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Review

How Mediterranean Ecosystem Deals with Wildfire Impact on Soil Ecosystem Services and Functions: A Review

Marcos Francos [1,*], Fernando Colino-Prieto [1] and Carlos Sánchez-García [2]

[1] Department of Geography, University of Salamanca, C/Cervantes s/n, 37002 Salamanca, Spain; fernandocolinop@usal.es
[2] Department of Geography, Autonomous University of Madrid, Calle Francisco Tomas y Valiente, 1, 28049 Madrid, Spain; carlos.sanchezg@uam.es
* Correspondence: mfq@usal.es

Abstract: Wildfires are a common phenomenon in Mediterranean environments. This study seeks to synthesize the main results of existing studies from the last decade on this topic and to highlight the need for managing soil impacted by wildfires in the Mediterranean environment. Researchers have found that the impact of fire during a forest fire on the soil, and the subsequent consequences on soil ecosystem services and functions, is great and produces negative consequences for the soil. The physical, chemical, and biological properties of soil have been extensively analyzed, and a very high number of studies during the last ten years have been performed on different study areas with a common component: the Mediterranean ecosystem. However, the effects of these fires on the multifunctionality of the soil itself, ecosystem services, and soil functionality, which they provide to humans, have not. It is therefore essential to know the impact of fires in a fire-prone ecosystem such as the Mediterranean one on the soil and how these services and functions are affected. In this way, the decision can be taken to carry out restoration measures, especially after very severe forest fires and if the recurrence is high. This conclusion is even more important in the context of global change in which more severe and recurrent fires are expected, and therefore actions to be considered are expected to be more necessary to avoid land degradation, as many of the studies compiled here have shown.

Keywords: soil chemical properties; wildfire risk; global change; land degradation; soil multifunctionality

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1. Introduction

Fire is a natural phenomenon that occurs in all ecosystems. However, it is particularly characteristic of the Mediterranean region, where, in many cases, it acts as a very useful ecological control tool, benefiting both the soil and vegetation, and serving as a soil-forming agent [1,2]. Since the emergence of humans, fire has also been used as a tool for various actions such as deterring predators, providing warmth, pest control, cooking, and burning areas to make them habitable [3,4]. The earliest evidence of human use of fire dates back to 1 million years ago, although records of widespread fire control date back to about 400,000 years ago [5].

Therefore, from ecosystems like savannas and grasslands, where wildfires occur annually, coinciding with the dry season, to ecosystems where the frequency of fire occurrence is much lower, such as the taiga, fire has shaped the different biomes of the planet throughout history [6]. However, in the case of much of the world, during the 20th century, fire began to be perceived as a detrimental element. This is due to the increase in the number of forest fires and, especially, the hectares burned in them. Some causes of this increase include the abandonment of rural areas, the loss of economic interests in forest management, and the increase in the frequency and intensity of forest fires [7].

In recent decades, there has been a shift in the perception of fire, acknowledging it as a natural element that has played and continues to play a crucial ecological role, particularly in Mediterranean climate areas. With this new perspective on fire, the importance of fire as a key planetary process, alongside climate, in shaping the Earth's biomes has been increasingly recognized [6].

Forest fires are also part of increasingly common natural hazards as a consequence of climate change [8]. The rise in temperature and variation in precipitation patterns create ideal conditions for the development of large forest fires [9].

In the development of forest fires, especially in more recent times, two fundamental aspects must be considered: the so-called "fire suppression", which indicates that intensive firefighting efforts lead to the phenomenon known as the "fire paradox". This paradox involves the fact that the more work and investment that are put into firefighting, the greater the availability of fuel becomes, which, in turn, can lead to more significant forest fires. This "fire paradox" has caused many areas in Australia, the United States, South America, and Europe to experience the largest forest fires in their recent history over the last three decades [3]. These policies in many Mediterranean countries were developed during the 1990s and 2000s. However, such policies are a double-edged sword as they can lead to very large accumulations of vegetation and thus increase the risk of medium- to long-term fires such as those we are currently encountering.

Therefore, several authors [2,10] have agreed that controlled burns, always of low severity, have a positive influence on natural cycles due to the improvement of ecosystem productivity through the contribution of organic matter to the soil via ashes and the subsequent nutrient expansion with combustion. Consequently, low- and medium-severity forest fires are not always catastrophic; it is the large, high-severity forest fires that pose a real threat.

Indeed, in Mediterranean regions, large forest fires constitute a serious problem [1] as the concurrent occurrence of the dry season and high temperatures creates ideal conditions for the initiation and development of fires in the forest. In addition to summer aridity, torrential fall rains increase the risks associated with forest fires [11]. Thus, the rainy season, which generally follows the dry season, can erode large amounts of soil, especially if it has experienced the combustion of organic matter, leading to increased soil fragility, nutrient runoff, and soil microbiota losses [6,12].

Some of the causes of the increased severity of forest fires in the Mediterranean ecosystem include:

- Rural abandonment: Demographic issues in rural areas lead to reduced forest management, resulting in the abandonment of wooded areas and an increase in available fuel in the event of a fire [13].
- Changes in land use in general: The widespread cultivation of non-native and non-fire-adapted species, causing complete ecosystem burning [14,15].
- Climate change: Climate change tends to desynchronize fires from traditional periods and increases the areas where fires occur, spreading to places where they were not as common [8].

The consequences of these factors have led to an increase in forest fires since the 1970s when climatic conditions began to favor them. Fires occur more frequently, and although Mediterranean ecosystems can coexist with them, this change in the fire regime can have adverse effects [16].

Forest fires are not exclusive to the Mediterranean ecosystem; they are a global phenomenon [17]. Many studies on mega-fires have been conducted in Mediterranean basin countries such as Portugal, Spain, Greece, Algeria, and Israel [18–22]. Additionally, research has been carried out in countries with Mediterranean ecosystems, like Chile [23,24], and in radically different countries such as Russia [15,25], Lithuania [26,27], and Finland [28].

Furthermore, as previously mentioned, the unique climatic characteristics of Mediterranean ecosystems—intense drought during the hot season, promoting the burning of existing fuel, and torrential rains in the post-fire period [29]—make many of these areas highly prone to soil erosion with topographical conditions as a cross-cutting factor. It is worth noting that due to the current dynamics of fires and the trend toward the desynchronization of forest fires outside their typical season, the degree of erosive impact from intense precipitation is greater, as the period between the fire and rainfall is shorter [30].

Given this, the potential post-fire forest management or handling becomes of great importance. In many cases, techniques such as logging and wood extraction with heavy machinery contribute to soil degradation, while others like "mulching" reduce it, despite not being a suitable measure for soil biodiversity and not being the best technique to apply in all cases [31–33]. Post-fire management should be carried out in specific areas that are more susceptible to degradation because the management choices we make can have both positive and negative impacts on the soil. Therefore, the goal of this management should be to facilitate soil recovery following the disturbance caused by a large forest fire [34].

The aim of this study is to conduct a literature review using the PRISMA protocol to examine the impact of forest fires on soil ecosystem services within the context of Mediterranean ecosystems, with a particular focus on the Iberian Peninsula. The selected ecosystem services for the study include climate regulation, nutrient cycling and fertility, water retention, moderation of extreme events, and water quality. Despite the association of forest fires with the Mediterranean ecosystem, a search through bibliographic databases reveals a limited number of studies addressing the relationship among ecosystem services, the Mediterranean ecosystem, and the role of forest fires in this context. Therefore, this study is considered to shed light on this intersection and aims to determine the progress made in recent decades.

2. Study Area

The scope of the present study focuses on the Mediterranean ecosystem (Figure 1). To define this area, the Köppen–Geiger climate classification was employed, specifically the climates classified as Cs, which are characterized by a dry season coinciding with the period of highest temperatures (summer) [35]. It is a transitional climate between the temperate and tropical climates and occurs in five regions worldwide: the Mediterranean Basin, California, Chile, South Africa, and southwest Australia [36]. According to the Köppen climate classification, Mediterranean climates have the following characteristics for their definition [35]:

- Average temperature of the coldest month between 0 °C and 18 °C, and the average of the warmest month exceeds 10 °C.
- Rainfall pattern with a dry summer: the precipitation of the driest month in summer is less than one-third of the precipitation of the wettest month, and some months have precipitation less than 40 mm.

Based on the average of the warmest month, there are two types of Mediterranean climates:

- Subtropical: The average of the warmest month is above 22 °C, and at least 4 months exceed an average temperature of 10 °C.
- Cool summer: The average of the warmest month is below 22 °C, and at least 4 months exceed an average temperature of 10 °C.

In general, the global areas with a Mediterranean climate primarily extend across the Mediterranean Basin and also include parts of central Chile, the west coasts of the United States, Australia, South Africa; and specific points around the world in a more localized manner.

The choice of this study area is driven by the recurrence of forest fires in these regions due to the mentioned climatic characteristics (coincidence of warm and dry periods). Even in the current context of climate change, these areas continue to face significant fire risks. Nevertheless, it is crucial to acknowledge that fire has been a fundamental ecological factor in the formation of these ecosystems. This type of study can be developed for all global ecosystems as the studies and scientific evidence that provide objective answers to the impacts and the recovery of soil properties and functions in these ecosystems progress. In our case, we applied it to the ecosystem in which fires play a more relevant role and have a greater recurrence.

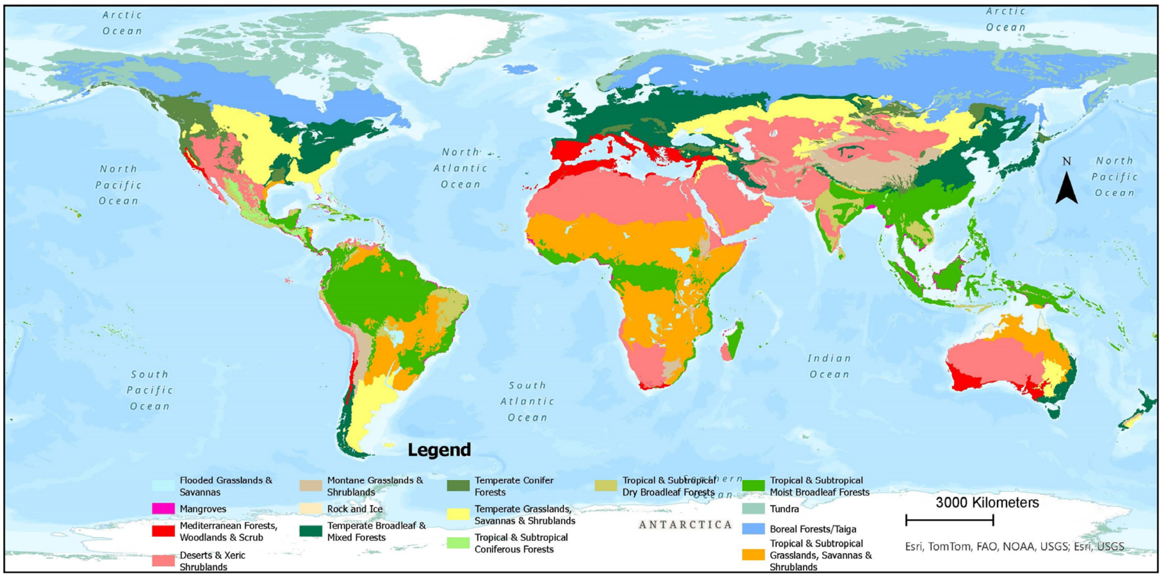

Figure 1. Distribution of Mediterranean forest ecosystem. (Source: ArcGIS online free data).

3. Methodological Procedure and Literature Review

For the execution of the bibliographic study, a systematic review of the scientific literature was carried out following a structured order and planning [37]. Initially, a review protocol was defined based on the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines [38], chosen to ensure scientific quality and ensure a transparent and systematic review [39]. The PRISMA protocol is composed by six steps: (I) scoping, (II) planning, (III) identification and search, (IV) screening articles, (V) eligibility assessment, and (VI) presentation and interpretation. (I) Once the keywords for the study topic were established, (II) it was decided to work with two main databases, Web of Science (WOS) and Google Scholar, to maximize the number of potential studies included in the work [40].

Aligned with the purpose and objectives of the study, the following keywords were used for the investigation: 'soil ecosystem services', 'wildfire', 'forest fire', '*servicios ecosistémicos del suelo*', and '*incendio forestal*'. These keywords were combined with Boolean operators, primarily AND and OR. The search was restricted to the title, and keywords were also searched in the abstracts to narrow down the possible results to align with the study's focus [41].

As can be seen in Table 1, (III) the lack of scientific literature that combines the two main topics of work in the text, ecosystem services and forest fires, is very remarkable, as there are no articles on the subject in either of the two languages used in the search. This fact is what gives the study its novelty and is the basis of the structure presented in the content of this study. For this reason, for steps (IV), (V), and (VI), it was necessary to work on this topic of study indirectly. Because there are no studies about wildfires and their impact on soil ecosystem services, the results had to be inferred from studies of soil properties and forest fires and soil ecosystem services (without fire impact) and a table with information on soil indicators and ecosystem services had to be applied (see Section 6).

Table 1. Search results for these keywords.

Keyword	Number of Results
"Servicios ecosistémicos" and "Incendio Forestal"	0
"soil ecosystem services" and "forest fire"	0
"soil ecosystem services" and "wildfire"	0
"soil ecosystem services"	309
"forest fire"	10,500
"wildfire"	14,500
"Servicios ecosistémicos" and "suelo"	81

The choice of two languages (English and Spanish) for the search is primarily due to the higher quantity of scientific publications on the study topic and in general as scientific journals are predominantly written in English. The difference in the prevalence of English articles is significant compared to other languages [42]. Spanish was chosen as it is the native language of the author and is also the language of several areas under study, such as Spain and Chile.

The PRISMA protocol, applied in the bibliographic search, was considered the most appropriate. However, it is important to note some limitations in the search, including the existence of articles in other languages (only articles in Spanish and English were considered); technical reports, studies, and projects that were not included because they were not published in the consulted sources; and, related to the study topic itself, the occurrences of unexplored forest fires or fires that happened in uninhabited areas, leading to very limited or even non-existent literature.

To narrow down the articles within a relatively recent time frame, only publications dated between January 2003 and December 2022 were considered. The search took place in March/June 2023, and additional queries were conducted throughout the first semester of 2023 as needed for the study. The temporal restriction was chosen because there was a very limited number of articles before the first year of the chosen interval. It is noteworthy that the majority of the articles found are from the second chosen decade (2013–2022), indicating an increasing relevance of the studied topic over the years.

Although the bulk of the consulted publications adhered to the mentioned parameters, some earlier studies and other types of articles (grey literature) were also consulted to aid in the explanation, contextualization, and discussion of certain dynamics. In this sense, the studies considered for each of the following four sections are incorporated in Table 2 as well as the information of the topic addressed (Table 2).

Table 2. Studies included after bibliographic search.

References	Soil	Wildfire	Ecosystem Services	Mediterranean Ecosystem
[1]	X	X		X
[10]	X	X		
[24]	X	X		X
[39]			X	X
[43]	X	X		X
[44]	X	X		X
[45]	X	X		

Table 2. *Cont.*

References	Soil	Wildfire	Ecosystem Services	Mediterranean Ecosystem
[46]		X		X
[47]	X	X		X
[48]	X	X		X
[49]	X	X		X
[50]	X	X		X
[51]	X	X		
[52]		X		
[53]	X	X		
[54]	X	X		X
[55]	X	X		X
[56]	X	X		
[57]	X	X		X
[58]	X	X		X
[59]	X	X		
[60]	X	X		X
[61]	X	X		
[62]	X			X
[63]	X			X
[64]	X			X
[65]		X		X
[66]	X	X		X
[67]	X	X		X
[68]	X	X		X
[69]	X	X		X
[70]	X	X		
[71]	X			X
[72]	X	X		X
[73]	X			X
[74]	X			X
[75]	X	X		X
[76]	X	X		X
[77]		X		X
[78]	X	X		X
[79]	X			
[80]	X			
[81]	X			X
[82]				X
[83]		X	X	X
[84]	X		X	
[85]	X		X	
[86]	X		X	

Table 2. *Cont.*

References	Soil	Wildfire	Ecosystem Services	Mediterranean Ecosystem
[87]			X	X
[88]	X	X		X
[89]	X	X		X
[90]	X	X	X	
[91]		X		X
[92]			X	X
[93]			X	X
[94]	X	X	X	
[95]		X		X
[96]			X	X
[97]	X	X		
[98]	X	X		X
[99]	X	X		X
[100]		X	X	X
[101]		X	X	X
[102]		X	X	X
[103]		X		X

4. Overall Characteristics after Wildfires in Mediterranean Ecosystems

Fire has different impacts on the soil that, depending on its severity and intensity, can be more or less detrimental or, in the case of low-intensity burns, even beneficial for soil fertility.

Focusing on the Mediterranean region, fire is the primary element that causes forest destruction in these ecosystems [43]. Regarding fires, most authors typically categorize them into three types based on their intensity (severity): low-, medium-, and high severity. Depending on the level of severity, soil properties will be affected in different ways, being beneficial in some cases and detrimental in others [44].

Another key factor previously mentioned in terms of the impact of fire is the soil's land use prior to the fire, as some soils are more prone to suffering more harmful consequences from fires [34]. Specifically, in the objectives outlined in the introduction, various studies have explained the different impacts of fire on soils, including those that investigate it through indicators such as nutrients [45]. Thus, the reduction in or elimination of vegetation cover leads to soil degradation due to increased exposure to erosion. Additionally, forest fires bring about changes in the water cycle, altering the soil's infiltration capacity and increasing its hydrophobicity [46–48]. To achieve this, other factors that also influence nutrient content must be taken into account, such as topography, vegetation type, litter layer thickness, and soil type [45].

Fires are the primary agent responsible for the disturbance and renewal of forests. Low-severity fires, such as prescribed burns used in forest management, promote the renewal of dominant vegetation by eliminating unwanted species and transiently increasing pH and available nutrients [2]. In general, fires play a significant role in altering floristic composition [49] and tree regeneration [50], improving wood production [51], and influencing human ecology [52]. The extent and duration of these effects depend primarily on the severity of the fire, which, in turn, is controlled by various environmental factors affecting the combustion process, such as the quantity, nature, and moisture of live and dead fuel; air temperature and humidity; wind speed; and site topography.

Fire severity comprises two components: intensity and duration. Intensity is the speed at which a fire produces thermal energy. Although heat is transported more rapidly and penetrates more deeply into moist soil, the latent heat of vaporization prevents the soil temperature from exceeding 95 °C until all the water is vaporized [53]. Subsequently, the temperature typically rises to 200–300 °C [54]. In the presence of heavy fuels, the surface soil temperatures can reach 500–700 °C [55], but occasional instantaneous values of up to 850 °C can be recorded [56].

5. Soil Properties and Wildfires

Through the soil properties, the effects of fire are detailed. The first of these is the so-called carbon sink (or stock). In this case, the soil constitutes the world's largest carbon retention element. During forest fires, especially in more severe ones, there is a significant volatilization of the organic carbon available in the soil [56]. Thus, in the short term, there can be a very significant decrease in carbon availability in the soil due to various factors: the mineralization and subsequent volatilization of carbon, removal of ashes by the wind, soil erosion, and surface runoff [57]. However, later on, there tends to be an increase in soil carbon once the ashes are incorporated into the soil, vegetation recovery begins, and some burned wood fragments decompose [45]. Recovery is slow and very gradual in areas experiencing repeated fires. Various studies indicate significantly lower available carbon values in the soil than in unburned control areas, both in the medium and long terms [58–60].

The second of the analyzed properties is nitrogen. Like carbon, there can be a loss through volatilization and oxidation at temperatures above 200 °C [57,61]. The behavior is highly variable and depends, once again, on various factors [62]. In prescribed burns and low-severity fires, there is an increase in nitrogen due to the rapid incorporation of ashes rich in this element into the soil [63]. Conversely, in areas where fires have higher recurrence (every 2 years), there is a loss of the total nitrogen level [64].

Other relevant nutrients are calcium and magnesium, which behave differently than carbon and nitrogen as they have a very high volatilization temperature, preventing losses through this pathway [65]. In calcareous soils, where the calcium content can represent up to 25%, loss can occur through leaching. In this case, calcium levels can increase in the short term with ash incorporation into the soil, but due to loss through runoff and erosion, the recovery is less than in unburned areas [66]. Regarding magnesium, its behavior is very similar to that of calcium, leading to increases in the short term and sometimes achieving equilibrium in the medium term, with values becoming less variable than in unburned areas due to the reduced soil dynamics in a fire-affected zone [1].

In the case of phosphorus, it also has a high volatilization temperature (770 °C). Once again, if ashes are incorporated into the soil, there is an increase in the p value in it, although loss can also occur through wind erosion or runoff. However, in some cases, significant long-term increases in total phosphorus in the soil have been observed after a fire [67].

Potassium and sodium, once again, exhibit more similar characteristics to each other, causing them to have similar behaviors. Thus, they have a significant leaching loss capacity, resulting in a washing of the soil nutrient levels and a decrease in their availability in the ashes [1]. According to some authors [62,63], the recovery of the pre-fire potassium content can occur even more than a year later due to the mentioned leaching loss and vegetation consumption after starting its recovery.

Soil fertility can be affected by the acidity level, measured through pH, which, in all fires, undergoes an increase due to the decrease in acidity due to the contribution of cations (calcium, magnesium, potassium, silicon, and phosphorus, primarily), as well as other microelements and oxides present in the ashes [1]. Similarly to other elements, the degree of pH variation will be determined by the fire intensity (changes are insignificant in prescribed burns and low-severity fires). Thus, if the ashes are not quickly incorporated into the soil, for example, by wind action, the pH level reaches pre-fire levels relatively quickly in the medium term.

Soil electrical conductivity exhibits behavior somewhat similar to pH. Thus, conductivity tends to increase in fires and prescribed burns because there is a release of soluble ions through the combustion of organic matter [62]. However, the maintenance of these values over time will depend on the factors mentioned earlier in the case of pH. In this case, climatic conditions and, especially, the level of precipitation in the affected area will determine the evolution of electrical conductivity over time (if there is runoff and the salts are removed, a new decrease in conductivity will occur) [1]. In general, there is no consensus on the long-term effects of fire on conductivity. In any case, it will depend on the recurrence of fire and the type of soil, with higher electrical conductivity values found in forests and lower values in grasslands [62].

An additional soil characteristic of relevance that must be analyzed after a forest fire is hydrophobicity. The formation of hydrophobic substances with this property causes a decrease in soil permeability and an increase in surface runoff. These substances result from the accumulation of mineral ashes and the combustion of organic matter, especially when temperatures exceed 300 °C [6]. This water repellency will vary depending on several factors: the prior soil conditions (hydrophilic or hydrophobic), the quantity and type of vegetative fuel [68], and the aforementioned fire intensity. However, it is worth noting that high-severity fires can lead to the destruction of hydrophobic substances, resulting in a decrease in soil water repellency [57]. Nevertheless, it cannot be conclusively stated that in all low-severity forest fires, the produced hydrophobicity is lower, as high-intensity (and severity) fires often lead to a greater accumulation of the ash layer [69].

As for soil texture, there is a consensus that it does not undergo alterations at temperatures below 500 °C [70]. Nevertheless, in some cases, relevant increases in sand content have been found in sandy loam soils in Spain after a prescribed burn [71]. However, a week after the measurement, the sand content in the soil had returned to pre-fire levels. This temporary increase was due to the formation of unstable aggregates. There are few studies that have focused on the modifications to soil texture after a forest fire, and it could be interesting to investigate the effects of fires on soils with different texture types [62].

Regarding the infiltration capacity, it is closely related to the aforementioned hydrophobicity, as increased water repellency leads to decreased infiltration values and increased runoff [72]. Vegetation is the primary agent responsible for reducing runoff and promoting infiltration adequately. Therefore, if vegetation does not recover quickly after a fire, the impact of water droplets (especially during torrential rains typical of the Mediterranean ecosystem) on bare soil will destroy aggregates and finer particles will clog pores, drastically reducing infiltration [73,74]. This, in turn, leads to increased erosive action on the soil [39]. Mataix-Solera et al. [75] consider that elevated water repellency (hydrophobicity) tends to imply lower infiltration rates.

As previously mentioned, one of the fundamental impacts of fire on soil is on microbiological activity and invertebrates. Fire can affect this soil biological community directly or indirectly. The effects of fire on a soil's biological properties depend mainly on the characteristics of the fire itself (intensity, residence time, and severity), fuel loading, microtopography, and soil moisture [104]. In this sense, it is essential to consider the intensity and severity of the fire to determine the degree of impact on these soil properties. Low-intensity fires such as prescribed burns can favor the fungal biomass, invertebrate density, and microbial biomass [76,105]. Wildfires can significantly affect these parameters by affecting ecosystem services and ecosystem functions where they are critical, such as supporting functions and the maintenance of habitats and biodiversity [106]. Lastly, there are properties that are severely affected by fire, and their recovery is essential for the ecosystem. One such property is the vegetation cover, which tends to be temporarily eliminated even in low-intensity fires [57]. The recovery of the vegetation cover varies depending on the capabilities different species have for regrowth [77]. Some species have a significant regrowth capacity, allowing for a relatively complete recovery of the vegetation cover in a short period [78]. Additionally, the use of so-called "fire retardants" during firefighting operations has detrimental effects on the soil. Typically, these substances consist of inorganic elements (primarily phosphorus and nitrogen) that are effective for firefighting but are non-biodegradable. Furthermore, these compounds are washed into aquifers, leading to eutrophication processes [79].

6. Soil Properties and Ecosystem Services

Ecosystem services are defined as the direct and indirect contributions of ecosystems to human well-being [80]. According to the [81] FAO (2023), ecosystem services can be classified into four major groups:

- Regulation Ecosystem Services: Benefits obtained by regulating ecosystem processes (maintenance of air quality, climate regulation, water purification, erosion control, etc.).
- Provisioning Ecosystem Services: Material goods (water, wood, food, etc.) obtained from ecosystems.
- Supporting Ecosystem Services: Services necessary for the production of other ecosystem services.
- Cultural Ecosystem Services: Non-material benefits obtained from ecosystems (recreational and health activities, esthetic appreciation, etc.).

Five specific ecosystem services of the soil were chosen for analysis: climate regulation, nutrient cycling and fertility, water retention, moderation of extreme events, and water quality (see Section 1). This selection is not arbitrary; these services are considered the most relevant due to their importance and contributions to human well-being, as their consequences can significantly impact people's lives. Additionally, changes in the soil following a forest fire have a clear and direct impact on these ecosystem services [24].

It is worth noting that there is a scarcity of scientific literature, as mentioned in the theoretical framework of this study, regarding the relationship between forest fires and ecosystem services. This scarcity necessitates a separate study of the soil properties, the ecosystem services associated with them, and the forest fires.

The following Table 3 is proposed as a study outline to understand the impact of fire on ecosystem services. The aim is to explore the relationship between ecosystem services and fire through these specified properties or indicators. As mentioned earlier, due to the lack or scarcity of scientific literature directly studying the impact of fire on soil ecosystem services (see Table 1), the relationship between indicators and ecosystem services was established to understand this impact effectively.

Table 3. Summary of analyzed properties and ecosystem services affected.

Soil Ecosystem Services	Indicator
Climate regulation	Carbon stock
Nutrient cycle and fertility	Nitrogen
	Calcium
	Phosphorus
	Potassium
	Sodium
	pH
	Electric conductivity
	Magnesium
	Biota

Table 3. *Cont.*

Soil Ecosystem Services	Indicator
Water retention	Hydrofobicity
	Soil texture
	Infiltration capacity
Regulation of extreme events and water quality	Vegetation cover
	Use of retardants in extinction

7. Soil Ecosystem Services and Multifunctionality after Wildfires

Due to the aforementioned scarcity of existing references on soil ecosystem services and fire, the concept of multifunctionality was introduced, which is relevant and similar and has seen an increased level of focused studies in recent years. Soil multifunctionality is a term closely related to ecosystem services, and although they are similar concepts, they are not exactly the same. Soil multifunctionality is defined as the soil's capacity to simultaneously provide various ecosystem services [82]. However, there are no specific studies that analyze the impact of wildfires on soil ecosystem services. Some authors have presented strong evidence that soil multifunctionality is negatively affected, with a significant reduction following a forest fire. Moreover, the implementation of proper post-fire forest management strategies helps recover the pre-fire values in the short to medium terms (approximately 5 years) after the fire [83].

7.1. Climate Regulation

As mentioned earlier, soil is the largest carbon reservoir on the planet, making it a crucial agent in climate regulation. Following a wildfire, a substantial amount of this carbon is released, resulting in massive emissions of greenhouse gases that significantly impact the climate. These emissions contribute to approximately one-third of the world's total emissions [84]. As a consequence, the soil loses a significant portion of its climate regulation capacity, leading to substantial air pollution due to the release of large amounts of carbon. The carbon content in the soil is estimated to be 1.5 times that accumulated in the vegetation [85]. It has been estimated that wildfires are responsible for emitting up to 30% of the total carbon stock stored in the soil [86], releasing in a matter of hours the carbon accumulated over many years [87].

7.2. Nutrient Cycle and Fertility

The significant changes in nutrient proportions in the soil following a high-severity forest wildfire lead to a loss of soil fertility, which, in turn, can hinder and delay vegetation recovery in the short and medium terms. The loss of nutrients through volatilization or oxidation results in substantial soil degradation, limiting it for less-demanding plant species. However, the impact is not always negative. In low- or moderate-severity wildfires, when ashes and burned organic matter are incorporated, there is an increase in fertility [88]. In some instances, this soil ecosystem function is positively affected, promoting recovery after the wildfire. For this positive impact to occur, a low-severity wildfire must take place, where only the aboveground parts of the vegetation are lightly burned [10]. Nevertheless, in large, high-severity forest wildfires, the quantity and quality of organic matter and nutrient availability decrease, causing significant soil degradation and fertility loss [89]. The biota is essential for supporting functions, such as the function of maintaining biota habitats and, consequently, biodiversity, which is a provider of ecosystem functions. In this sense therefore, soil micro-organisms and invertebrates play a fundamental role in the soil by supporting nutrient cycling processes and actively participating in soil fertility [107]. This biota can be affected by the ashes generated after a high-intensity fire, producing adverse effects on the soil biota and the functions it develops [90].

7.3. Water Retention and Water Quality

The changes that occur in soil properties such as texture, hydrophobicity, and infiltration capacity after a forest wildfire are crucial for understanding how soils lose a significant portion of their water retention capacity, promoting runoff and causing a greater erosive impact. The modifications in soil texture (alterations in aggregate stability) resulting from a forest wildfire, the increased hydrophobicity due to the incorporation of ashes with this characteristic into the soil, and consequently, the reduction in infiltration capacity, lead to the loss of the soil's crucial water retention function [57]. Moreover, this is related to the following Section 7.4, as increased runoff contributes to the occurrence of flash floods when rains follow the passage of the fire.

7.4. Regulation of Extreme Events and Water Quality

The phenomenon of global climate change is causing an increased recurrence of extreme events of all kinds [91]. Specifically, elevated temperatures result in variations in hydrological cycles, increasing the magnitude and frequency of events such as intense droughts and strong, sudden floods [92,93]. After a wildfire, the total or partial destruction of the vegetation cover leads to increased runoff (while decreasing infiltration capacity), causing maximum river flows [94]. Consequently, flash floods tend to affect larger areas when they occur in areas previously affected by a wildfire [95]. In addition to the increased risk of flooding, heavy rains following a wildfire can degrade water quality due to an increase in concentrations of harmful particles and organic carbon [96]. The use of so-called "retardant substances" (such as fluorosurfactants) during the fire extinction process, which are incorporated into the soil after the first rains, contaminate groundwater [97] or are carried away by runoff, adversely affecting water bodies [98]. Therefore, studies by Brogan et al. [99] have concluded that the ability to regulate water flows and soil flooding is particularly damaged in areas affected by high-severity fires or in soils with extremely dry conditions. Additionally, the desynchronization of the wildfire season causes them to occur in purely autumnal months like October, increasing the likelihood of intense rainfall immediately after the fire and thus increasing the probability of flash floods [100]. Despite the Mediterranean ecosystem's significant adaptation to fire, the recurrence and intensity of high-severity forest fires have strong negative impacts on soil multifunctionality [101] and, therefore, on its ecosystem services. Furthermore, there is a delay in vegetation recovery after the fire [102] that can severely affect the capacity to regulate floods in previously burned areas, especially in the current context of climate change where an increase in the recurrence of forest fires in an area is expected. The factors affecting water pollution are the same as those impacting the regulation of extreme events (floods) [103]. Several studies have found negative effects on flora and fauna in the short, medium, and long terms after a wildfire [108].

8. Conclusions

The damage to the soil vary locally depending on various factors: the presence of a high fuel load promotes a significant release of energy with a greater impact on the soil; areas with significant slopes, which favor runoff, cause the dragging of soil particles after a fire; moreover, prominent rainfall events after the fire lead to marked soil erosion following the fire-induced loss of protection. Among the most impactful consequences of forest fires are the increases in runoff and erosion, phenomena that can cause significant floods and inundations, posing a consequential risk to human lives, infrastructure, and various resources within and outside the burned area. Additionally, this event results in soil degradation. These risks are either mitigated or exacerbated depending on whether a contingency plan is developed and urgent actions are taken after the fire. Although forest restoration actions in the medium and long terms have a more extended trajectory, short-term actions (more immediate) have had minimal development in the Mediterranean context.

For all these reasons, this work presents some restoration and forest management strategies that could be implemented after the occurrence of a high-severity fire [3,109–113]. The goal of these tasks is to mitigate the impact of the fire, promoting a correct and rapid soil recovery. These post-fire forest management measures were developed with defined objectives, typically interconnected and categorized into immediate, short-term, medium-term, and long-term actions:

- Immediate and within the 1st year after the fire: Emergency stabilization measures should be implemented through tree cutting to halt soil degradation, reduce erosion and runoff, preserve drainage networks, maintain riverbeds, and indirectly promote natural vegetation regeneration.
- Between 1 and 3 years after the fire: Rehabilitation efforts involve repairing infrastructure to mitigate damage and supporting an accelerated natural ecosystem recovery. This can be achieved through silvicultural interventions to support natural regeneration, recovery of gallery forests, invasive plant control, fuel management, and promoting wildlife recovery.
- Over 3 years after the fire: Restoration measures focused on productivity recovery, reducing flammability, enhancing biodiversity and ecosystem quality, and restoring resilience should be implemented. These goals are achieved through forestry practices and proper fuel management.

Therefore, it can be concluded that soil is an important agent in climate control and is even more relevant in the current context of global warming. It plays an ecosystemic regulatory role that should be the focus of preventive measures due to its significance for biodiversity in general and for humans in particular. Moreover, it is a non-renewable resource, emphasizing the importance of efforts dedicated to its protection and care. The absence of studies in the Mediterranean ecosystem also opens a window of possibilities to analyze the impact of fires on soil ecosystem services in different ecosystems and terrestrial ecosystems and the response of these ecosystems. These fires can emit polluting gases and affect both directly and indirectly ecosystems in which there is currently significant growth in terms of the number of events and hectares burned, such as mountain areas or high latitudes [114]. For this reason, it is essential for the future to understand that these areas will be subject to more recurrent and intense fires and that they must adapt their forest structures as well as plan post-fire management to mitigate the impact of these disturbances [115].

Throughout the entire work, the importance of soil has been highlighted in terms of what it provides to humans. In addition to the measures that can be taken after a wildfire, preventive measures should also be implemented. These involve reducing the risk of large forest fires and implementing some of the actions discussed in different sections that have been shown to have a positive impact on the soil. Therefore, resources should be allocated to the protection of this system, the soil, which has crucial ecosystemic functions as analyzed earlier.

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