fire

Review

A Review of the Occurrence and Causes for Wildfires and Their Impacts on the Geoenvironment

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Abstract: Wildfires have short- and long-term impacts on the geoenvironment, including the changes to biogeochemical and mechanical properties of soils, landfill stability, surface- and groundwater, air pollution, and vegetation. Climate change has increased the extent and severity of wildfires across the world. Simultaneously, anthropogenic activities—through the expansion of urban areas into wildlands, abandonment of rural practices, and accidental or intentional fire-inception activities—are also responsible for a majority of fires. This paper provides an overall review and critical appraisal of existing knowledge about processes induced by wildfires and their impact on the geoenvironment. Burning of vegetation leads to loss of root reinforcement and changes in soil hydromechanical properties. Also, depending on the fire temperature, soil can be rendered hydrophobic or hydrophilic and compromise soil nutrition levels, hinder revegetation, and, in turn, increase post-fire erosion and the debris flow susceptibility of hillslopes. In addition to direct hazards, wildfires pollute air and soil with smoke and fire suppression agents releasing toxic, persistent, and relatively mobile contaminants into the geoenvironment. Nevertheless, the mitigation of wildfires' geoenvironmental impacts does not fit within the scope of this paper. In the end, and in no exhaustive way, some of the areas requiring future research are highlighted.

Keywords: wildfires; geoenvironment; climate change; hazards; soil and groundwater conditions

1. Introduction

Wildfires are an integral part of terrestrial ecosystems with both beneficial and adverse impacts. Despite the complicated relationship between climate, weather, and fire, climate change has been implicated in the increasing number of forest fires [1]. Many countries have recently been experiencing megafires, i.e., wildfires that burn more than 40,500 ha of land, as per the U.S. National Interagency Coordination Center (NICC), or have an unusually large impact on people and the environment. Unparalleled in the last 200 years, the Australian "Black Summer" 2019–2020 bushfires burned more than 8 million hectares, and up to 67–83% of globally significant rainforests, eucalyptus forests, and woodlands, putting into question their regeneration and recovery of the species and landscape [2]. The Amazon wildfires in 2019 burned an area approximately the size of New Jersey and were repeated, with 2500 major fires erupting from May to November 2020, and again in 2021, mostly set deliberately in order to claim land to cultivate [3]. More recently, in 2023, Canada faced one of its worst wildfire seasons on record, with over 17 million hectares burned, impacting air quality across North America and highlighting the increasing severity and frequency of wildfires due to climate change [4,5]. Similarly, Greece and other Mediterranean countries experienced devastating wildfires in the summer of 2023, leading to large-scale evacuations and raising concerns over the region's preparedness for future climate-related fire events [6,7].

Increasing fire activity around the world, fueled by a warmer and drier climate, has led to a tenfold rise in wildfires since the 1980s [8,9]. Wildfire spread and reduced vegetation cover are expected to continue due to the changing climate [10]. In combination with climate change, human activities are responsible for the initiation of wildfires because of development/urbanization pressures [11] and the fire risk posed by communities within or near forest areas, as well as the replacement of rural by urban populations at WUI zones [12] and the interaction of abiotic, biotic, and human factors [13]. Human activities that cause wildfires span the entire range, from accidental or negligent actions to deliberate arsons to clear up land for cultivation, as in Brazil, or for tourist and second home developments, as in many Mediterranean countries [14–16].

Wildfires are classified as first-, second-, and third-generation based on fuel continuity, intensity, and speed. Fourth-generation fires take place at the wildland–urban interface (WUI), and the fifth generation describes the simultaneity of fire events, which exceed national resources. Finally, sixth-generation fires create their own atmosphere with pyrocumulus clouds and cannot be contained with airplanes or other fire suppression measures [17]. The increase in megafires resulting from global climate change has led some authors to describe pessimistically the coming era as the *Pyrocene epoch* [18].

However, the objectives of this review paper are twofold, first to appraise the occurrence and causes of wildfires in the U.S., Europe, Australia's bushfires, and the fires in the Amazon, and second, to provide a comprehensive overview of their impacts on the geoenvironment. Specifically, this review aims to identify the dominant processes affecting the physicochemical properties of the soil, water resources, geomorphology, and vegetation patterns in wildfire-affected regions.

This paper evaluates several hypotheses, including (i) the statistically significant correlation between global climate change parameters (e.g., temperature and precipitation patterns) and the increase in wildfire activity; (ii) the impacts of fire-induced changes in soil properties (e.g., alterations in soil structure, porosity, and plasticity) on its overall health and stability; (iii) the development of hydrophobicity in wildfire-affected soils, its impact on hydrologic responses, and the challenges in accurately modeling and remediating these effects; (iv) the impact of wildfires on soil desiccation cracking and plant–soil interactions, contributing to increased soil erosion, slope instability, and landslides; (v) the hydrogeological effects of wildfires, including substantial sediment inputs to stream networks, extreme sediment yields in burned basins, and the role of wildfires in ecosystem dynamics; and (vi) the effects of fire on soil carbon content, nutrient availability, and leachability, and their influence on soil fertility and broader environmental consequences.

2. Occurrence and Causes of Wildfires and Megafires

A large portion of wildfires are initiated by humans, mainly due to a lack of care, and the rest are initiated by natural events such as dry lightning. However, the probability and extent of the resulting wildfires have drastically increased due to the higher level of availability of fuel for wildfires. In other words, the improper care taken to extinguish the fires during camping and recreational activities by human beings is one of the primary reasons. On the other hand, warmer, drier, and longer summers have supplied abundant fuel for wildfire (e.g., dry brush), which in turn have increased wildfire activity across much of western North America by an order of magnitude since the 1980s [8,19]. This is also the case in Australia and most recently Europe.

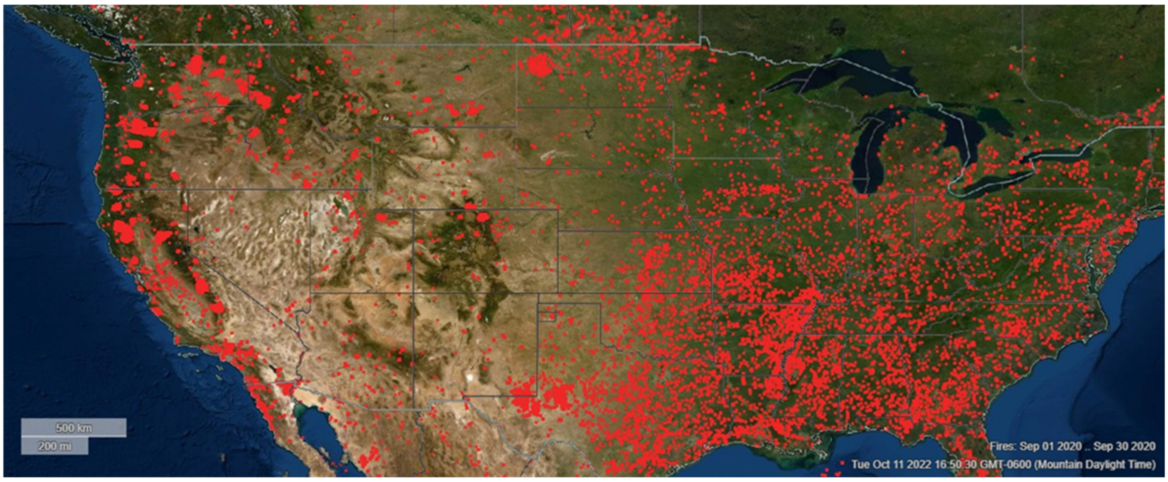
In the past decades, large wildfires have increased in the U.S. at an alarming rate, especially in the western part of the U.S.A. Between 1984 and 2011 in the Western U.S., the number of large fires (>400 ha) increased at a rate of seven fires per year with an increase in associated fire area of 355 km^2 per year [20]. The smoke from the 2020 Western U.S. wildfires extended across the U.S.A., reaching the United Kingdom and Northern Europe [21]. Figure 1 shows the extent of these wildfires and the poor air quality in the Western U.S. as a result of them. Near-surface smoke in this figure refers to air that hovers within 8 m of the ground surface and causes asthma attacks and burning eyes.

In the Western U.S., wildfires have expanded spatially and temporally, with fires early in the spring and late in the fall and winter due to earlier warming and drying seasons (Figure 2). The U.S. NICC reported that 68,988 wildfires occurred in the United States in 2022, which was noticeably higher than the 10-year average, compared to 58,985 wildfires reported in 2021, consuming about 7.5 million acres. Moreover, this trend has continued, with approximately 70,000 wildfires burning around 8 million acres in 2023 [24]. As of August 2024, there have been about 29,028 wildfires, consuming approximately 4,982,054 acres [25]. These years have continued to witness some of the most destructive fire seasons on record, reflecting the growing severity and frequency of wildfires. The increase in fires is partly due to their occurrence in more remote, forested areas, which are less accessible. Of those, 89% were caused by human activities, which were responsible for about 44% of the burned areas [26]. Anthropogenic climate change has doubled the Western U.S. forest fire area since 1984 [27].

Detrimental short- and long-term health impacts of wildfires include increased mortality and aggravated respiratory, cardiovascular, mental, and perinatal health issues [29], adding to the vulnerability to pandemics. Wildfires have imposed an economic toll of USD 76 B and USD 450 B on the Western U.S. annually, from short- and long-term exposure to wildfire smoke, respectively [30]. The impacts of wildfires extend beyond a burned region and over many years, imposing a chronic, complex driver on ecosystems.

The situation in Europe is similar to the U.S.A., with the likelihood of occurrence and severity of wildfires increasing, especially in the Northern and Eastern European countries and the Mediterranean region (Figure 3), with 2018 exhibiting 40% more fires than the previous year [31]. About half a million hectares are burned in Europe annually, 75% of which are in Mediterranean countries. In the north of Europe, countries such as the United

Kingdom, Ireland, Finland, Latvia, Germany, Poland, Sweden, and Norway have seen unusual fire waves since 2018 (as seen in Figure 3). Expenditures for fire prevention and suppression in Europe approached USD 3B per year, and economic damages during the period of 2000–2017 exceeded USD 60.5B [32,33].



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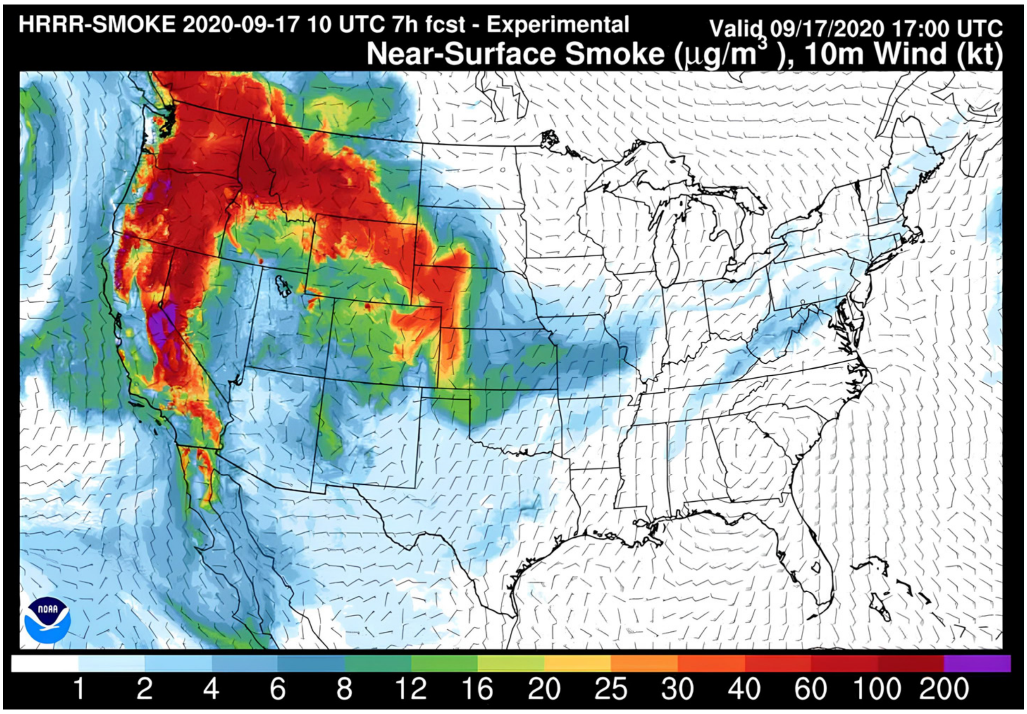


(**b**)

Figure 1. (**a**) Map of Western U.S. active fires in September 2020 [22]; (**b**) near-surface smoke (μg/m^3) over Western U.S.A. on 17 September 2020 [23].

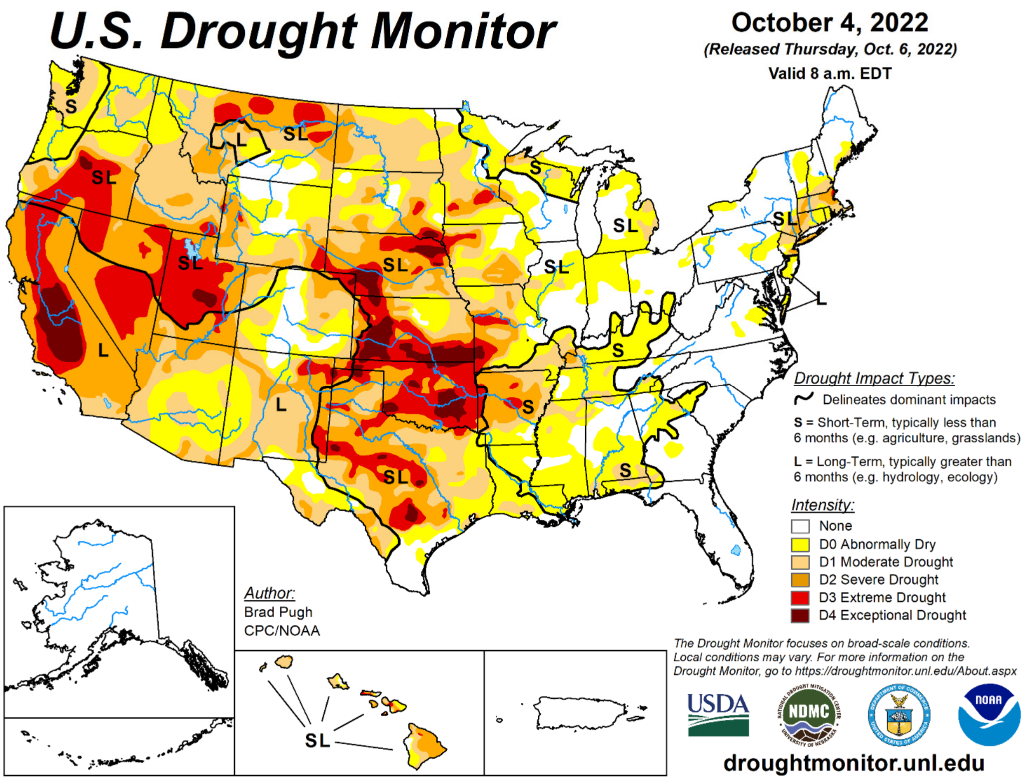


Figure 2. U.S. drought monitor map of 4 October 2022 [28].

Figure 3. Wildfire regions in Europe, Western Asia, and North Africa on 24 August 2021 [34].

Portugal, Spain, Greece, Italy, and France are listed as the top five countries in Europe with regard to the occurrence and extent of wildfires (Figure 4). The fire statistics between 2009 and 2018 indicate that 2.84% of Portugal's forests were burned on average each year, with the equivalent numbers for Greece, Italy, Spain, and France being 0.77%, 0.66%, 0.35%, and 0.17%, respectively [35,36]. Incidentally, it can be observed that all European countries discussed above are in the southern part of the continent, which is prone to high temperatures and longer dry periods, which are conducive for wildfires to occur. Turco et al. [37] conducted Monte Carlo simulations to estimate the effect of climate change on rural fires in the Mediterranean region and found that, depending on the global warming scenarios, the amount of burned area would increase from 40% to 100%.

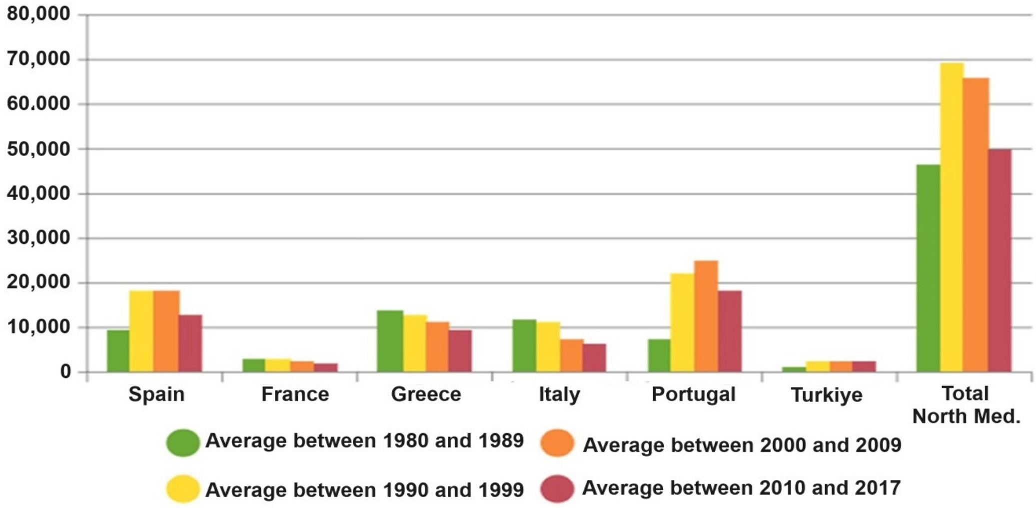


Figure 4. Number of fires in Mediterranean countries from 1980 to 2017 [36].

The Mediterranean region is vulnerable because the conditions for the so-called megafire triangle, or 30-30-30 rule, hold during most of the summers. The rule refers to surface temperatures over 30 °C combined with relative humidity less than 30% and wind speeds over 30 km/h [38]. At the same time, the Mediterranean region has become the top tourist destination in the world, with a 32% share of the international travel industry (World Tourism Organization) [39]. As a result of this, arsons, aiming to expand urban summer housing and resort developments inside forest areas—especially in coastal locations—have become responsible for 26% of the fires (in Spain almost 55% of rural fires are considered intentional) [40]. This situation is accentuated by poor urban planning that allows the embedding of communities within or in the vicinity of forested areas, classified as the wildland–urban interface (WUI), with little public understanding, participation in forest protection, and infrastructure measures [32,36]. Due to the spread of wildfires, railroad and transportation operations have been impacted, and operation teams must implement new procedures to reroute train flows affected by fires. For example, BNSF railways in California rerouted some trains to the Central Rockies, and even on some longer routes further east, to reach their destinations [41]. In addition to the direct hazard of fire on rail transportation, the embankment can be impacted by the deteriorating impacts of wildfires. However, further research is needed. In the absence of research results, most transportation authorities for the time being have resorted to prescribed low-severity fires to mitigate this impact [42]. In addition, monocultures—such as eucalyptus, which accounts for almost 25% of Portugal's trees, and the Aleppo pine forests in Greece (Figure 5) and France—with their rapid burning rate and flying sparks that can travel great distances, make ground fire-suppression efforts extremely difficult to be successful.

(**a**)

(**b**)

Figure 5. Photo (**a**) before and; (**b**) after the August 2021 megafire on the Island of Euboea, Greece.

3. Wildfire Effects on Soil Properties

In a burned area, the physical, chemical, biological, and hydrological properties of the soil change, especially the shallow soil, which is difficult to recover to their initial levels several years or even decades after a fire. Depending on fire intensity, severity, and frequency, fire events may significantly alter the soil's physical properties, such as soil gradation, soil structure and texture, plasticity, bulk density, porosity, soil water-repellence, infiltration rates, and water storage capacity. The impacts of wildfire on the geoenvironment are broad and diverse. Some of these impacts are not known or foreseen, and even for a large fraction of impacts that have been observed or well-documented, quantitative evaluation of the impacts may not be available.

3.1. Fire Impact on Organic Matter and Clay

Organic matter (OM) serves as a powerful aggregating agent, holding sand, silt, and clay particles into aggregates. Hence, a loss of OM results in a loss of soil structure and a reduction in macropore void space. Even in low-severity fires, soil OM undergoes a series of physical and chemical transformations depending on the burning conditions.

Charring/oxidation of soil OM typically commences at temperatures of ~85 °C [43], with free moisture vaporized as soon as temperatures approach 100 °C. Lignin and hemicellulose begin to degrade between 130 and 190 °C, those reactions being endothermic. The decomposition of lignin and hemicellulose becomes rapid at 200 °C, while cellulose undergoes chemical dehydration at 280 °C. About 35% of the total mass loss occurs before soil OM reaches 280 °C, with exothermic reactions predominating, while OM ignites once soil temperatures exceed 280 °C. When the surface temperature of soil OM reaches 500 to 600 °C, glowing combustion occurs if oxygen is not excluded from the char surface [44].

For severe fires, the decrease in soil OM and resulting ash generally produce increased soil bulk density, reduced porosity, and a decrease in water storage capacity. In addition to the resulting physical–chemical properties, changes in soil OM of the surface horizons may affect the microbiological properties of the underlying mineral soil. Following severe fires, changes in soil properties are greatest at the 0–5 cm depth since the temperature rarely exceeds 100 °C below this depth [45].

Most volatilized OM is lost upward as smoke; however, for intense burns, a small number of hydrophobic substances in the litter layer are forced downward along steep temperature gradients in the upper 5 cm of soil, condensing to form a water-repellent layer. These hydrophobic organic compounds coat soil aggregates or minerals creating a discrete water-repellent soil layer parallel to the ground surface. Water-repellent soil layers are reportedly formed at temperatures of 176–288 °C and destroyed at >288 °C [46].

In addition to organic matter, clay minerals in soil are also susceptible to modification under elevated temperatures. The texture and structure of clays can be irreversibly altered when temperatures reach around 400 °C [47,48], as structural hydroxyl ions are removed, leading to the destruction of the clay's crystalline structure. As temperatures continue to rise, fusion of clay mineral particles can occur at temperatures between 600 °C and 700 °C, and complete destruction of clay may occur at 700–900 °C [49]. The fusion of clay particles could cause aggregation of clay particles to form stable sand-sized particles, thus increasing sand content at the expense of clay content [50].

After clayey mineral soils are burned between 100 °C and 300 °C, the liquid limit (LL) monotonically decreases, with minimal impact from a temperature rise above 400 °C. On the other hand, the plastic limit (PL) decreases rapidly up to 300 °C, reaching a nonplastic (NP) state at 400 °C [51], indicating that such soils can only retain small amounts of water despite their low abundance of clay minerals.

Supporting these observations, Noraini [52] reported that wildfires reduced the Atterberg limits of clayey soil (major minerals being montmorillonite) from initial LL = 55% and PL = 35% (plasticity index of I_P = 20%) to final values of 30% and 14% (I_P = 16%), respectively, such that the investigated soil transitions from the high-plasticity silt type to that of low-plasticity clay. Similarly, Awn et al. [53] performed four burning cycles on natural fine-grained soils, with burning temperatures of 150 and 300 °C, producing progressive reductions in the Atterberg limits from LL = 56% and PL = 51% for the natural soil to LL = 42% and PL = 39% for the fourth burning cycle, respectively. However, it is important to note that some aspects of laboratory tests (e.g., a 10-h burn cycle duration) make the results not directly relevant to real wildfire scenarios [54]. Furthermore, the burning methodology can influence the outcome, e.g., heating soils in a muffle furnace does not address the movement of hydrophobic substances into a soil profile and does not allow for testing the direct effect of flames on the soil.

Building on the understanding of fire's impact on soil structure and mineral composition, it is also essential to consider how these changes affect the soil's carbon content, nutrient availability, and the potential for nutrient leachability.

3.2. Effect on Carbon Content, Soil Nutrient Availability, and Leachability

Soil is the largest reservoir of Carbon I, storing 2157–2293 Pg of C in the top 1 m of soil, where 1462–1548 Pg of Carbon (C) is soil organic carbon (SOC) and the remaining is soil inorganic carbon (SIC) [55,56]. This vast carbon storage capacity means that soil and surface litter contain two or three times as much C as the atmosphere, playing an important role in the global carbon balance [57]. Forests account for the largest quantities of global soil carbon pools [58].

SOC is mainly formed from the decay processes of plant litter [59], the metabolism of organisms, and the substances of microbes and fungi [56]. SOC is closely related to soil fertility and carbon cycling, the structure, and properties of soil [60], the adsorption of contaminants [61], water retention and pH buffering [62], and soil biodiversity [63]. In contrast, SIC is present mainly in the form of soil carbonates from the weathering process of silicate carbon, as well as CO_2 in the gas phase, and CO_3^{2-} and HCO_3^- in the liquid phase. SIC is the main form of soil carbon in arid and semi-arid areas [64]. Despite the fact that SIC is a large C pool, it is generally considered not to affect the concentration of atmospheric CO_2. It is worth mentioning that available studies showed that SIC may also sequester CO_2 and has a promising application prospect [65].

Considering the significance of these carbon pools, it is essential to evaluate how natural disturbances, like fires, affect them. Fires on forests and peatlands constitute one of the most important natural disturbance modes in forest ecosystems, with the global annual burned area varying from 301 to 377 Mha from 1997 to 2011 [66] and causing emissions to the order of 0.4 Pg C or 1.3 Pg CO_2 per year, which have a great impact on the carbon balance and global climate [67].

The effect of fires on SOC depends on the fire severity, frequency, season, soil types, forest type, and terrain. Some studies have found that burning increases SOC content [68]. On the other hand, others have shown that fires either reduce the SOC content in soil [69,70] or that they do not significantly change the SOC content in soil but only redistribute SOC. For example, Johnson and Curtis [71] found no significant effect on carbon content after a fire but observed a significant long-term fire-induced increase after 10 years due to the decline in mineralization rate.

The effect of fire on SOC content is complex and varies across different contexts. For instance, Zhao et al. [72] found that the SOC content in spring-burned plots is higher than in autumn-burned plots, due to the consumption of burned litter and soil OM by snowmelt and wind erosion. Frequent fires have a dual effect on SOC content; they reduce lower biomass and litter, thus leading to a reduction in organic inputs to soils and to a decline in the SOC content [73]. In contrast, frequent fires can increase the SOC in some cases by promoting the establishment of more productive plant species, burning more dead roots, and leaching more ash downward into soils [74]. The loss of the SOC content by wildfires is generally higher than in prescribed fires [75]. High-severity wildfires are associated with large SOC losses, while moderate- and low-severity wildfires can promote the renovation of dominant vegetation, physically protect SOC, and increase the quantity of carbon mineralization [69].

Another notable effect of wildfires is on soil pH, which can increase due to the liming effect of calcium oxide (CaO) in combustion ash [76]. The influence of fires on phosphorous availability is more complex. It was observed that the phosphorous availability could be reduced due to the following: (i) adsorption on the exposed/created hydroxides based on Fe and Al; and/or (ii) precipitation. On the contrary, the phosphorous availability could increase due to the following: (i) degradation and partial oxidation of OM; and/or (ii) desorption of phosphorous from hydroxides of Fe and Al owing to an increase in the pH caused by the liming activity [77].

Wildfires also significantly impact nutrient availability and leachability, which are both critical for soil fertility. For instance, Chungu et al. [76] observed that the total nitrogen (TN) was doubled after a fire, promoting the growth of *Eucalyptus Grandis*, which was attributed to the increase in ammonium (NH_4^+) and nitrates (NO_3^2) in the soil. However, these findings contradict the study by Murphy et al. [77] that reported a decrease in the TN and an increase in the mineral nitrogen due to the heat-induced degeneration of organic nitrogen. It should be noted that the former used an oxidation method for the measurement of TN that ignores the inorganic form of nitrogen.

However, these variations in nutrient availability and leachability highlight the broader impact of wildfires on soil properties. Consequently, these changes in nutrient dynamics and soil chemistry also influence other critical aspects of soil health, such as hydrophobicity. The alterations in soil carbon content and nutrient levels induced by fires contribute to shifts in soil hydrophobicity, affecting water repellency and overall soil–water interactions.

3.3. Wildfire-Induced Hydrophobicity

Wildfire-burned soils can show varying levels of hydrophobicity depending on the severity of the fire, the amount of OM left, and the ultimate temperature the soil was under for a given duration of time [69]. Water repellence in soils is generated by five dominant mechanisms: fungal and microbial activity, growth of particular vegetation species, organic matter, heating of the soils by wildfires, and soil characteristics. The fluctuation in levels of water repellence following a wildfire can lead to significant changes in the hydrologic response of soils [78], enhancing runoff and erosion [79] or increasing unsteady or reduced infiltration [80,81]. Due to soil heterogeneity, the cause of the changing levels of water repellence is often unclear and can be considered as an accumulation of the influence of several factors. Lower temperatures at depth result in vapor cooling and condensing on the fabric of the soil, coating particles in the cooled organic substance [82]. Similarly, aliphatic hydrocarbons are released from OM when subject to extreme heat, generating hydrophobic compounds [83]. Temperatures between 175 °C and 280 °C are necessary to cause an increase in hydrophobicity, whereas temperatures beyond this range lead to the nonuniform spread of water repellence close to the surface [82,84]. While elevated levels of water repellence are seen initially, they break down over time due to instability. As Figure 6 suggests, given a longer timescale, hydrophobicity levels begin to rise, and this is thought to be due to organic matter recovery.

To measure soil hydrophobicity, the Water Droplet Penetration Test (WDPT) is widely used. The method is, however, subjective when used beyond identification and for classification. The method does not consider differing site conditions, environmental factors, grain sizes, and soil types; other test methods are needed to classify soil water repellence; and the method needs to be calibrated for grain size or other environmental conditions. The authors investigated the impact of various levels of hydrophobicity on soil samples of various grain sizes during the WDPT [85]. A hydrophobicity-inducing surrogate, at various rates of dilution in deionized water, was used to highlight the impact of lifted hydrophobic particles on delaying water droplet infiltration across soil grain sizes and hydrophobicity levels. Particle lift, especially in coarser soils, delays water droplet penetration. Hydrophobicity-induced particle lift causes instability, leading to randomly occurring distinct regimes (Figure 7). Therefore, the authors suggest these effects should be considered when measuring hydrophobicity using the WDPT. In Figure 7, all drops are repeated versions of the same measurement. The figure intends to show the lack of repeatability in these measurements due to the potential particle lift.

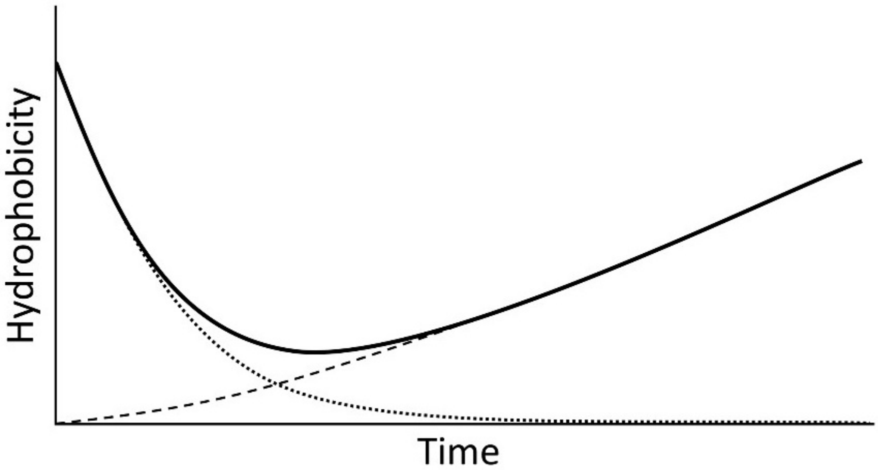


Figure 6. Hypothesized long-term changes in soil water repellence [83]. Solid line: overall response; dotted line: short-term changes generated from fire; dashed line: long-term changes induced by increased biotic activity.

Biotic factors also influence soil hydrophobicity. Increased vegetation and microfauna populations can lead to increased levels of water repellency [86]. Certain species of plants, such as evergreens and differing eucalyptus species, can induce stronger hydrophobicity in soils [83]. Contrary to this, as ash settles on the surface, a wettable layer can be deposited and reduce the effects of heating on the soil leading to a reduced water repellency and less risk of surface runoff and erosion [79,87].

The temperature of the ash layer can have a significant effect on the hydrologic response with the ash that settles on the surface, either increasing or decreasing runoff depending on the temperature of the burn [88]. Lower-temperature ash usually contains significant amounts of organic carbon, inducing hydrophobicity and increasing runoff, while higher temperatures destroy said carbons, leaving the layer more hydrophilic and causing water ponding/storage in the ash layer (and decreasing surface runoff) with a gradual release to the underlying layer. In case of high-temperature fires, there will then be hydrophobic-burned soil covered with layers of hydrophilic ash that can retain water after a wetting event. The heat generated during wildfires dries water present in (i) larger pores, (ii) inter-aggregate pores, and (iii) intra-aggregate pores [89]. This heat can be sufficient to drive off residual water, leading to the creation of hyper-dry conditions (soil-water content < 0.02 cm^3/cm^3) similar to oven-dried soils and causing the decomposition of OM [89]. Thus, the ponded water cannot readily infiltrate through the hyper-dry burned soil until the water uptake mechanism transitions from adsorption to capillary condensation [90,91].

The transition water content is soil-specific and corresponds to 65% to 85% relative humidity [91]. During the transition, burned hillslopes are more prone to runoff-dominated erosion and associated debris flows. A fire event can cause hydrophobicity within the top few inches of the ground surface, creating a layer that significantly increases runoff—by more than ten times the average rate—especially when exterior stabilizers like root systems are removed. This increased runoff not only heightens erosion risks but also makes steep slopes more susceptible to landslides and debris flows. A tragic example of this occurred in Montecito, California, in 2018, where heavy rainfall on the Thomas Fire burn scar triggered debris flows that killed 23 people and damaged or destroyed over 400 homes [92].

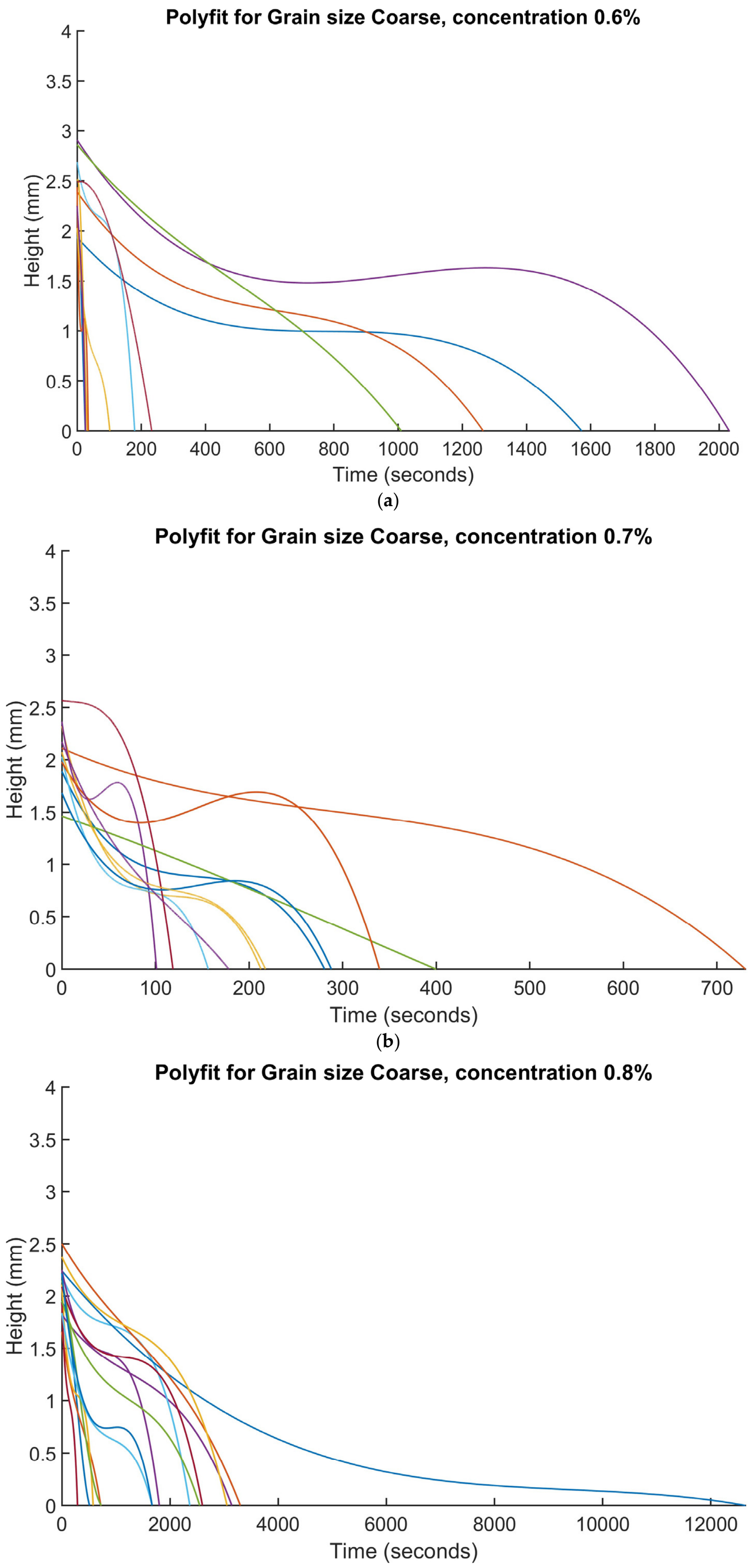


Figure 7. Water Droplet Penetration Test (best-fit third-order polynomial) for a coarse-grained soil sample at hydrophobicity-inducing surrogate dilutions of (**a**) 0.6%, (**b**) 0.7%, and (**c**) 0.8%.

In this context, Gabet and Sternberg [93] and Ebel and Moody [94] studied saturated soils' water content, sorptivity, and the wetting-front potential of the 2017 Thomas Fire in California that produced catastrophic debris flows. Their results indicated that the presence of wildfire ash reduced the field-saturated hydraulic conductivity. In addition, soil-water repellency behavior was also observed due to a decrease in sorptivity and wetting front potential at the burned sites [95]. Hydrophobic soils burned by high-temperature fires present a Type-II isotherm shape, which shows incremental adsorption of water molecules onto particle surfaces, unlike other hydrophobic materials that exhibit a nonuniform behavior in adsorbed water content at high relative humidity. Even though the shape of the isotherms is not influenced, the amount of adsorbed water content was found to be different in hydrophobic soils [78,96]. As the Type-II isotherm shape is maintained in hydrophobic soils, isotherm models that are based on incremental adsorption remain valid.

The deposited hydrophilic ash layer will eventually clear, highlighting its importance in short-term water repellency levels post-fire [97]. This process could be the cause of reduced levels of hydrophobicity found when trying to replicate wildfire-induced changes [98]. As the ash cover deteriorates, the topsoil will be left with no vegetation, which has been seen to be the primary cause of increased runoff and erosion rates [99]. Similarly, as the short-term water repellency increases on the surface, the coatings upon the minerals will impede the formation of a soil crust, causing an increased risk of splash erosion [100].

Rill erosion is also observed, due to the water-repellent layer causing a build-up of pore pressure and consequent reduction in shear strength in the overlying saturated soil [101,102]. Fingered flow can also result from this, as the distinct paths caused by rill erosion offer less resistance to infiltration. With increasing levels of hydrophobicity as well as distinct paths of eroded soil, the chances of preferential flow and fingering are much higher, which often arises from changes in wettability [103,104]. Currently, there is little modeling work related to the processes of wildfire-induced changing water repellency, with most research focusing on either varied wettability or wildfire effects as unconnected processes [105].

Erosion because of increased repellency has been explored through the Morgan–Morgan–Finney (MMF) model [106], which has seen varying advancements in the past decade [107,108]. Zema et al. [109] modified the MMF model to include the effects of water repellency, to quantify the impact of wildfire on seasonal runoff and soil loss prediction. Similarly, the Limburg Soil Erosion Model (LISEM) [110] was evaluated in its applicability for representing rainfall–runoff response based on varied stages of vegetation recovery [111]. A multiple regression model that tested several key factors for their impact on erosion found that erosion processes were mainly due to rainfall intensity and ground cover [112].

Building on this, the instability of infiltration following wildfires has been studied, with Nyman et al. [81] addressing the poor depiction of water retention and preferential flow in existing models by experimental simulating ash-covered soils. This layered model was able to depict the accelerated transport of water, synonymous with the preferential flow. Malkinson and Wittenberg [83] included erosion and OM in a model to analyze wildfires' long-term effects on soil water repellency. Timescales in the analysis of wettability effects [113], OM, and fungal/bacterial processes should also be considered when modeling the development and impact of soil hydrophobicity by wildfires.

Even though hydrophobicity has become a key area of research in post-fire events, almost all research analyzes specimens in the field at the location of the burn or in the laboratory after a specimen has been collected from the field. However, beyond the immediate effects of hydrophobicity on soil hydrology, the intense heat from wildfires also leads to soil desiccation cracking, which further affects the interaction between soil and plant roots.

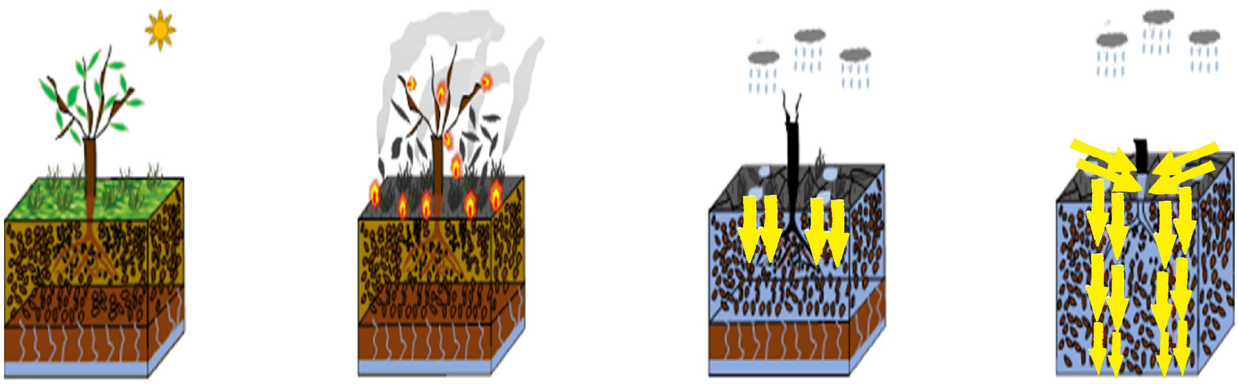
3.4. Effect on Soil Desiccation Cracking and Plant–Soil Interaction

The heat during a wildfire can lead to rapid reduction in water content in the shallow soil and even induce desiccation cracking. Under an elevated temperature, the vapor–

pressure gradient of the soil–air interface increases, and the evaporation of water from the soil intensifies [114–116]. This continuous evaporation, driven by the heat of the fire, leads to significant drying-induced shrinkage of surface soil and numerous desiccation cracks. Fires with larger intensity led to simpler soil cracking morphology with a larger surface–crack ratio and crack depth. This is because as the evaporation rate of soil-water increases with temperature, a large gradient tension–stress field develops within a brief period of time, leading to the creation of desiccation cracks more rapidly and more severely [117,118].

The generation of desiccation cracks destroys the integrity of soil, greatly weakens its bearing capacity, increases its compressibility, and reduces its shear strength, exacerbating slope instability and landslides, aggravating soil erosion, and damaging the ecological environment [119].

Furthermore, wildfires can negatively affect the reinforcement provided to the soil by plant roots [120]. The failure of the root–soil system evolves [76,95], as shown in Figure 8. Kamchoom et al. [121] observed exponential reduction with the time of tensile strength and Young's modulus of *Cynodan dactylon* during a one-year root decay after burning. This was explained by the decline in root chemical components that provide root biomechanical strength, such as lignin and cellulose [122]. Experimental campaigns carried out by Ni et al. [123] and Ng et al. [124] have demonstrated that the process of root decay could substantially reduce the water retention capacity but increase both the saturated and unsaturated hydraulic conductivity of soils. Eventually, the soil not only loses its mechanical reinforcement but also becomes more fragile than that without vegetation cover, creating conditions for soil instability. A numerical study by Ni et al. [125] indicated that the root-induced changes could lead to landslides and debris flow under heavy rainfall events as well as soil erosion. Initially, after a fire, post-fire debris flows are dominated by a surge in surface runoff [126], while several years after a fire, the slope instability is mainly due to the decrease in soil strength, which triggers shallow landslides [127].



(**a**) (**b**) (**c**) (**d**)

Figure 8. Schematic diagram of root–soil system failure evolution with time after fire: (**a**) before the fire; (**b**) in the event of a fire; (**c**) one year after the fire; (**d**) two years after the fire, where → indicates infiltration (created based on [128]).

This weakening of soil structure and loss of vegetation not only exacerbates soil instability but also contributes to significant hydrogeological impacts, as detailed in the subsequent section.

3.5. Hydrogeological Effects of Wildfires

In steep landscapes, post-fire mass-wasting events generate substantial, sometimes dramatic, inputs of sediment to stream networks [87,126,129]. Such events, which transport most of their material from storage in small channels, provide the dominant source of sediment to streams. Mass-wasting events take the form of debris flow caused both by the bulking of overland flow leading to gully erosion or the formation of debris flow initiated by shallow landslides [126,130]. Hydrologically, bulking debris flow is driven primarily by intense rainfall on water-repellent soils, typically by summer convective storms [87]. On the other hand, shallow landslides are more commonly initiated by long, heavy rainfalls [131] or rainfalls combined with rapid snowmelts exacerbated by the loss of the canopy [132].

The yield of sediment from severely burned basins can be extreme, with values ranging up to 280,000 T/km^2 per event, and values of several tens of thousands of T/km^2 being common [130,132]. Long-term small-basin yields tend to be limited by soil formation rates and are of the order of 100 T/km^2/yr [133]. Yields in the years after fires are very large compared to long-term average rates, owing to the need for fuels to regrow. Under undisturbed conditions between periodic pulses from fire, small-basin sediment yields are of the order of 10 T/km^2/yr [134].

The impact of these sediment inputs varies between punctuated and chronic sediment supplies. Punctuated sediment supplies from large debris flows tend to cause sediment to "smear" down the channel over time, resulting in a more consistent gravel-sized sediment supply in downstream reaches despite the infrequency of severe events in smaller basins [135]. Only a fraction of topographic hollows generally fail or gully after a given fire event, taking many centuries to refill from hillslope processes. Additionally, extreme sediment yields from debris flows in very small catchments (less than one km^2) tend to diminish rapidly with scale [136].

While the hydrogeological effects of wildfires can be dramatic, it is important to recognize that wildfires also play a crucial role in many ecosystems. They are integral to ecosystem dynamics, pest population regulation, and species preservation. In areas where frequent fires occur, local plant species have adapted to fire events. Species that successfully survive fires are referred to as fire-resistant species (pyrophytes). Certain species form a thick layer of nonflammable tissue (cork) on their surface, e.g., *Quercus suber*. *Pinus palustris, Sequoiadendron giganteum,* and *Sequoia sempervirens* are also capable of resisting fires. Additionally, some species need a mild fire to release seeds from cones, e.g., *Pinus halepensis* and *Pinus contorta* [137].

4. Conclusions

This paper reviews and critically analyses the cause of various impacts of wildfires on the geoenvironment. A range of impacts on the geoenvironment is discussed and, in most cases, qualitatively analyzed. Historically, wildfires have been caused mostly by human activities as well as in part by natural causes such as dry lightning. However, warmer and drier weather has resulted in an abundance of ample fuel and favorable wildfire conditions, which have been accentuated by anthropogenic activities. Wildfires have short- and long-term impacts on the environment in general and on the geoenvironment.

These environmental impacts are particularly evident in the way wildfires alter soil properties, including physical, chemical, biological, and hydrologic characteristics within the burned areas. The extent of this alteration depends on the intensity, severity, and frequency of the wildfires. Natural recovery from this alteration takes years or decades. The heat from wildfires can provoke desiccation cracks in relatively fine-grained soils, destroying soil integrity by reducing bearing capacity, increasing compressibility, and decreasing shear strength. Such soil deterioration can lead to the exacerbation of slope instability and landslides, aggravate soil erosion, and harm the ecological environment. Depending on fire severity and intensity, burned soils can also exhibit various degrees of hydrophobicity (leading to water repellency) or hydrophilicity. On one hand, high-severity wildfires result in significant SOC losses, whereas moderate- and low-severity wildfires can promote dominant vegetation renovation, physically protect SOC, and increase the amount of carbon mineralization. These post-wildfire changes in water repellency can cause major changes in the soil hydrologic response, leading to lower infiltration, increased runoff, erosion, and soil instability. Additionally, wildfires can also degrade soils through plant root decay, loss of vegetation, and nutrient leachability. Furthermore, field studies have discovered elevated amounts of chemical and organic pollutants long after fire events. Beyond the impacts of individual fires, frequent fires have a dual effect on soil organic carbon content. Unlike the above-mentioned negative impacts and despite the direct loss of some nutrients by wildfires, wildfires can also have positive impacts on nutrient availability and leachability, improving soil fertility.

However, wildfires can also contribute to soil contamination with post-fire ash, polyaromatic hydrocarbons (PAH), and the debris caused by wildfires. At the same time, human response methods can also be problematic and cause soil contamination, e.g., current fire-suppression agents can release toxic, persistent, and mobile contaminants (e.g., PFAS) into the geoenvironment.

Interestingly, as a natural response to wildfires, some local plant species have adapted to frequent fire events, either forming a thick covering of nonflammable tissue on their surface or becoming fire resistant.

Nevertheless, some impacts are still not well understood, and some are only qualitatively analyzed. Further research is needed to quantify these impacts in order to better prioritize properties in need of attention as well as outline the minimum level of restoration for each affected area.

Moreover, changes in the spatial and temporal scales and the nature and extent of wildfires—due to the progressing climate change—can lead to new unforeseen impacts or extensions and changes in the nature of known impacts. These calls for increased research to better understand the impacts of wildfires on the geoenvironment and a complete rethinking of national and international policies and measures in the prevention, mitigation, control, and suppression of fires, as well as forest and landscape restoration actions. At the national level, policies such as the U.S. National Cohesive Wildland Fire Management Strategy, which emphasizes fire-adapted communities and resilient landscapes, may need to incorporate more stringent guidelines on urban development in fire-prone areas and the integration of advanced fire prediction technologies and evacuation guidelines. For example, incorporating knowledge about the cascading impacts of wildfires into evacuation protocols could prevent tragic incidents such as the one in Montecito, California, in 2018, where mudslides caused significant loss of life and property [92]. Internationally, agreements like the United Nations' Sendai Framework for Disaster Risk Reduction could be expanded to include specific provisions for wildfire prevention, recovery, and adopting new restoration technology, focusing on transboundary cooperation and shared research on fire-management techniques. The growing frequency and intensity of wildfires due to climate change further amplifies the urgency of such comprehensive strategies, highlighting the need for adaptive policies that can evolve alongside emerging environmental data and technological advancements.

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