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Effects of Prescribed Fire on the Post-fire Hydrological Processes in Agro-forest Ecosystems: A Systematic Review and a Meta-analysis

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Abstract

Prescribed fires are one of the most effective tools to reduce the risk of wildfires but this treatment may negatively affect the hydrological and erosive response of soil, with noticeable increases in surface runoff and soil erosion. Many studies have been published on this matter but there is no consensus in the literature on the magnitude and duration of these effects since the relevant hydrological conditions are site-specific. Moreover, the relationship between post-fire hydrology and its main environmental drivers has been little explored. This study has carried out a bibliographic review and a meta-analysis of the changes resulting from prescribed fire applications (water infiltration, soil water repellency (SWR), surface runoff and soil erosion) using a database of 85 case studies from 41 academic papers that have been published over the last 23 years. The effects of annual precipitation, soil slope, burn severity, fire application season, post-fire ground cover, and vegetation type on those changes have also been statistically explored.

The bibliographic review has revealed that previous case studies have not been equally distributed across the globe but concentrated in only a few countries, mainly the USA and Spain. The meta-analysis has revealed that: (i) water infiltration generally decreases and soil water repellency appears with noticeable increases in surface runoff and soil erosion immediately after the prescribed fire, while the pre-fire values progressively recover over time; (ii) the window of disturbance in burned soils may last a few months (with some exceptions); (iii) annual precipitation and soil slope significantly influence water infiltration and surface runoff, but not soil erosion, in both the short-term and medium-term; (iv) moderate-to-high levels of soil burn severity severely enhance surface runoff and soil erosion, and noticeably reduce water infiltration in the short-term; (v) the level of ground cover burning is important for reducing the runoff rates, but it plays a minor role in water infiltration and soil erosion rates; (vi) the prescribed fire applied in spring results in lower increases in short-term runoff and erosion, while fire applications in summer and in shrublands produce the highest increases in soil loss.

The following practical recommendations arise from this study: (i) research should be better distributed across all environmental contexts on a global scale; (ii) post-fire management actions should be immediately implemented after the prescribed fire application; (iii) prescribed fire should be carried out in spring and the soil burn severity should be kept low during burning; (iv) the monitoring studies should be prolonged at least for some years (more than two or three) after prescribed fire; (iv) the catchment-scale investigations, although more difficult and expensive, should be encouraged (avoiding, however, areas to sparsely burnt in the context of the whole catchment); (v) the monitored variables should also include the most important physical, chemical and biological properties of soil, the cover and structure of regenerating vegetation, as well as the water quality parameters; (vi) the effects of repeated applications of prescribed fire should be experimentally assessed; (vii) guidelines for standardized and appropriate measurements and analytical methods in experimental activities should be set up. These indications support the use of land managers in the monitoring of the hydrological impacts of the prescribed fire and in the choice of sites where post-fire management actions must be implemented. The last recommendation of this study is the creation of an experimental database supporting the bibliographic review and the meta-analysis, which is made available to other researchers and land managers, to create a public, easily-accessible and comprehensive tool for future research needs and professional use.

Keywords: water infiltration; soil water repellency; surface runoff; soil erosion; annual precipitation; soil slope; soil burn severity; burn season; post-fire ground cover; vegetation type.

1. INTRODUCTION

One of the most commonly used strategies to reduce the wildfire risk in forests, shrublands and grasslands is the application of prescribed fire (Úbeda *et al.*, 2005; Neary and Leonard, 2021). Prescribed fire is a controlled fire that partially or totally removes dry litter, and herbaceous and shrub vegetation, which are prone to catching fire in forests in dry periods under suitable weather conditions (e.g., humid air and absent wind) and topographic (low-density and mild steepness) conditions (Fernandes *et al.*, 2013). Generally, prescribed fire is done at low intensity and in a scattered nature (Cawson *et al.*, 2012; Pereira *et al.*, 2021). These characteristics help to reduce the fire impacts on the different components of the affected forest ecosystems (Cawson *et al.*, 2012;

Francos and Úbeda, 2021). The impacts of prescribed fires on soil properties are not generally detrimental, thanks to the limited burning temperature and fire duration (Cawson *et al.*, 2016; Pereira *et al.*, 2018; González-Pelayo *et al.*, 2015). However, prescribed fires can negatively affect soil properties (Alcañiz *et al.*, 2018; Francos and Úbeda, 2021), since even fires with low intensity remove vegetation and modify the hydrologic and chemical properties of soil (Certini, 2005; Shakesby, 2011; Cawson *et al.*, 2012). When the forest soil is left bare due to vegetation removal, rainsplash erosion and particle detachment by overland flow generally increase (Lucas-Borja *et al.*, 2022b). Water infiltration, which is often high in undisturbed forest soils (Robichaud, 2000), can decrease, and soil hydrophobicity may appear (Zema *et al.*, 2021a, 2021b). Moreover, on forest hillslopes with steep profiles, surface runoff and soil loss may be more severe than on sites with milder profiles, with possible off-site effects, such as excess runoff, pollution of water bodies and transport of huge amounts of sediments to the valley areas (Shakesby and Doerr, 2006).

The complexity of the hydrological processes in forests burned by prescribed fires derives from several environmental components (e.g., climate, soil, vegetation, and management). This complexity has been the focus of several studies (e.g., Shakesby and Doerr, 2006; Zavala *et al.*, 2014; Pereira *et al.*, 2018), resulting in a large and eminent body of literature about the impacts of prescribed fire on soil hydrology. However, the results of many studies on runoff and erosion after prescribed fires have not been conclusive and have often been contradictory (Cawson *et al.*, 2012; Shakesby *et al.*, 2015). For instance, González-Pelayo *et al.* (2010) and Vega *et al.* (2005) report increases in runoff and erosion by one and two orders of magnitude after prescribed fires, in comparison to unburned areas. In contrast, according to Coelho *et al.* (2004), de Dios Benavides-Solorio and MacDonald (2005), and Morris *et al.*, (2014), erosion after prescribed fire is minimal. Even Keesstra *et al.* (2014) state that erosion in areas burned by prescribed fire is lower compared to unburned forests, despite comparable runoff. There has also been a lack of consensus in the literature over the time scale of these hydrological impacts on soil properties. A fire, regardless of its severity or intensity, creates a “window of disturbance” in the soil’s hydrological behaviour (Prosser and Williams, 1998). In this period, lasting some months from the prescribed fire’s application, the soil is left bare due to vegetation removal and the changes in its properties are more severe than after other disturbances. The recovery of pre-fire soil properties, and of undisturbed hydrological and erosive responses may take place over short (Zhao *et al.*, 2015) or long (Alcañiz *et al.*, 2016) periods. This time scale depends on many factors in the case of prescribed fires, such as the temperature and residence time of the fire, orography of the burned area, weather characteristics, and level of vegetation recovery (Úbeda *et al.*, 2018; Girona-García *et al.*, 2021).

The magnitude and prolongation of prescribed fire impacts on soil hydrology are driven by several variables, such as the level of ground cover removal due to fire, weather patterns, burn severity, application season and soil slope (Cawson *et al.*, 2012; Alcañiz *et al.*, 2018). All these factors, being site-specific, are variable in different environments according to the climatic, geomorphological, and ecological characteristics of the fire-affected forests, but are also not replicable across time even in the same burned soil. This means that a better understanding of the effects of prescribed fires in environments with contrasting characteristics requires the site-by-site evaluation of the hydrological and erosive response to a specific fire and rainstorm (Hubbert *et al.*, 2006; Hueso-González *et al.*, 2018). Due to the practical impossibility to carry out these evaluations in each site that is potentially prone to wildfire, it is essential to rely upon systematic reviews of published literature coupled with a quantitative evaluation of the relevant data. This method allows for the extraction of general and conceptual knowledge about extremely complex and variable processes, such as those related to post-fire hydrology, thus overcoming the site-specific variability of the hydrological processes, which is a typical limitation of local studies.

The availability of sophisticated analytical techniques, such as meta-analysis, allows the linking of the data reported in the literature to important drivers of post-fire soil hydrology, such as the climate, burn severity, soil slope, vegetation characteristics, and post-fire ground cover, using a quantitative approach. Meta-analysis is increasingly used to quantitatively evaluate whether a variable (e.g., soil burn severity) affects an environmental process (e.g., erosion) compared with reference conditions (e.g., unburned plots) across a range of studies, and to test the variable's statistical significance (Gurevitch *et al.*, 2018; Girona-García *et al.*, 2019). For example, Girona-García *et al.* (2021) carried out a systematic review and a meta-analysis on the effectiveness of mitigation treatments in post-fire soil erosion, successfully demonstrating how these analytical techniques can provide insights applicable to scientists and technicians working in environmental contexts with similar characteristics.

Other important reviews and/or meta-analyses of fire effects have been published in recent years. In addition to the paper of Girona-García *et al.* (2021), Vieira *et al.* (2015) have explored the effects of soil burn severity on post-wildfire runoff and inter-rill erosion based on rainfall simulation studies. Concerning prescribed fire, Cawson *et al.* (2012) have published a review that analyzed surface runoff and soil erosion after prescribed fire in forests and shrublands, while Alcañiz *et al.* (2018) have reviewed the studies specifically dealing with the effects of prescribed fires on soil properties. More recently, Klimas *et al.* (2020) reviewed prescribed fire effects on sediment and nutrient exports in forested environments. However, the latter studies have not carried out any meta-analyses and show some research gaps: (i) some important factors that are associated with soil hydrology due to the application of prescribed fires have not been compared among the reviewed studies, e.g., surface runoff in Alcañiz *et al.* (2018) and Klimas *et al.* (2020), infiltration and soil water repellency in Klimas *et al.* (2020); (ii) the paper by Cawson *et al.* (2012) is dated from more than ten years, and therefore several recent papers have not been included in the analysis.

To fill these literature gaps, this study proposes a review and a meta-analysis of the effects of prescribed fire on water infiltration, soil water repellency, surface runoff and soil erosion on a global scale. To this aim, the relevant literature published in the last 23 years has been systematically reviewed, and the published data about those environmental variables have been statistically analyzed, to explore their associations with some important driving factors (e.g., precipitation patterns, soil slope, post-fire ground cover, vegetation type, fire application season, soil burn severity) of soil hydrology after a prescribed fire. Research questions include: (i) Is the role of prescribed fire as a management tool recognized worldwide? (ii) How much do water infiltration, soil water repellency, surface runoff and soil erosion vary between unburned and burned soils? (iii) How long does the window of disturbance last for soil to then recover the pre-fire hydrological and erosive rates? (iv) Do the effects of prescribed fire vary across different climatic and morphological characteristics? (v) What are the effects of soil burn severity on post-fire soil hydrology? (vi) Does the amount of post-fire ground cover left by burning (including herbs, shrubs, and litter) have a significant effect on the hydrological and erosive response of soil? (vii) What is the ideal time and vegetation type for prescribed fire application? The replies to these research questions could give scientists a better understanding of the magnitude and duration of the hydrological and erosive effects of prescribed fires. The experimental database supporting the bibliographic review and the meta-analysis is made available to other researchers and land managers, to create a public easy-accessible and comprehensive tool for future research needs and professional activities. The results of this study may help land managers and technicians to predict and control the effects of prescribed fire on flooding and on causing hydrogeological hazards downstream of the treated agro-forest ecosystems.

2. METHODS

2.1. Paper Search and Selection

Comprehensive bibliographic research was carried out in late March 2023 on Scopus®, Web of Science® and Google® Scholar® databases to find academic papers relevant to prescribed fire and soil hydrology published between the year 2000 and the present (Figure 1). The following individual keywords or combination of keywords were used: prescribed fire, prescribed burning, water infiltration, soil hydraulic conductivity, soil water repellency, soil hydrophobicity, surface runoff, soil loss and water erosion. We excluded technical reports, M.Sc. and Ph.D. theses because these documents did not undergo peer review, and papers not published in English. This bibliographic research returned 68 papers, of which 27 were discarded for their: (i) being carried out in a laboratory; (ii) not providing quantitative data about the hydrological variables; (iii) not containing measures in unburned areas; (iv) not being peer-reviewed or published in international conference proceedings.

[Insert Figure 1]

2.2. Data Collection and Database Compilation

All papers with the reported case studies were carefully analyzed, to compile a database in an Excel® file (see Supplementary Material). This database consists of the values of the following hydrological variables: precipitation (depth and intensity); water infiltration rate (mm/h); soil water repellency (hereafter indicated as "SWR", expressed as WDPT, WRI or MED, see below); surface runoff volume (mm); soil loss (tons/ha). Moreover, the following features (hereafter referred to as "environmental conditions") were also derived from each paper and included in the Excel® database:

a) general data: country, region, monitoring period (years)
b) fire: burn season, soil burn severity, repeated burning, post-fire treatments
c) climate: type, annual precipitation (mm)
d) vegetation: type (shrubs, trees, grasses), tree species, density, diameter and height, vegetation cover after burning (%), litter presence
e) soil: altitude (m a.s.l.), aspect, main type and texture, slope (%), organic matter content before fire (%)
f) experimental characteristics: temporal and spatial scales, measurements of soil properties, measurements of water quality parameters, changes detected and their statistical significance, the reason for changes, the recovery time of pre-fire values (years)

Many of the 41 selected papers contain more than one case study. In other words, since the authors varied the experimental conditions (e.g., site, burn season, fire severity, tree species), more than one observation (from one to six) for the hydrological variables was available in many papers, totalling 85 case studies. None of the case studies contained all the hydrological observations, which means that, in many cases, only infiltration, SWR, runoff or erosion data were present; moreover, in most studies, data was not reported for both short-term and medium-term effects. Regarding precipitation, studies carried out under both simulated (38% of the total number) and natural precipitation (42%) were considered, to get a more representative sample of observations (despite the different temporal and spatial differences between the two hydrological inputs).

2.3. Bibliometric Analysis

The 41 papers selected for this review were classified according to the following criteria: publication year; country; publishing journal; citation (total number or number standardized per year of publication, equal to the ratio between the total number and the years since publication until present); climate; vegetation type; site altitude; burn season; soil texture; duration of the monitoring period; spatial scale; temporal scale. This classification was reported in relevant charts or tables.

2.4. Data Processing

The specific post-fire response is considered from the point of view of the three major processes (infiltration, runoff, and soil erosion and transport) of soil hydrology in addition to precipitation (Moody *et al.*, 2013). In both the unburned and burned states of each site, the hydrological and erosive variables (observations of water infiltration, SWR, surface runoff, and soil loss) and environmental characteristics of the experimental sites were extracted for the 85 case studies. In the case of burned sites, this data was extracted at two dates: immediately after the prescribed fire (hereafter "short-term") and at the end of the monitoring period in the relevant study ("medium-term"), which had a duration of a few months to three years (in two cases eight years). This separation in extraction dates was done to consider the different soil's hydrological response to fire throughout the window of disturbance and the following period when the pre-fire soil properties and vegetation cover are progressively recovering. Moreover, to consider the variability of precipitation from one experimental site to another, the coefficient of runoff and the unit erosion were calculated as the ratios between the runoff volume or the soil loss and the rainfall generated in the period adopted by each study. The use of normalized indicators of runoff and soil erosion that consider the rainfall amounts allows the standardized comparison among the experimental data on the global scale (Girona-García *et al.*, 2021). The site in its unburned condition was assumed to be the "reference" or "baseline" value for each of the four investigated hydrological variables. For each case study, the so-called "effect size" (e.g., Vieira *et al.*, 2015; Girona-García *et al.*, 2021) for the change between the burned site and the unburned area was calculated for both the short-term and medium-term. This effect size was estimated as the natural logarithm (ln) of the response ratio (Curtis and Wang, 1998; Hedges *et al.*, 1999) - hereafter "log response ratio" or "LRR" - using the following equation:

$$LRR = \ln \frac{x_B}{x_{UB}} \qquad (1)$$

where x_B is the mean value of the response variable measured in the site treated with the prescribed fire and x_{UB} is the corresponding value measured in the unburned condition at the same site. Therefore, in this study, three LRRs were calculated, namely “LRR(Infiltration)”, “LRR(Runoff)”, and “LRR(Erosion)”, which are the log response ratios of each variable to the prescribed fire effects. The value of the LRRs expresses the magnitude of the impact of prescribed fire on a given soil on a logarithmic scale (e.g., Kalies *et al.*, 2010). A negative LRR means that the related hydrological variable of a burned condition is lower compared to the same variable measured in the unburned site (Lucas-Borja *et al.*, 2022d). The LRR also gives the order of magnitude of this increase. The standard deviations of the analysed variables were treated as weighting factors of the individual observations (“moderator variables”) (Vieira *et al.*, 2015; Girona-García *et al.*, 2021), in order to estimate the weighted least squares relationship between the moderator variables and the true effects (Viechtbauer, 2010).

The wide range of conditions, in which the experimental observations have been carried out, and the different methodologies used to measure the studied variables do not hinder the results of this meta-analysis. This is because the calculation of the size effect has been made in both unburned and burned plots under the same conditions and monitoring period in each study (Vieira *et al.*, 2015; Girona-García *et al.*, 2021). The standardisation of the studied variables allows the analysis of data from different sites and under different experimental and environmental conditions (Lajeunesse, 2015).

The LRRs of each hydrological variable were calculated for some of the most important drivers of the effects of the prescribed fire, as identified in the aforementioned environmental conditions: (i) “annual precipitation”; (ii) “soil slope”; (iii) “burn season”; (iv) “soil burn severity"; (v) “vegetation type”; and (vi) “ground cover immediately after burning” (hereafter simply indicated as "post-fire ground cover"). The values of these conditions were conventionally grouped into classes, as follows:

(i) annual precipitation (mm): < 500; 501-1000; 1001-1500; 1501-2000
(ii) soil slope (%): < 10; 10-20; 20-30; 30-40; 40-50; > 50
(iii) burn season: spring; summer; autumn; winter
(iv) soil burn severity: low; low-to-moderate; moderate; moderate-to-high; high
(v) vegetation type: grasses; shrubs; trees
(vi) post-fire ground cover (%): < 25; 25-50; 50-75; >75.

When the case study did not report one environmental condition, the LRR was not calculated.

Regarding the precipitation data, while all studies using rainfall simulators reported the rainfall intensity (which is the most important driver of soil erosion), most of the papers with observations under natural precipitation did not report those values or the data were only reported as mean values (which may be misleading considering the high spatial and temporal variability of this hydrological variable). For this reason, we adopted as a climatic parameter the annual precipitation, which gives rough information about rainfall patterns in a specific site. Soil slope was included among the drivers since this parameter is related to the geomorphic characteristics of the site (Moody *et al.*, 2013).

About SWR, in the selected papers three methods were adopted for its measurements: (i) Water Drop Penetration Time (WDPT, Woudt, 1959; Letey, 2001); (ii) Water Repellency Index (WRI, Pierson *et al.*, 2001); and (iii) ethanol determination (MED test, King, 1981). Since this inhomogeneity in measuring methods hampers a direct comparison among the case studies, the SWR classes that correspond to the ranges of values reported in the studies were considered. Accordingly, SWR was classified into four classes: (i) non-repellent soil; (ii) slightly-repellent soil; (iii) strongly-repellent soil; (iv) severely-repellent soil. The change in SWR was calculated by comparing the SWR class of both unburned and burned soils (the latter both in the short-term and medium-term). These changes were modulated as follows: a transition between two adjacent SWR classes was considered as a "low" change ("low decrease" or "low increase"), otherwise, the change was considered as "high" ("high decrease" or "high increase"), e.g., transition from a "non-repellent" to a "strongly-repellent" or a "severely-repellent" soil. "No change" means no variation in the SWR class.

2.5. Statistical Analysis

A two-way ANOVA was applied to the following as independent factors: LRRs of each hydrological variable (infiltration, runoff and erosion); the environmental conditions ("post-fire ground cover", "soil burn severity", "burn season", "vegetation type", "soil slope" and "annual precipitation"); the time elapsed since prescribed fire application. To satisfy the assumptions of the statistical tests (equality of variance and normal distribution), the data was subjected to a normality test or was square root-transformed whenever necessary. The pairwise comparison by Tukey's test (at $p < 0.05$) was also used to evaluate the statistical significance of the differences in the response variables.

Moreover, following Vieira *et al.* (2015) and Girona-García *et al.* (2021), the significance of residual heterogeneity of the moderator variables was tested using Cochran's QE-test (Cochran, 1954), to evaluate whether the variability in each effect size, that is not accounted for by the moderator variables, is larger than expected.

All the statistical tests were carried out with the XLSTAT software, release 2019, Addinsoft, Paris, France, except the Cochran's QE-tests that were performed using the "R" statistical package.

3. RESULTS

3.1. Bibliographic review

The highest number of papers (24.4% of the total) were published between 2000 and 2005, followed by a decrease in the number of publications until 2015. In the last 7-8 years, this number increased (15 papers published between 2016 and 2022, 39.6% of the total number) (Figure 2).

[Insert Figure 2]

The 41 selected papers were published in 23 international and peer-reviewed journals, while one paper was published in conference proceedings. "Geoderma" was the journal with the highest number of papers (5, 12.2% of the total), followed by "Science of the Total Environment", and "Journal of Environmental Management", which published three papers per journal (7.3%) (Figure 3).

[Insert Table 1]

The analyzed papers totalled 1976 citations, on average about 48 per article. Two papers by (Robichaud, 2000; Huffman *et al.*, 2001) achieved more than 100 citations. If the number of citations is standardised by the time elapsed since publication, four papers received more than 10 citations per year (Robichaud, 2000; Huffman *et al.*, 2001; Plaza-Álvarez *et al.*, 2019; Carrà *et al.*, 2021a) (Table 1). No correlation was detected between the number of citations and time elapsed sicne publication ($r^2 = 0.27$, data not shown).

[Insert Table 2]

The selected papers contain case studies carried out in sites located in seven countries, with 80% of these papers using case studies in only three countries: Spain (23.5%), Portugal (7.1%) and the USA (48.2%) (Figure 3).

[Insert Figure 3]

The largest number of the 85 case studies analyzed in this review was located in areas under semi-arid climatic conditions (44.7%). Many other studies were conducted in continental climates (23.5%), while only two and three case studies were found in temperate (3.5%) or tropical (2.3%) climates (Figure 4).

[Insert Figure 4]

Most case studies (54.1%) were located in sites at altitudes between 501 and 2000 m a.s.l., while 16.5% and 8.2% were carried out in areas located at altitudes lower than 500 or higher than 2000 m respectively. Surprisingly, in 18 case studies (21.2% of the total number) the altitude of the experimental area was not indicated (Figure 4).

The distribution of the analyzed case studies per soil type is scattered, but many sites with sandy loam (29.4%) and silt loam (17.7%) soils were observed. The information about this soil feature was given in all of the analysed case studies (Figure 4).

The monitoring period of the selected case studies was less than two years in 87.1% of the case studies and only one year in 36.5%. Only 11 case studies (12.9%) were observed for more than two years. For 82.3% of the case studies, the investigation was conducted using a plot scale, while 10.6% used a catchment scale. The spatial condition was not explained in six case studies (7.1%) or, at least, this information could not be identified. The highest number of case studies were monitored at the event scale (80%), while 17.7% were observed on the yearly scale. The daily scale was adopted in two cases-studies (2.35%). This information was available for 100% of the case studies.

3.2. Meta-analysis

3.1. Variability of Water Infiltration, SWR, Surface Runoff and Soil Erosion among soil Conditions

Water infiltration was variable between extremely low values (close to zero, reported in both unburned and burned conditions, the latter in the short-term) up until to a maximum of 1130 mm/h (under burned conditions and in the short-term). On average, the mean infiltration followed the gradient burned-medium-term (19.6 ± 69.1 mm/h) > unburned (61.5 ± 94.7 mm/h) > (burned-short-term (61.5 ± 188 mm/h) soils, with a large variability of values (Figure 5a).

The unburned soils did not show repellency in 48% of the case studies, and this percentage decreased to 16% and 38% for burned conditions (short-term and medium-term, respectively).

While the share of extremely repellent soils was very low under all soil conditions (< 4%), the prescribed fire increased the frequency of strongly repellent soils in the short-term (from 17% in unburned conditions up to 55% in burned soils). It is worth noting that the percentage of burned and strongly-repellent soils in the medium-term (25%) is close to the corresponding value reported for the unburned conditions (17%) (Figure 5b).

The runoff coefficient was in the range of 0 to 0.67, the latter reported for burned conditions and in the short-term. This coefficient, which was on average equal to 0.21 ± 0.27 in the unburned soils, in the burned soils increases to 0.31 ± 0.21 for short-term observations and decreases to 0.16 ± 0.15 in the medium-term (Figure 5c).

The highest value of unit soil erosion was 0.97 tons/ha-mm, reported in burned soils and in the short-term, while no erosion was observed in very few cases in the unburned soils. Compared to an average erosion of 0.015 ± 0.065 tons/ha-mm reported in unburned soils, the values observed in burned conditions were noticeably higher (0.067 ± 0.183 and 0.031 ± 0.116 tons/ha-mm, for the short-term and medium-term, respectively (Figure 5d).

In general, the range of soil erosion values (with minimum and maximum coefficients of variation of 275%, burned conditions and short-term, and 434% in unburned soils) is more variable compared to the variability of the runoff coefficient (from 69%, burned conditions and short-term, to 129%, unburned soils).

[Insert Figure 5]

3.2. Effects of Prescribed Fire on Water Infiltration

Data about water infiltration was reported for 41 case studies at unburned sites, and, in burned sites, for 35 case studies the data was reported (85.4% of that number) in the short-time and 25 in the medium-term (60.1%).

ANOVA showed that LRR(Infiltration) was significantly distinct among sites characterized by different annual precipitation, soil slope, burn severity and vegetation types (in other words, it was significantly distinct from one precipitation class to another), while time elapsed and all the interactions between those factors and the time elapsed were not influential (Table 3). In the short-term, negative LRR(Infiltration) was observed under all weather, fire severity, and vegetation type, and soil slope over 40% (Figures 5a to 5f). For the other soil burn severities, short-term LRR(Infiltration) was close to zero. Compared to unburned sites, water infiltration increased (positive LRRs) in sites with precipitation between 500 and 1000 mm/yr (Figure 6a), soil slope between 20% to 40% (Figure 6b), while slight or no variations were reported for precipitation between 1500 and 2000 mm/yr (Figure 6a), soil slope < 20% (Figure 6b), low-to-moderate soil burn severity (Figure 6d) and in shrubs (Figure 6e).

Some months after fire application (medium-term), water infiltration remained unvaried (LRR equal or close to zero) under all soil conditions (Figures 6a to 6f). Only in sites with precipitation < 500 mm/yr (Figure 6a), soil slope between 10% and 20% (Figure 6b), in grasslands (Figure 6c) water infiltration was lower compared to unburned sites, while in areas burned by high-severity fires and with slopes between 40% and 50% increases were reported (Figures 6d and 6b).

Overall, the maximum reduction in water infiltration was in sites with precipitation between 1000 and 1500 mm/yr (Figure 6a), soil slope between 40% and 50% (Figure 6b), burned by moderate-severity fires (Figure 6d) and tree cover (Figure 6c) in the short-term, while the highest LRR(Infiltration) was observed in grasslands (Figure 6c) and areas with slope between 20% and 30% (Figure 6b).

[Insert Table 3]

[Insert Figure 6]

3.3. Effects of Prescribed Fire on Soil Water Repellency

A sample of 42 case studies measured SWR in burned sites; of this sample, 39 case studies reported short-term data (92.9% of the total number), and 21 (50%) medium-term data. However, in this review, only one change in SWR was reported for each case study, since, in all case studies, the variations between the short-term and medium-term values were either zero or no coupled short-term and medium-term data was reported.

In most case studies, the SWR increased after the prescribed fire application. The highest percentage of case studies with increased SWR was 75% for the 1000-1500 mm/yr class. The SWR only decreased in case studies with precipitation < 500 mm/yr and between 500 and 1000 mm/yr (Figure 7a).

[Insert Figure 7]

The SWR decreased only in sites with the lowest soil slopes (< 10%). In contrast, increases were always detected under all the other soil slope classes, up to a 100% increase for a slope between 20% and 30%. In general, these increases were high (up to 100% of cases with a slope over 60%), except in sites with the lowest slope class (< 10%), where the changes were always low. Several case studies without SWR changes were reported, especially at a slope between 30% and 40% or over 50% (Figure 7b).

When the prescribed fire was applied in the drier seasons (spring and summer), the SWR generally increased. Prescribed fires in autumn generally did not show changes in SWR, while, in winter, only high increases or no changes in SWR were detected (Figure 7c).

The SWR increased or did not change after the prescribed fire at all soil burn severities, with the exceptions of the highest severity classes (100%), for which only a decrease was observed. For many case studies (100% for the moderate class), the SWR did not change after the prescribed fire. Overall, the percentage of case studies with increases in SWR ranged from 33.3% (moderate-to-high soil burn severity) to 60% (low-to-moderate) (Figure 7d).

The prescribed fire application produced increases in SWR in areas covered by grass (100% of case studies) and forests (57%), and no changes in shrublands (50% of case studies) (Figure 7e).

No changes in SWR were detected in case studies where the ground cover after the prescribed fire was over 50%. In contrast, where the fire removed less than 50% of post-fire ground cover, SWR increased (always with the highest magnitude) (Figure 7f).

3.4. Effects of Prescribed Fire on Surface Runoff

Surface runoff was measured at unburned sites in 41 case studies, while short-term and medium-term data sets were available in 36 (87.8% of those 41 case studies) and 23 (56.1%) burned sites, respectively.

According to ANOVA, all factors individually and in their interaction had a significant effect on surface runoff, while the differences over time were not significant (Table 3).

Immediately after the prescribed fire application (short-term), the LRR(Runoff) was positive under all precipitation classes (Figure 8a to 8f). Only in sites with a slope between 10% and 20% (Figure 8b) and burned with moderate fire (Figure 8d) were no significant variations in surface runoff observed when comparing unburned and burned areas.

Surface runoff measured over time produces conflicting results. Decreases were reported in sites with precipitation between 500 and 1000 mm/yr as well as 1500 and 2000 mm/yr (Figure 8a), slope < 10%, and between 10% and 20% or 30% and 40% and 50% (Figure 8b), burned in autumn (Figure 8c) at moderate-to-high severity (Figure 8d), with post-fire ground cover < 25% (Figure 8d) and in shrublands (Figure 8c). In contrast, sites with precipitation < 500 mm/yr (Figure 8a) and residual cover between 25% and 50% (Figure 8f) underwent a further increase over time in surface runoff. These variations led to the following changes in the medium-term: (i) positive LRR(Runoff) under all conditions; (ii) unvaried runoff in sites with slope < 10% (Figure 8b) and post-fire ground cover < 25% (Figure 8f); and (iii) decreased runoff in sites burned in autumn (Figure 8c) at moderate-to-high severity (Figure 8d).

Overall, the maximum short-term LRR(Runoff) was reported in areas with precipitation between 1500 and 2000 mm/yr (Figure 8a), slope between 40% and 50% (Figure 8b), burned in autumn (Figure 8c) and by fire with moderate-to-high severity (Figure 8d), in shrublands (Figure 8e) and with post-fire ground cover between 50% and 75% (Figure 8f). In the medium-term, the highest LRR(Runoff) was measured in sites with precipitation < 500 mm/yr (Figure 8a), slope < 10% (Figure 8b), burned in summer (Figure 8c) and by low-severity fire (Figure 8d), in grasslands (Figure 8e) and with post-fire cover between 25% and 50% (Figure 8f).

[Insert Figure 8]

At all soil slope classes, in the short-term, the LRRs were positive, while medium-term runoff decreased for all slopes, except for slopes between 10% and 20%. For slope classes < 10% and 20% to 30% the surface runoff was noticeably higher compared to the unburnt sites (Figure 8b).

The short-term LRR was always positive, while LRR became negative in the medium-term in the case of fire application in autumn (Figure 8c).

In the short-term, soils across all burn severities showed positive LRRs. In the medium-term, the LRRs increased for the lower soil burn severities and decreased for the higher severities down to negative values detected for moderate-to-high and high soil burn severities (Figure 8d).

The LRR in the short-term was positive for all vegetation types, with the highest values in grasslands and shrublands. In the medium-term, the values of LRR, although always remaining positive, increased in grassland and tree-covered forests, and decreased in shrublands (Figure 8e).

In the short-term, the LRRs were positive for all the post-fire ground cover classes, while, over time, surface runoff decreased compared to unburnt sites only for sites with the lowest cover class (Figure 8f).

3.5. Effects of Prescribed Fire on Soil Erosion

Data about erosion was reported in 47 case studies at unburned sites (55.3% of the total number), and, at burned sites, in 28 case studies (59.6% of that number) in the short-term, and in 32 case studies (68.1%) in the medium-term.

The statistical analysis by ANOVA revealed that, among the identified drivers, only soil burn severity, vegetation type and burn season were individually influential on LRR(Erosion). Statistically significant effects were also observed in the interaction between annual precipitation, soil burn severity and burn season, and time, while time elapsed did not have a significant effect on erosion dynamics between burnt and unburnt sites (Table 3).

In the short-term, the LRR(Erosion) was always positive for all soil burn severities and seasons as well as vegetation types. Compared to unburned areas, all sites over time underwent decreases in erosion rates regardless of the vegetation type (Figure 9e). At the end of the window of disturbance, the erosion rates were always higher compared to the unburned conditions except in grasslands (Figures 9c) and sites burned by fires with moderate-to-high severity (Figure 9d), which showed comparable erosion.

Overall, the highest LRR(Erosion) was observed in the short-term in sites with precipitation between 1500 and 2000 mm/yr (Figure 9a), slope between 40% and 50% (Figure 8b), burned in summer or winter (Figure 9c) and by fire with moderate-to-high severity (Figure 9d). In the medium-term, these values were at the maximum in sites with precipitation between 500 and 1000 mm/yr (Figure 9a), slope between 30% and 40% (Figure 9b), burned in winter (Figure 9c) and by fire with low or high severity (Figure 9d). LRR(Erosion) was the highest for both observation periods in shrublands (Figure 9d) and sites with post-fire ground cover between 25% and 50% (Figure 9f).

[Insert Figure 9]

Immediately after the prescribed fire application, the LRR was always positive. Over time, for soil slopes < 10%, 20% to 30%, and 40% to 50% the LRRs decreased, while, for the other classes (slope 10% to 20%, and 30% to 40%), these ratios increased (Figure 9b).

The short-term LRR was positive for all burn seasons, and the relevant values generally decreased in the medium-term for prescribed fire applied in autumn and summer (Figure 9c).

All soil burn severities resulted in positive LRRs in the short-term, which did not vary over time except in moderate-to-high severity case studies, showing decreased and even negative LRR (Figure 9d).

In the short-term, the LRRs were positive for prescribed fire applied to shrublands and forests, and negative in the grassland. Over time, these LRRs decreased for shrublands and grassland, in the latter case becoming negative, and increased for forestlands (Figure 9e).

The LRR was positive in the short-term for all post-fire ground cover classes, and these values decreased for cover lower than 50% (Figure 9f).

Finally, it is interesting to highlight the presence of possible correlations between pairs of the studied variables either in the short-term or in the medium-term. In more detail, while the regression analysis between LRR(Infiltration) and LRR(Runoff) shows a low coefficient of determination at both observation dates ($r^2 < 0.24$, data not shown), the correlations were higher and always significant ($p < 0.05$) between LRR(Runoff) and LRR(Erosion) (r^2 equal to 0.48, short-term, and to 0.76, medium-term (Figure 10).

[Insert Figure 10]

4. DISCUSSION

4.1. The Role of Prescribed Fire on a Global Scale

The literature about the hydrological effects of prescribed fire is not abundant. We recorded the publication of about forty papers, almost equally distributed across the last two decades. In more recent years there has been an uptick in the rate of these publications compared to previous years.

The bibliographic classification of the 22 publishing journals demonstrates that almost all the selected papers have been published in journals of the highest rank (first quartile, Q1). Only three papers (Robichaud, 2000; White and Loftin, 2000; O'Dea and Guertin, 2003) were published in non-indexed journals ("Journal of Rangeland Management") or conference proceedings.

The 85 case studies found in the reviewed papers were carried out only in seven countries, mostly concentrated in the USA and Iberian Peninsula (80%). Moreover, a large number of the case studies (60%) have studied sites in semi-arid climates, where the precipitation is scarce, and high temperatures in hot periods may trigger wildfires in forests (Shakesby, 2011). A significant share (23%) is concentrated in continental areas (mainly western and central parts of the USA), where prescribed fire has been used for many years with generally successful results (Shakesby and Doerr, 2006; Cawson *et al.*, 2012; Moody *et al.*, 2013; Klimas *et al.*, 2020; Girona-García *et al.*, 2021).

More than 50% of the case studies have studied hilly and mid-mountainous areas (altitudes between 501 and 2000 m a.s.l.), while less than 25% were in lowlands and high mountains. More than 80% of the experiments were carried out at the plot scale, while only 10% were with burned catchments. This is presumably due to the lower cost of monitoring individual hillslopes compared to entire catchments. Another influencing factor may be the small extension of areas for prescribed fire application (often for experimental purposes) that are usually allowed by public authorities. In general, the experiments were set up at the event scale, which is the most suitable choice in arid or semi-arid areas. Here, surface runoff and erosion rates depend on only a few rainstorms per year, while the contribution of more frequent and less intense events to erosion is minor (Lucas-Borja *et al.*, 2020; Zema *et al.*, 2020a, 2020b). In other climatic environments (e.g., tropical or continental areas), the annual scale should be preferred, since the hydrological response of soil depends on almost all precipitation throughout the year.

The duration of the monitoring period is generally short (one or two years), with very few exceptions (13% with a longer duration). This short duration may depend on insufficient money for more complete or longer observations. Several authors reported that the post-fire window of disturbance is shorter than one or one year and a half (e.g., Vieira *et al.*, 2015, 2018; Carrà *et al.*, 2021b, 2022). However, a longer monitoring period (> two years) may show when the pre-fire values of several hydrological variables fully recover, statistically comparing the differences in soil's hydrological response between burned and unburned areas.

4.2. Magnitude of Changes in the Hydrological Variables between Unburned and Burned Sites

The effect size of water infiltration is negative in 76% (short-term) and in 43% (medium-term) of the analyzed case studies. This means that water infiltration generally decreases immediately after the prescribed fire application, and in many cases (close to 50%) this decrease lasts beyond the monitoring period. Our meta-analysis reveals that prescribed fire may decrease infiltration also by more than one order of magnitude, practically lowering the soil hydraulic conductivity to zero in extreme cases (Cawson *et al.*, 2016), in eucalypt stands in Australia, under semi-arid conditions, and soils with a slope between 40% and 50% and low soil burn severity). Often infiltration remains lower compared to the unburned conditions in the medium-term. This occurrence is reported by Pierson *et al.* (2008) and Chief *et al.* (2012) in arid or semi-arid forestlands with trees or shrubs in the USA (where, however, the soil burn severity was low-to-moderate and moderate-to-high, respectively) as well as by Plaza-Álvarez *et al.* (2019) in semi-arid pine stands of Spain, in this case burned by low-severity prescribed fire.

In more than 50% of case studies the SWR increased, and in 78% the level of change was high. The more severe increases in SWR were mainly found in sites with medium to high annual precipitation, medium soil slope, low-to-moderate soil burn severities, fire application in summer, almost complete removal of vegetation due to burning, and dominant cover of grasses. SWR is considered one of the main reasons for reduced [Missing word?] (Martin and Moody, 2001; Moody *et al.*, 2013). However, fire-induced SWR does not necessarily lead to a noticeable reduction in infiltration (Shakesby and Doerr, 2006).

Of the 35 case studies reporting the values of surface runoff under burned and unburned conditions, 80% and 82% showed increases in short-term and medium-term, respectively. This means that prescribed fire application generally increases runoff generation, which usually lasts several months after the fire. Surface runoff in areas treated with prescribed fire may be 22-fold the values measured in untreated sites (González-Pelayo *et al.*, 2010). These authors have demonstrated that runoff may be even higher (by about 10%) in the medium-term compared to the observations immediately after the fire. This statement agrees with Morales *et al.* (2000), who found an 18-fold runoff compared to the short-term value one year after the fire. Several authors (e.g., de Dios Benavides-Solorio and MacDonald, 2005; Stoof *et al.*, 2012; Moody *et al.*, 2013) explain these increases in post-fire runoff for several reasons: (i) the reduction in infiltration; (ii) the appearance of SWR or its noticeable increase; (iii) the increase in overland flow velocity and connectivity, due to large bare areas left by fire; (iv) the decrease in canopy interception and evapotranspiration; (v) the lack of surface water storage; and (vi) the effects of soil-sealing and air entrapment. In general, the increase in runoff is explained by the prevalence of the Hortonian generation mechanism on progressive soil saturation (Soto and Díaz-Fierros, 1998), due to the reduced eater infiltration and SWR (Shakesby and Doerr, 2006). Only two case studies showed decreases in surface runoff in the short-term after the fire (Robichaud, 2000; Cawson *et al.*, 2016), and three in the medium-term (Townsend and Douglas, 2000; Pierson *et al.*, 2009; Zavala *et al.*, 2009). In two case studies, the reduction in the runoff rate was noticeable (+70-90%) (Townsend and Douglas, 2000; Zavala *et al.*, 2009).

Research about the changes in soil erosion after fire is not unanimous: some studies report very low erosion compared to other post-fire disturbance effects (e.g., Kutiel, 1994; Shakesby, 2000), while others report no signs of post-fire erosion despite high fire temperatures, or, exceptionally, slight decreases (e.g., Kutiel and Inbar, 1993; Cerdà, 1998). However, no consensus exists about noticeable increases in soil loss in burned sites compared to undisturbed sites (e.g., Shakesby *et al.*, 2000; Moody and Martin, 2001; Shakesby and Doerr, 2006; Moody *et al.*, 2013), and the magnitude of these increase is correlated with the fire severity (Prosser and Williams, 1998; Shakesby and Doerr, 2006; Vieira *et al.*, 2018; Lucas-Borja *et al.*, 2022a). In agreement with Vieira *et al.* (2015), the meta-analysis revealed that the changes in post-fire soil hydrology are more pronounced for the erosion response than for runoff. In this meta-analysis, 93% and 68% of the analyzed case studies show increases in soil loss immediately after the fire and one-two years after, respectively. In 10 sites erosion increased by more than one order of magnitude in the short-term. The highest increases (from 26-fold to 676-fold the values of unburned soils) were reported in Pierson *et al.* (2009), González-Pelayo *et al.* (2010), Fernández *et al.* (2012) and Shakesby *et al.* (2015). In two of these case studies, the soil loss was very noticeable also in the medium-term (636-fold and 76-fold) (González-Pelayo *et al.*, 2010; Shakesby *et al.*, 2015). In (Pierson *et al.*, 2009), the erosion in the medium-term increased compared to the unburned condition, and, in (Fernández *et al.*, 2012), no observations were available in the medium-term. Soil loss decreased in comparison to unburned soils only in two case studies in the short-term (Pierson et al., 2009; Robichaud, 2000). Several months after the fire, erosion was still very high in six sites (by more than one order of magnitude), and even the highest value (soil loss higher than 1000-fold the unburned value) was observed by Lucas-Borja *et al.* (2019). This means that, in general, prescribed fire noticeably increases the erosion rates in burned sites, and these effects may last for many months after fire application. The reasons for this severe increase are many. First, the removal of ground cover leaves the soil surface bare immediately after the fire application, and the kinetic energy transferred from raindrops to the soil (Moody *et al.*, 2013) favours the erosion process (DeBano *et al.*, 1998; Robichaud, 2000). Second, soil heating due to fire with moderate severity consumes organic matter and mineral bindings (Mataix-Solera *et al.*, 2011), thus resulting in a reduction in soil aggregate stability (Larsen and MacDonald, 2007; Fernández *et al.*, 2010; Parson *et al.*, 2010) and critical shear stress. Third, the induced SWR and soil crusting, synergistically with the breakdown of soil aggregates, decrease the infiltration capacity of burned soils (Girona-García *et al.*, 2019; Silva *et al.*, 2019).

The significant correlation detected between surface runoff and soil erosion, particularly noticeable in the medium-term, means that, while infiltration has a temporary influence on surface runoff, the latter hydrological variable is a significant driver of soil erosion, especially after several months from prescribed fire application. The higher r^2 found in the medium-term between this pair of variables should be ascribed to the steadily decreasing impact of fire on soil properties over time (e.g., soil burn severity, ground cover, restoration of the pre-fire values of physicochemical characteristics). These correlations are in agreement with other studies exploring the associations between prescribed fire effects and soil hydrology, such as Lucas-Borja *et al.* (2022c) and Zema *et al.* (2022), who reported a direct correlation between the runoff coefficient and sediment concentration in forests of Central Eastern Spain and Southern Italy, respectively.

It is important to assess whether soil loss due to prescribed fire exceeds the tolerance limits suggested in the literature for rural areas. Verheijen *et al.* (2009) state that, in Europe, the upper limit of tolerable soil erosion is close to 1.5 tons/ha-yr, while Wischmeier and Smith (1978) and Bazzoffi (2009) suggest limits between 3 and 11 tons/ha-yr for agricultural lands. If we adopt the lowest limit (1.5 tons/ha-yr), the database supporting our meta-analysis identifies ten (in the short-term) and five (in the medium-term) case studies overcoming this value. Four case studies indeed exceed the limit also in unburned areas (showing high erodibility of the undisturbed soil), but it is also evident that, in some cases, the application of prescribed fire may lead to a noticeable aggravation of natural erosion even at the event scale. Moreover, we should consider this risk more severe, since some of the erosion rates reported in the analyzed case studies are related to individual high-intensity rainstorms, which mobilize high amounts of sediments (Shakesby and Doerr, 2006).

4.4. Duration of the "Windows of Disturbance"

According to the literature, the "window of disturbance" of the hydrological characteristics of soil shows a variability that depends on many factors (fire intensity, soil characteristics, vegetal species, degree of vegetation removal), and can last from several weeks to years or decades (e.g., DeBano *et al.*, 1998; Shakesby, 2000; Shakesby and Doerr, 2006). As outlined above, the papers selected in this meta-analysis generally carried out observations for a limited time, rarely over two years (about 10% of the analyzed case studies). This meta-analysis has highlighted that often the recovery of the pre-fire values of the monitored hydrological variables is incomplete or even totally absent in the observation time (that is, when the medium-term values are similar or even higher compared to the short-term runoff or erosion). In more detail, in 58% of the case studies the time needed by the burned soil to restore the pre-fire runoff or erosion rates was less than the duration of the monitoring period. Only in about 10% of these case studies the complete recovery of the unburned conditions was not fully or partially achieved. Therefore, we can conclude that, in general, the "window of disturbance" of prescribed fire on the hydrological and erosive response of soil is between one and two years. Unfortunately, 32% of the case studies did not report this information, and this happens for two reasons: (i) the monitoring of the hydrological observations was only performed in the short-term after the prescribed fire application; and (ii) no quantitative observations of water infiltration, runoff and/or erosion were available, but only a qualitative classification of SWR. Wagenbrenner *et al.* (2021) report that it is very hard or even impossible to find a definition of recovery of the pre-fire conditions in burned areas. Their review of the post-wildfire hydrologic recovery in Mediterranean climates shows that in sites where vegetation recovers rapidly, there is no post-fire response or hydrologic recovery occurs before the end of the monitoring study, at least under semi-arid conditions. However, the authors conclude that, since the relations between post-fire ground cover and hydrology are complex, vegetation regrowth alone is not a clear indicator of hydrologic recovery (Wagenbrenner *et al.*, 2021).

4.3. Variability of Prescribed Fire Effects across Different Climates and Soil Slopes

This meta-analysis shows that, immediately after the prescribed fire application, the variability in water infiltration according to precipitation and soil slope gradients, is quite dissimilar. Most sites experienced a decrease in soil hydraulic conductivity (e.g., those with precipitation between 1000 and 1500 mm/yr, and the steepest slopes, e.g., Cawson *et al.*, 2016). However, cases with no significant variations or even increases were also reported (Huffman *et al.*, 2001, +167%) and (Vadilonga *et al.*, 2008, from +762% to 1386%). In most cases, water infiltration increased over time (including the case studies where the reduction was very high), with some exceptions (O'Dea and Guertin, 2003; Chief *et al.*, 2012; Pierson *et al.*, 2014; Plaza-Álvarez *et al.*, 2019).

In almost all studies under all climatic and morphological conditions (with very few exceptions) occurrence of SWR or its increase was reported. The appearance of hydrophobicity or an increase in it may have played an essential role in decreasing infiltration rates immediately after the prescribed fire application, although SWR is not the only reason for this decrease (Zema *et al.*, 2021a, 2021b). Moreover, the SWR increases were strong in practically all case studies, especially in sites where the rainfall is relatively low and soil is steeper than 10%. Reductions in SWR were only reported by Huffman *et al.* (2001), Chandler *et al.* (2018) and Zavala *et al.* (2009).

The meta-analysis showed that, despite the significant variability, the magnitude of changes in surface runoff generally did not increase with soil slope nor with precipitation. Presumably, runoff generation mechanisms reflect not only geomorphological or climatic factors but also other drivers, such as ground conditions, variability in infiltration, vegetal canopy cover, etc. Moreover, the significant variability of surface runoff with different annual precipitation derives from the distinct climate regions observed. What is surprising is that the meta-analysis does not show significant effects of annual precipitation and soil slope on soil erosion. However, although not significant, an increasing trend of erosion with both annual precipitation and soil slope is observed. Per Girona-García *et al.* (2021), we think that this result may be misleading, since sites with the same total annual precipitation may produce different post-fire hydrological and erosive responses as a consequence of differences in rainfall intensity. Several authors (e.g., Robichaud *et al.*, 2013; Malvar *et al.*, 2017; Vieira *et al.*, 2018) state that rainfall intensity is more influential on hydrological and erosive processes after a fire compared to the total rainfall on the annual scale (Malvar et al., 2017; Robichaud et al., 2013b; Vieira et al., 2018). Few studies analyzed in this review report values of rainfall intensity except for those carrying out rainfall simulations. However, this information is equally essential for investigations in natural precipitation (Girona-García *et al.*, 2021), since soil loss is driven by rainfall erosivity that is directly associated with its intensity. Another possible explanation for the lack of significance of soil slope on the variability of erosion rates may be the dominance of the rainsplash process on particle detachment due to overland flow on the overall erosion process, considering that soil slope should be a factor of lower importance. Moreover, most investigations were carried out on a small scale (plot or micro-plot) and using small rainfall simulators, which make it difficult and often impossible to measure overland erosion (Lucas-Borja *et al.*, 2022b). It is also worth mentioning that, in general, surface runoff and soil erosion decreased over time with both annual precipitation and soil slope compared to the short-term values, as shown by the statistical significance of the interaction between these factors and time. The cases of the lowest annual precipitation class and soil slope class between 10% and 20% are the only two exceptions (e.g., Morales *et al.*, 2000; González-Pelayo *et al.*, 2010; Pierson *et al.*, 2014; Lucas-Borja *et al.*, 2019, 2022b).

4.5. The Role of Soil Burn Severity on Post-fire Soil Hydrology

Prescribed fire is carried out under controlled climatic and morphological conditions that avoid the triggering of high-severity fires. However, the soil burn severity, although not burning the tree canopies, may also be moderate and high, and this may noticeably alter the hydrological properties of burned soils (Lucas-Borja *et al.*, 2022b; Lucas - Borja *et al.*, 2022e). According to this meta-analysis, water infiltration underwent significant variations among classes of soil burn severity, and noticeably decreased at moderate severities, while the effects of low and low-to-moderate severities were lower or absent in the short-term. This should be due to the soil only heating to a limited temperature, which did not significantly change the physicochemical properties of burned soils (Cawson *et al.*, 2012; Pereira *et al.*, 2018; Carrà *et al.*, 2022). At moderate and moderate-to-high soil burn severities, the changes in water infiltration were the highest among all classes (e.g., Chandler *et al.*, 2018, and Pierson *et al.*, 2008). This should be ascribed to the almost full removal of ground cover (which also alters the root distribution in the soil surface) as well as to the strong changes in soil aggregate stability, which reduces soil macro-porosity. In contrast and quite surprisingly, water infiltration was not affected or even increased after the prescribed fire with high severity (e.g., Vadilonga *et al.*, 2008). Although this effect was detected only in one case study (which may affect its significance), this may be justified by the fact that, when the fire severity is high, the soil temperature due to heating is not able to influence the SWR (e.g., Pereira *et al.*, 2018; Zema, 2021), and therefore soil hydraulic conductivity. However, this effect requires more attention, since at those temperatures soil aggregate stability is irreversibly disrupted (Shakesby and Doerr, 2006).

The effects of soil burn severity on SWR follow the same trends as those identified for water infiltration, the highest changes being detected at low and moderate severities and the appearance of strong SWR, and no changes shown at the highest class.

Both surface runoff and erosion noticeably increased at all soil burn severities, however at different magnitudes. Immediately after the prescribed fire application, the highest increases were mainly recorded at moderate-to-high severity (Pierson *et al.*, 2009). In the medium-term, at the stated soil burn severities, the values of runoff noticeably decreased compared to the short-term, although remaining lower than those of the unburned conditions. In contrast, at the lowest and highest severities, both runoff and erosion did not noticeably vary compared to the short-term observations. One case of a very high increase in delayed runoff response (about 90-fold the values measured in the unburned soils) was also found (Cawson *et al.*, 2013). According to Vega *et al.* (2005), both low and high-fire severities produce noticeably more runoff compared to unburned sites during the first year after a prescribed fire, while erosion is significantly enhanced only after a fire of the highest severity. In contrast, Vieira *et al.* (2015) detailed significantly greater effects of fires with moderate severity, compared to low or high severities, which are more difficult to understand than when comparing high and low severities.

Since prescribed fire is commonly applied at low severity (about 75% of the analyzed case studies), it is worth highlighting that the related erosion dynamics were highly variable among the analyzed case studies. While soil loss generally remained very high throughout the monitoring period (e.g., González-Pelayo *et al.*, 2010; Lucas-Borja *et al.*, 2022b), in some cases studies erosion significantly increased in the medium-term, when low rates were detected immediately after the fire (e.g., Lucas-Borja *et al.*, 2019). However, in this case study, erosion was minimal at both monitoring periods. In six case studies, medium-term soil loss decreased compared to both short-term observations and unburned soils.

4.6. The Importance of Post-fire Ground Cover on the Hydrological and Erosive Response of Soil

The literature about the role of residual ground cover on the hydrological and erosive response of soil after a prescribed fire is quite scarce (only 21 papers among those reviewed in this paper reported this information), while this relation has been widely investigated in the case of wildfires. In our meta-analysis, while no significant effects were revealed on water infiltration and erosion, increases in post-fire runoff were observed in both short and medium terms regardless of the ground cover, with high values being observed at the intermediate classes of ground cover after fire (between 25% and 75%) (e.g., González-Pelayo *et al.*, 2010; Fernández *et al.*, 2012). In the medium-term, the hydrological response of soil to prescribed fire seems to decrease, but the reliability of this statement is limited by the availability of data only for the lowest classes of ground cover. Presumably, the regrowth of vegetation is very different from one case study to another depending on the climatic and edaphic characteristics of the investigated sites, and this influences the surface runoff rates many months after fire application. The presence of ground cover on burned soils is essential, as soil protection is a key feature to reduce the hydrological response of forest soil to burning and precipitation (Vieira *et al.*, 2018; Girona-García *et al.*, 2021). Post-fire runoff is commonly attributed to the partial or complete removal of vegetation and litter (Neary *et al.*, 1999; Vieira *et al.*, 2015), and this effect in post-fire hydrology points us to the changes in soil properties due to heating (Neary *et al.*, 1999; Úbeda and Outeiro, 2009; Mataix-Solera *et al.*, 2011), such as aggregate stability and water repellency. Prats *et al.* (2014), Ferreira *et al.* (2015) and Girona-García *et al.* (2021) recommend a bare soil cover below the 30% threshold to reduce runoff and erosion rates after fire, while a threshold of 60-70% bare ground explains post-fire erosion caused by increased runoff (Moody *et al.*, 2013). Further reduction in the post-fire ground cover below 10% leads to increases in overland flow of more than 70% (Robichaud, 2000; Shakesby and Doerr, 2006). This so-called "bare-ground hypothesis" was suggested by Cerdà (1998), and further explored by other authors using rainfall simulations or field experiments (Johansen *et al.*, 2001; de Dios Benavides-Solorio and MacDonald, 2005; Pierson *et al.*, 2009; Moody *et al.*, 2013).

4.7. Ideal Season and Vegetation Type for Prescribed Fire Application

Prescribed fire may be applied in different seasons, but treatments immediately before the highest wildfire risk are preferable. The meta-analysis found case studies of prescribed fire applications in all seasons and post-fire weather patterns have driven different hydrological and erosive responses from the soil. While no significant effects of burn season were detected for water infiltration, SWR underwent noticeable variations, with particularly high increases for prescribed fires applied in summer. The short-term runoff rate in soils burned in autumn was the highest among the burning seasons, while, in this observation period, the highest erosion was observed for prescribed fires applied in summer. A case with very high erosion after winter burning was reported by Shakesby *et al.* (2015) 80-fold (short-term) to 100-fold (medium-term) soil loss compared to the values measured in the unburned soils. However, this was the only case study with prescribed fire applied in winter. The recovery of the pre-fire runoff and erosion rates was different among the different seasons, since prescribed fire applied in summer increased medium-term runoff and reduced soil loss, while burning in spring resulted in increased runoff and did not noticeably change erosion. Presumably, the prescribed fires applied in the drier and hotter seasons are followed by intense rainstorms, which produce an enhanced erosion response on hydrophobic soils. In contrast, in the case of spring prescribed fires, the soil has enough time (three to four months) to restore its undisturbed characteristics, lowering its erodibility.

The vegetation type significantly affected all the studied variables. More specifically, the decrease in water infiltration is much higher in forests covered by trees compared to shrublands both in the short-term and medium-term. General increases in soil hydrophobicity, often at the highest level, were also detected in forests covered by trees, while in shrublands the case studies with no changes or slight or strong changes were homogeneously distributed. In this regard, the highest short-term reduction in water infiltration (-99%) was reported by Cawson *et al.* (2016). Unfortunately, only one case study of prescribed burning in grasslands is reported in the selected literature (O'Dea and Guertin, 2003).

Surprisingly, runoff and erosion rates measured in the analyzed case studies did not follow the same patterns as water infiltration and SWR, although the variability was always significant. In more detail, the highest increases in short-term runoff and soil loss were observed for shrublands, while those measured for grasslands and forests covered by trees were both comparably lower. The highest short-term increases in runoff and erosion were both measured by González-Pelayo *et al.* (2010). It is worth noting that medium-term runoff decreased in shrublands and increased in tree forests and grasslands. In contrast, medium-term erosion decreased in grasslands (often under the value typical of unburned soils, such as in White and Loftin (2000)) and shrublands, and increased in forestlands, where soil loss remained similar or slightly higher compared to the short-term observations.

4.8. Practical Implications

The meta-analysis has, in general, demonstrated a large increase in infiltration, strong fire-induced SWR, and much higher surface runoff and soil erosion in burned soil in the short-term in comparison to unburned areas. However, this increase in the post-fire hydrological and erosive response was often transient in the case studies, since pre-fire values of the physical properties of soil as well as ground cover quickly recover, and SWR vanishes. These undesired effects of prescribed fire on soil hydrology require timely and effective post-fire management techniques. These actions should be applied when and where the negative impacts of fire on runoff and erosion may be heavier, due to the high costs of post-fire treatments. However, despite the importance of post-fire management of burned areas, only one case of adoption of countermeasures in areas treated by prescribed fires was found in this meta-analysis. In this regard, Carrà *et al.* (2021a; 2022) have demonstrated that soil mulching with fern, although having a low effect on infiltration and SWR, reduced the runoff and soil loss in the four to five months after fire. According to the statistical database of this meta-analysis, the areas to be prioritised for post-fire management are those located on the steeper slopes (over 40%, where erosion is the highest) regardless of the climate area (since increases in runoff and/or erosion are generalized). Post-fire management is essential in the early phases of the window of disturbance since the variations in the monitored hydrological and erosive variables are much higher throughout one or two years after fire application compared to the medium-term. Management actions with durable effects (e.g., log erosion barriers, contour felled log debris) may be welcome in those environments where the recovery of the pre-fire rates of runoff and erosion, and SWR disappearance are longer, as reported for instance by Hubbert *et al.* (2006), Pierson *et al.* (2009), Fonseca *et al.* (2017), Chandler *et al.* (2018), Karban *et al.* (2022) and Lucas-Borja *et al.* (2022b).

Moreover, both the soil burn severity and level of ground cover burning during the prescribed fire operations must be carefully controlled. Many studies have highlighted that the largest decrease in water infiltration, and a more severe hydrological and erosive response in the short-term, occur when the fire severity is moderate or moderate-to-high (presumably due to dense shrub and herb cover). This does not mean that prescribed fire operations must be avoided in sites where the herbaceous and shrub vegetation may represent an easy fuel for burning. However, prescribed fire should be shortly extinguished, to avoid long-lasting burning and higher temperatures in soils as well as a full removal of understorey vegetation. The latter measure is also important to reduce the areas left bare by fire and thus the undesired increase in the hydrological and erosive response in the short-term after the fire.

This meta-analysis also suggests to landscape and forest managers that prescribed fire treatment should be discouraged in summer in the northern hemisphere and in winter in the southern part. Under the hottest and driest weather conditions infiltration can noticeably decrease and SWR can increase in the short-term, which may result in increased erosion, as compared to prescribed fires applied in spring or autumn. The latter seasons (respectively in the northern or southern hemispheres) seem to be the optimal seasons to reduce fuel potentially triggering high-severity fires since they precede the seasons with the hottest temperatures and driest air and soil conditions, where the wildfire risk is the highest. In contrast, the application of prescribed fire before the wet season should be discouraged, since surface runoff and erosion in burned soils may be the highest in the short-term. In any case, caution should be paid to treat shrublands with prescribed fires, since these lands may provoke runoff and erosion responses higher than forestlands and pastures with grasses.

4.7. Open Research Issues

The bibliographic research and the meta-analysis conducted in this review have analysed a large number of investigations that have explored important drivers of soil hydrology after prescribed fire application. However, despite the eminent literature published on this topic, we think that research is still far from being exhaustive for several reasons.

First, investigations have been carried out in only a few environments (mainly the United States and the Iberian Peninsula), while many other areas with different climatic, geomorphological and ecological areas have been generally neglected by research. Indeed, some studies have not been considered in this review, since the papers were not published in English, Spanish or Italian, and this limits the diffusion of those studies to a vast international readership. The distribution of the reviewed studies has been presumably due to national funding priorities or existing research teams dedicated to studies on fire prevention but it has limited the variety of the analyzed environments (Girona-García *et al.*, 2021). Special attention has been paid to some semi-arid areas in the Mediterranean Basin and continental zones with a very hot and dry climate in summer. This attention is justified by the fact that these areas are more prone to wildfire risk compared to other environments and represent the area of greatest concern, due to human population and hazards of destructive flooding, erosion and debris flow events after a wildfire (Girona-García *et al.*, 2021). However, the recurrence and damage due to wildfires may be high in many other areas, such as boreal and tropical forests. For instance, to the authors' knowledge, there are no studies dealing with the treatment of various ecosystems with prescribed fire in Central and Northern Europe or Africa. In the first environments, the forest areas are vast and often very dense and the tree heritage is high; in Africa, the increasingly high temperatures and desertification trends due to climate change forecast an increase in wildfire frequency and hazard. This research gap should encourage the adoption of many other case studies that should cover almost all the climatic, edaphic and orographic conditions on a global scale.

Second, in almost all studies, the hydrological and erosive effects of the prescribed fire have been monitored only for one or two years after its application, while longer-term investigations are practically absent. Often, most field measurements of runoff and erosion are carried out only over short periods, and therefore, long-term perspectives of fire impacts are few and confined to short timescales (Moody et al., 2013). This short duration of the monitoring window, in addition to the frequent shortage of financial support for long-term projects (Girona-García *et al.,* 2021), is due to the common knowledge that the prescribed fire impacts are temporary and, in most cases, last only a few months after its application. This has been shown in many studies, which have demonstrated that the durability of the window of disturbance of the prescribed fire is limited, lasting from a few months to a year and a half or two years. However, as outlined by this meta-analysis, the pre-fire values of the monitored hydrological variables are not always restored throughout this time, and therefore the exact date when the burned soil comes back to the undisturbed runoff and erosion rates is highly uncertain. Therefore, the time scale of the relevant studies should be properly extended, to precisely identify the duration of the "window of disturbance" of the prescribed fire. We agree with

Wagenbrenner *et al.* (2021), who suggest that long-term post-fire research in the same sites would provide interesting and useful data as well as better indications for understanding hydrologic recovery in fire-prone ecosystems. The same authors also state that it is much easier and less expensive to conduct continuous monitoring of an existing site than installing a new research site. They also suggest reducing measurement intervals over time without losing too much important information about the ecological and hydrological response to fire (Wagenbrenner et al., 2021). Studies, whether short or longer-term, need to monitor precipitation intensity, since the frequency and duration of intense precipitation controls many of the hydrological and erosive effects discussed in the literature.

Third, the investigations at experimental plots (with areas ranging from a few square metres to entire hillslopes) are the most common in terms of spatial scale (according to Shakesby and Doerr, 2006; Girona-García *et al.*, 2021), a statement confirmed by this meta-analysis. This method is feasible for studies aiming at better understanding soil hydrology at the hillslope scale but may lead to unrealistic results at larger scales. Often, observations made at one scale cannot be scaled up at different temporal and spatial scales (Moody *et al.*, 2013), since some hydrological processes are site-specific and others can not be measured at every scale. For instance, surface runoff and soil loss are often measured using portable rainfall simulators, which give important indications about the mechanisms of runoff generation and rainsplash erosion. However, these devices might underestimate or overestimate these variables, since the effects of concentrated flow and overland erosion are not measured. Moreover, some key hydrological and erosive processes that are not fully captured at the hillslope scale (e.g., sedimentation, channelised water flow) may be better estimated using catchments burned by prescribed fires. One must bear in mind that the hydrological and erosive response to soil disturbances due to fire and precipitation exert their effects on hydraulically-independent physiographic units, such as the catchment scale. The hydrological responses to fire at this scale have received much less international attention compared to smaller-scale studies, mainly due to practical difficulties and costs (Shakesby and Doerr, 2006; Shakesby, 2011) as well as the realistic impossibility of treating entire catchments with prescribed fire. To overcome these issues, we think that catchment-scale investigations should be further encouraged, carefully avoiding burned areas insignificantly small in the context of the whole catchment. Continuous post-fire runoff and sediment records at catchment outlets, which rarely exist because they are expensive (Girona-García *et al.*, 2021), would allow the analysis of the related temporal dynamics in real-time.

Fourth, since almost all case studies of this review have evidenced severe increases in the surface runoff and erosion rates compared to the pre-fire values, this paper supports the adoption of effective post-fire management actions for vegetation restoration and erosion control immediately after the prescribed fires. If not properly controlled, these increases can result in an aggravation of the off-site impacts of fire, such as flooding and damage to civil infrastructures. Society increasingly requires effective actions to mitigate the risk of post-fire erosion and runoff, to preserve water quality, control soil degradation, and protect people and infrastructures (Girona-García *et al.*, 2021). However, only three papers have reported evaluations of the soil's hydrological response after a prescribed fire and post-fire management (Pierson *et al.*, 2014; Carrà *et al.*, 2021a, 2022). This means that the effectiveness of the various post-management actions (e.g., afforestation, mulching, log erosion barriers, contour felled log debris, soil preparation, check dams, and so on, Girona-García *et al.*, 2021; Lucas-Borja, 2021; Zema, 2021) has not received proper attention in the relevant literature and therefore is still unknown. More research is therefore expected in the future, preferably based on comparisons between different actions and an untreated and/or unburned control site.

Fifth, prescribed fires exert not only hydrological and erosive effects but also may affect other soil and vegetation properties as well as the quality of downstream water bodies, despite the temporally and spatially confined actions and the limited heat transferred to soil due to fire. Therefore, prescribed fire may be a factor of degradation for soil and water bodies (Alcañiz *et al.*, 2018; Carra *et al.*, 2021; Agbeshie *et al.*, 2022), but can also result in loss of biodiversity (Shakesby, 2011). In our meta-analysis, about 40% of the analyzed studies analyzed both soil and vegetation properties and only 5% explored water quality in addition to hydrological effects. Often the monitored parameters were few (most frequently organic matter, pH and nutrients) and the study aims were different from the assessment of soil and water quality. Therefore, considering the large variability of soil properties and the risk of severe pollution of water bodies draining water from burned forests, the monitored variables should be properly integrated. We suggest exploring, when financially possible, a significant ensemble of physical, chemical and biological properties of soils (e.g., enzymatic activities and microbial community composition), ground cover (such as those of shrub and herbaceous layers, ash, dead wood material), structure and diversity of regenerating vegetation as well as the main parameters associated with quality of surface water bodies (as in many studies focusing on wildfire effects on quality of water streams, mainly carried out in USA).

Sixth, although repeating burning is usually applied in some forestlands (e.g., Hutchinson *et al.*, 2005; Klimas *et al.*, 2020), few studies reviewed in this work have monitored the hydrological effects of repeated applications of fire (Morales *et al.*, 2000; Townsend and Douglas, 2000; González-Pelayo *et al.*, 2010; Strydom *et al.*, 2019; Quigley *et al.*, 2021). In addition to the small sample size, those studies have not made comparisons between sites treated with repeated and individual applications of prescribed fire. Therefore, it is unclear whether the hydrological and erosive response of forest soils to repeated fires is governed by the superposition principle or not. In other words, we are not aware whether the runoff and erosion rates noticeably increase after a new application of prescribed fire or, in contrast, repeated applications of prescribed fire do not play any significant effects on soil hydrology. Moreover, the ideal frequency of repeated burning should be assessed, not only in terms of minimization of future risk of wildfire but also from a hydrological point of view.

Seventh and finally, this meta-analysis has shown that the methodological approach to monitoring soil hydrology dynamics after prescribed fires is not consistent among the different investigations. For instance, some studies did not carry out comparisons between soils treated with prescribed fire and unburned sites. Often, the different measurement units have made the comparison of post-fire hydrological and erosive responses among the different studies very difficult, time-consuming and sometimes impossible, as also observed by Shakesby and Doerr (2006) and Moody *et al.* (2013). Moreover, the spatial and temporal scales of the studies show a large variability (from plot to catchment scale and from events lasting a few hours to their being multi-annual). This non-uniformity often prevents or makes very difficult the comparison of the hydrological and erosive response due to burning among studies with different environmental conditions (rainfall characteristics, soil properties, vegetation dynamics, fire features). To overcome this difficulty, it's necessary to organize the experimental data using a systematic and integrated approach. Despite the freedom in research, which is an essential requisite for the advances in science, guidelines for standardized and appropriate methods of measurement and analysis are welcome, to ensure the comparability of data and consistent interpretation of results. In this regard, a broader collaboration and consultation among researchers, technicians and authorities is essential, to identify the practical research needs and to select the most suitable measurement techniques.

5. SUMMARY AND CONCLUSIONS

This study has carried out a bibliographic review and a meta-analysis of changes in water infiltration, SWR, surface runoff and soil erosion due to prescribed fire application, using a database of 85 case studies from 41 academic papers published in the last 23 years. The effects of annual precipitation, soil slope, burn severity, fire application season, post-fire ground cover, and vegetation type on post-fire soil hydrology have been statistically explored.

The meta-analysis has helped to reply to some key research questions which have inspired this study, such as: (i) the role of prescribed fire as abfire management tool is not recognized worldwide, since the case studies are concentrated in only a few countries (mainly the USA and Spain); (ii) in the short-term after fire, water infiltration generally decreases, soil water repellency appears, and surface runoff (up to 20-fold the values measured in the unburned soils) and soil erosion noticeably increase (with peaks of 700-fold the pre-fire conditions); in contrast, after the "window of disturbance" ends, the pre-fire hydrological and erosive responses of soil progressively recover, although the pre-fire values are not restored; (iii) the window of disturbance in burned soils may be a few months, but some studies show that the pre-fire hydrological and erosive response to prescribed fire does not restore after two years; (iv) annual precipitation and soil slope significantly influence water infiltration and surface runoff, but do not affect soil erosion in either short or medium-term; (v) moderate-to-high levels of soil burn severity, a key influencer of water infiltration, severely increases surface runoff and soil erosion, and noticeably reduce water infiltration in the short-term; (vi) the level of ground cover burning is important in considering runoff rates, but it plays a minor role on water infiltration and soil erosion; (vii) prescribed fire applied in spring results in a lower increase in short-term runoff and erosion, while fire applications in summer and in shrublands produced the highest increases in soil loss.

This meta-analysis is based on comprehensive and quantitative data collected in a large variety of environments, and, as such, may overcome the limitations of local studies on post-fire soil hydrology. Therefore, the following practical indications arise from this study: (i) research should be better distributed worldwide throughout all environmental contexts; (ii) post-fire management actions should be adopted immediately after the prescribed fire application, in order to limit the increases in post-fire surface runoff and erosion; (iii) prescribed fire operations must be carried out in spring and the soil burn severity should be kept low during burning, in order to avoid the worst effects of rainstorms at the start of the wet season and a total removal of the ground cover; (iv) monitoring studies should be prolonged to last a few years (more than two or three) after prescribed fire, in order to precisely identify the duration of the "window of disturbance"; (iv) catchment-scale investigations, although more difficult and expensive, should be encouraged, since this scale is more realistic in terms of spatial variability of hydrological processes; (v) the monitored variables should also include the most important physical, chemical and biological properties of soil, the cover and structure of regenerating vegetation as well as water quality parameters; (vi) the effects of repeated applications of prescribed fire should be experimentally assessed, in order to verify the hypothetic superposition principle in the hydrological processes; (vii) guidelines for standardized and appropriate measurements and analytical methods in experimental activities should be setup, in order to ensure the comparability of data and consistent interpretation of results. These indications support land managers in the prioritisation of sites where the hydrogeological hazard after prescribed fire must be controlled using suitable post-fire management actions (a challenge when implementing on a large scale).

As a further aim of this study, the experimental database, on which the bibliographic review and the meta-analysis are based, is made available to other researchers and land managers, to create a public, easy-accessible and comprehensive public tool for future research needs and professional activities. We also hope that this database will be periodically maintained and integrated with experimental data and studies in the future, to increase the public knowledge about the hydrological and erosive effects of prescribed fire in the majority of environmental contexts.

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Data Availability

The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

Authors’ Contributions Statement

Both authors conceived the study, reviewed the papers, compiled the database, carried out the data analysis, and discussed and critically analysed the results. Demetrio Antonio Zema wrote the first and the final drafts, and Manuel Esteban Lucas-Borja revised these drafts. All authors agreed on the original and final versions.

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SUPPLEMENTARY MATERIAL

Table 1.SM – The experimental database of the 85 case studies reported in the 41 papers reviewed in this study.

TABLES

Table 1 - Distribution of the analyzed papers by publishing journal.

Journal	Number of papers	Relative frequency (%)
Geoderma	5	12.2
Science of the Total Environment	3	7.3
Journal of Environmental Management	3	7.3
Forest Ecology and Management	2	4.9
Land Degradation and Development	2	4.9
Catena	2	4.9
Journal of Hydrology	2	4.9
Ecosystems	2	4.9
Journal of Rangeland Management	2	4.9
Soil Science Society of America Journal	2	4.9
Hydrological Processes	2	4.9
Earth Surface Processes and Landforms	2	4.9
Geomorphology	1	2.4
Quarterly Journal of Engineering Geology and Hydrogeology	1	2.4
Forests	1	2.4
Ecological Engineering	1	2.4
Soil Science	1	2.4
Water Resources Research	1	2.4
Rangeland Ecology and Management	1	2.4
Journal of Environmental Quality	1	2.4
Journal of Soil and Water Conservation	1	2.4
Australian Journal of Soil Research	1	2.4
Hydrology	1	2.4
Conference Proceedings	1	2.4

Table 2 – Number of citations of the analyzed papers.

Authors	Journal	Year	Citations	
			Total number	**Number per year**
Morales et al.	Forest Ecology and Management	2000	29	1.3
Robichaud	Journal of Hydrology	2000	335	15.2
Townsend and Douglas	Journal of Hydrology	2000	80	3.6
White and Loftin	Journal of Rangeland Management	2000	20	0.9
Huffman et al.	Hydrological Processes	2002	216	10.8
O'Dea and Guertin	Journal of Rangeland Management	2003	21	1.1
Coelho et al.	Quarterly Journal of Engineering Geology and Hydrogeology	2004	53	2.9
Ferreira et al.	Australian Journal of Soil Research	2005	60	3.5
Robichaud et al.	Conference Proceedings	2005	0	0
Vega et al.	Land Degradation and Development	2005	89	5.2
de Koff et al.	Soil Science	2006	14	0.9
Hubbert et al.	Geoderma	2006	96	6.0
Fernández et al.	Land Degradation and Development	2008	50	3.6
Pierson et al.	Catena	2008	72	5.1
Vadilonga et al.	Hydrological Processes	2008	23	1.6

Pierson et al.	Earth Surface Processes and Landforms	2009	79	5.6
Ravi et al.	Ecosystems	2009	92	7.1
Zavala et al.	Earth Surface Processes and Landforms	2009	65	5.0
González-Pelayo et al.	Geomorphology	2010	32	2.7
Granged et al.	Geoderma	2011	87	7.9
Stoof et al.	Soil Science Society of America Journal	2011	41	3.7
Chief et al.	Soil Science Society of America Journal	2012	18	1.8
Fernández et al.	Journal of Environmental Management	2012	21	2.1
Cawson et al.	Forest Ecology and Management	2013	56	6.2
Pierson et al.	Rangeland Ecology Management	2014	37	4.6
Ozaslan Parlak et al.	Journal of Environmental Quality	2015	6	0.9
Shakesby et al.	Catena	2015	59	8.4
Cawson et al.	Geoderma	2016	38	6.3
Fonseca et al.	Geoderma	2017	49	9.8
Singh et al.	Forests	2017	5	1.0
Chandler et al.	Water Resources Research	2018	2	0.5
Plaza-Álvarez et al.	Science of the Total Environment	2018	30	7.5
Lucas-Borja et al.	Science of the Total Environment	2019	27	9.0
Nouwakpo et al.	Journal of Soil and Water Conservation	2019	7	2.3
Plaza-Álvarez et al.	Journal of Environmental Management	2019	31	10.3
Strydom et al.	Geoderma	2019	9	3.0
Carrà et al.	Hydrology	2021	17	17.0

Quigley et al.	Science of the Total Environment	2021	3	3.0
Carrà et al.	Ecological Engineering	2022	7	0
Karban et al.	Ecosystems	2022	0	0
Lucas-Borja et al.	Journal of Environmental Management	2022	0	0

Source of citations: Elsevier® Scopus® database; last access: 12 June 2023.

Table 3 - Results of ANOVA of log response ratio (LRR) of water infiltration, surface runoff and soil erosion calculated in the short and medium terms for six environmental characteristics (annual precipitation, spoil slope, burn season, soil burn severity, vegetation type and post-fire ground cover) in the analyzed case studies.

Factor	**Degrees of freedom**	**LRR**					
		Infiltration		**Runoff**		**Erosion**	
		F	**Pr > F**	**F**	**Pr > F**	**F**	**Pr > F**
Annual precipitation	4	13.635	< **0.0001**	5.902	**0.002**	1.632	0.218
Soil slope	6	21.088	< **0.0001**	18.780	< **0.0001**	0.850	0.536
Burn severity	5	7.414	**0.001**	22.001	< **0.0001**	9.459	**0.000**
Post-fire ground cover	3	2.124	0.133	11.167	< **0.0001**	3.047	0.050
Vegetation type	1	5.584	**0.030**	10.965	**0.000**	6.035	**0.012**
Burn season	2	1.919	0.176	7.593	**0.003**	3.117	**0.047**
Time	1	0.818	0.378	0.001	0.974	2.766	0.117
Annual precipitation x Time	3	1.441	0.264	4.401	**0.014**	6.095	**0.004**
Soil slope x Time	5	2.676	0.056	38.287	< **0.0001**	0.331	0.803
Burn severity x Time	2	0.028	0.972	46.079	< **0.0001**	3.176	**0.045**
Post-fire ground cover x Time	3	0.081	0.970	4.758	**0.019**	0.336	0.571
Vegetation type x Time	1	0.119	0.734	-	-	0.872	0.365
Burn season x Time	1	0.899	0.356	19.460	**0.000**	5.361	**0.035**

Note: bold characters refer to the statistical significance.

FIGURE CAPTIONS

Figure 1 - Flowchart of the procedure adopted for the bibliographic review and meta-analysis.

Figure 2 - Distribution of the analyzed papers by publication year.

Figure 3 - Map of the location of the study areas in the analyzed papers by country.

Figure 4 - Distribution of the analyzed case studies by climate (upper left), altitude (upper right) and soil texture (lower).

Figure 5 - Variability of water infiltration, SWR, surface runoff and soil erosion among soil conditions in the analyzed case studies.

Figure 6 - Log response ratio (LRR, mean and confidence interval) of water infiltration in the analyzed case studies. The number in brackets refers to the number of case studies in each class. The letters indicate significant differences in the short-term (lowercase) and medium-term (capital).

Figure 7 - Frequency of changes in soil water repellency in the analyzed case studies. The number in brackets refers to the number of case studies in each class.

Figure 8 - Log response ratio (LRR, mean and confidence interval) of surface runoff coefficient in the analyzed case studies. The number in brackets refers to the number of case studies in each class. The letters indicate significant differences between annual precipitation classes in the short-term (lowercase) and medium-term (capital).

Figure 9 - Log response ratio (LRR, mean and confidence interval) of soil erosion in the analyzed case studies. The number in brackets refers to the number of case studies in each class. The letters indicate significant differences between annual precipitation classes in the short-term (lowercase) and medium-term (capital).

Figure 10 – Linear regressions between Log response ratio (LRR) of soil erosion and runoff in the analyzed case studies.