clearly warranted.

Regarding our first hypothesis (that fire effects will vary in their impact across different ES in space and time), we detected a notable role of timescale on fire effects for erosion control and water quality (Figure 4). These two ES exhibited more negative effects in shorter terms than over longer periods after fire, most likely due to temporal patterns of post-fire vegetation recovery and the associated duration of the window of disturbance (Shakesby and Doerr 2006; Wittenberg *et al.* 2007). Fire had a significant (negative) impact on climate regulation in long-term studies, which may be partially related to the decline in post-fire carbon accumulation rates in ecosystems (Volkova *et al.* 2018). In contrast, effects on food provision and soil fertility did not differ considerably over time. In general, however, the number of entries for most ES is insufficient to draw robust conclusions for impacts over extended periods of time (>10 years).

Our results failed to provide support for our second hypothesis (of finding differences among pyromes/biomes based on the expected adaptation of ecosystems to specific fire regimes) (Archibald *et al.* 2013). Fitted models indicated that for climate regulation, fires in regions characterized by infrequent fires had fewer negative impacts than did fires in regions that experience greater fire frequency. However, we did not find evidence for lower levels of impact in regions with high-intensity fire regimes than in regions with low-intensity regimes (WebFigure 4; Figure 4), where, in accordance with our second hypothesis, it would be expected that ecosystems would be more adapted to fire (Keeley *et al*. 2011). Similarly, comparisons among biomes revealed very few significant differences (eg on water provision). It should be noted, however, that only a selection of frequently studied effects of fire were included in our analysis. In addition, interactions among explanatory variables can be potentially important, but we were unable to explore these because several combinations of factor levels were not represented (or had very low sample sizes) in our database. Several relevant ecological processes were also not included in our search, as we focused on the most common categories of ES indicators. For example, we did not compile information about snowpack dynamics in the case of water provision (Robinne *et al*. 2019) or pyrogenic carbon in the case of climate regulation (Santín *et al*. 2016). Finally, the information available in the compiled studies did not allow for detailed investigation into relationships between individual fire characteristics (eg fire intensity, severity), or current alterations in their natural/historical regimes, and their specific effects on studied ES. The resulting knowledge gaps and directions for future research identified in this global synthesis are described in Panel 1.

## Conclusions and implications for forest and land management

Fire plays a key role in the world's forest and woodland ecosystems, affecting fundamental aspects of their ecological functioning. Using a multi-ES approach, we analyzed and evaluated the fire effects on these ecosystems that have emerged over the past 30 years of research. The resulting global synthesis reveals that research has been largely focused on regulating-type services, and predominantly those relating to the soil component (eg soil fertility, erosion mitigation) as well as water and carbon cycles, with a strong geographical bias toward some countries (eg US, Spain) and biomes (eg temperate forests).

Fire is often perceived by society as a natural hazard with predominantly negative effects (Doerr and Santín 2016). Although our results demonstrated that only some fire effects on ES were statistically significant, and that prescribed burn effects on ES were generally less negative than the impacts of wildfires, these findings must be viewed with caution, given that most studies may have been focused specifically on detecting negative impacts. Indeed, most studies examined short-term impacts and were rarely designed to detect positive effects of fire on ES, even though fire is essential for maintaining fire-adapted ecosystems (Pausas and Keeley 2019).

Building a more complete picture of fire effects on ES and enabling well-informed ecosystem management decisions will require additional research in underrepresented regions and biomes as well as a stronger focus on identifying and assessing potential positive or neutral effects of fires on ES. These limitations, and the wide geographical scope of our analysis, imply that although the general outcomes reported here can provide useful guidance at regional or biome scales, they may not always be applicable at specific local scales. The recommendations for policy makers and forest managers presented in Panel 2 should therefore be viewed largely in a regional or biome

**Panel 1. Primary knowledge gaps and suggested future research directions**

(1) Assessment of fire effects in tropical and subtropical biomes.
(2) Assessment of fire effects on provisioning and cultural services.
(3) Integrated analyses, including quantitative information on fire behavior and characteristics, such as fire intensity (ie energy released), burn severity (ie organic matter/biomass destruction), and fire return interval.
(4) Monitoring long-term (>10 years) effects of fire.
(5) Comprehensive comparison of the effects of prescribed burns and wildfires for a wider range of ES.
(6) Comprehensive analysis of the role of fire as a provider of ES, as well its integration into management strategies to maximize specific services.
(7) Explicit assessment of the impact of future fire regimes, particularly those falling outside their natural/historical range of variability for different biogeographical/ecological regions.

**Panel 2. General recommendations for policy makers and forest managers**

(1) Integrated multi-ES approaches are recommended for developing land management and wildfire mitigation strategies at different (from local to supranational) spatial scales. Those ES that are not often assessed (such as cultural ES), as well as ES that were not included in this synthesis (such as the role of fire mitigating more severe future wildfires), should be taken into account before defining policies.
(2) This global assessment supports the use of prescribed burns as a management tool given its limited negative effects compared with wildfires for such ES as erosion control and water-quality regulation.
(3) Given the identified lack of knowledge on fire effects on ES for some specific pyromes and biomes (ie tropical and subtropical), caution is advised when extrapolating findings from certain regions to understudied areas.
(4) Most of the significant effects identified here do not last very long, and are attenuated within several years (>10 years) after the fire disturbance.

context, for instance to inform coarse-scale fire management strategies.

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