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Biogeochemical cycles: How wildfires affect soil and water quality

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ABSTRACT

Wildfires severely disturb biogeochemical cycles and greatly impact soil health, water quality, etc. These processes affect soil organic matter, indirectly mobilize heavy metals, and change water chemistry in terrestrial and aquatic ecosystems. These effects are immediate in consequence, including changes within the structure of a variety of organic carbon (SOC) and nutrient availability, sometimes causation disappearance patterns that improve short-run fertility; however, the implications will endure for ~150 years. The latter contribution comes at the cost of significant long-term depletions in nitrates (volatilization and leaching). This chemical can persist in the soil for centuries, but it may be more susceptible to decomposition by bacteria and fungus than previously thought. Black carbon is also produced during wildfires. The erosion and sediment transport following fires significantly increases sediment loads in water bodies, affecting water quality and aquatic habitats.

KEYWORDS

Wildfires; Soil Organic Matter (SOM); Nutrient availability; Black Carbon (BC); Biogeochemical cycles; Ecosystem recovery

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Introduction

Wildfires change biogeochemical cycles regarding nutrients and analysis of soil quality, and water in the catchment. As such, these natural disturbances disrupt the fragile balance of ecosystem nutrient cycling and thus have far-reaching impacts on both terrestrial and aquatic ecosystems. Wildfires not only cook the soil organic matter underground but also mobilize heavy metals and change water chemistry, cascading throughout watersheds.

Wildfires generate multifaceted impacts on biogeochemical processes. Here, we illustrate how these events affect soil organic carbon (SOC), nutrient availability, and sediment export through this article. It also addresses the effects of wildfires on water quality and aquatic habitats. It also discusses longer-term effects on ecosystem recovery and the implications for global biogeochemical cycles. This is critically important, as it provides the foundational understanding needed to effectively manage and mediate the environmental impacts of wildfires.

Wildfire Effects on Soil Organic Matter

Fires significantly affect soil organic matter (SOM) quantity, quality, and spatial pattern. In this wide context, their changes affect bio-fertilization, carbon sequestration, and ecosystem recovery.

Quantity and quality changes

The high temperature created by the wildfires affects SOM very much and plays an important role. SOC is an essential indicator of soil quality and varies significantly due to fire severity as well as duration. This loss of SOC starts at temperatures from about 200 to 250°C, but the combustion is total between 460 and up to around 500°C. This process can lead to virtually total loss of soil organic matter in some places [1,2].

However, the effects of wildfires on SOM quantity are not uniform. Low-intensity fires may increase SOC due to the formation of pyrogenic carbon from incomplete combustion of organic matter and the addition of ash [3,4]. This phenomenon highlights the complex nature of fire-induced changes in soil organic matter.

Black carbon formation

One of the most significant outcomes of wildfires on SOM is the formation of black carbon (BC), also known as pyrogenic carbon or biochar. BC is produced during the combustion of organic materials and is highly resistant to microbial decomposition [5,6]. This recalcitrant form of carbon can persist in soils for extended periods, ranging from hundreds to thousands of years.

The presence of BC in soil has been associated with an increased soil organic matter pool. However, recent research suggests that the long-term stability of BC may be overestimated. Some studies have found that carbon that has undergone forest fires and becomes black carbon can be more readily converted to carbon dioxide by microbes than previously thought [7-9].

Implications for soil fertility

The changes in SOM quantity and quality due to wildfires have significant implications for soil fertility. The loss of organic matter can reduce the soil's capacity to retain nutrients, water, and other essential resources for plant growth. However, the effects on soil fertility are not uniformly negative.

Wildfires may boost the presence of certain nutrients temporarily. For instance, research has shown significant increases in $NH4^+$–N and $NO3^-$–N levels after a forest fire. This increment is mainly attributed to greater ash depositional outputs associated with the increase in Nitrogen(N) mineralization and nitrification, dependent on temperature, pH, and microbial activities [10-14].

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The formation of black carbon can also alter the soil's physical, chemical, and biological properties, potentially affecting nutrient cycling and availability. While BC can enhance soil fertility in some cases, its effects are complex and depend on various factors such as fire intensity, soil type, and ecosystem characteristics.

In conclusion, the effects of wildfires on soil organic matter are multifaceted and can have both positive and negative implications for soil fertility and ecosystem function. Understanding these complex interactions is crucial for effective post-fire management and ecosystem recovery strategies.

Nutrient Availability Post-Fire

Wildfires significantly alter nutrient availability in forest ecosystems, leading to complex changes in soil chemistry and biogeochemical cycles. These alterations have profound implications for ecosystem recovery and plant regrowth.

Short-term nutrient pulses

Following a wildfire, there is typically a temporary rise in nutrient availability. This increase is mainly caused by the fast breakdown of organic material and the accumulation of ash rich in nutrients. Research has shown that soil fertility can increase after low-intensity fires, as the combustion process chemically converts nutrients bound in dead plant tissues and the soil surface to more available forms [15].

The addition of ash after full or partial burning of biomass and other organic matter has a very high impact on the changes in soil chemistry. The concentrations of exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) increase mainly as the fire intensity rises whereas phosphorus, similar to mineralized nitrogen amounts (NH_4^+ + NO_3^-), even ends up rising, also with increasing fire severity levels [16-21].

For instance, phosphorus availability frequently increases after fire. Zhang and Biswas (2017) pointed out that the mineralization of organic phosphorus in forest fires is mainly released to plant absorption as available orthophosphate (PO_4^{3-}) [22]. Fernández-García et al. results from a high-intensity wildfire that occurred in the Pinus pinaster forest in 2019 included topsoil with high accessible phosphorus at the burned plot compared to an unburned one [23].

Long-term nutrient depletion

Nutrient pulses dominate the immediate post-fire period but in a larger context of chronic wildfire nutrient depletion within forest soils. Forest fires generally deplete the total nutrient supply of a site by a complex process that includes oxidation, volatilization, and transport to ash, leaching, and displacement. As an example, a low-intensity slash fire decreased fuel nutrient pools by 54-75% nitrogen in understory and forest floor: 37-50% phosphorus; 43-66% potassium; 31-34% calcium; and 25% magnesium [24].

The impact on nitrogen is particularly significant. Most of the nitrogen is vaporized and lost to the atmosphere during a fire, leading to nitrogen-deficient soils in the long term. This loss is compounded by the fact that nitrogen-fixing bacteria are extremely susceptible to heat and are often destroyed by wildfires.

Research in the Central Siberian Plateau has shown that the effects of wildfires on nutrient availability can persist for decades. Nitrate concentrations were found to be elevated for up to a decade post-fire, while dissolved organic carbon (DOC) and nitrogen concentrations remained depressed for up to five decades [14].

Effects on plant regrowth

The post-fire nutrient dynamics have significant implications for plant regrowth and ecosystem recovery. The initial nutrient pulse can stimulate the rapid regrowth of fire-adapted species. However, long-term nutrient depletion, particularly of nitrogen, can limit plant growth and alter species composition.

In larch forests, the moss layer and storage of organic matter take a long time to develop after a fire, but the growing shrubs and larch seedlings that rely on fire for spreading, lead to a higher demand for inorganic nitrogen. This results in a complicated interaction between plant succession and nutrient availability.

The recovery of nutrient cycles and plant communities is closely linked. As vegetation re-establishes, it contributes to the rebuilding of soil organic matter and nutrient pools. This procedure, though, may take decades. Research has indicated that the stabilization of nitrogen and DOC concentrations in streams can occur up to 50 years after a wildfire disturbance, demonstrating the long-term nature of ecosystem recovery [14].

In conclusion, while wildfires initially create a nutrient pulse that can stimulate plant growth, the long-term effects often lead to nutrient depletion, particularly of nitrogen. This dynamic significantly influences plant regrowth patterns and ecosystem recovery trajectories, underscoring the complex and long-lasting impacts of wildfires on nutrient availability and ecosystem function.

Erosion and Sediment Transport

Wildfires significantly alter the landscape, leading to increased erosion and sediment transport. These processes have far-reaching consequences for both terrestrial and aquatic ecosystems, as well as human infrastructure and water resources.

Factors influencing erosion rates

The main elements influencing the likelihood of erosion after a wildfire include the fire's intensity, the degree of vegetation and soil surface damage, and the timing and quantity of precipitation following the fire. Fire intensity plays a crucial role in determining the extent of erosion. Intense fires result in the loss of ground cover and reduced infiltration rates due to ash or fine sediment deposition, which enhances runoff and surface erosion [25,26].

Erosion rates are also greatly influenced by topography. In contrast to gentle slopes with deep soils, steep watersheds with shallow soils are more vulnerable to significant increases in runoff and erosion. For example, the Obreguilla basin, a tiny catchment facing south, has high dNBR (differenced Normalized Burn Ratio) values and 40–45% slopes over most of its basin area, indicating severe burn consequences [25,27]

Sediment delivery to streams

Stream-bed sediment transfer is often highly erratic and can be strongly dependent on high-magnitude, low-frequency disturbance events of a magnitude consistent with large episodic storms or wildfires. These post-fire rainstorms frequently result

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in flooding, debris flows, and channel incision or aggradation. On slopes and rivers weathered granitic outcrops were identified as the most important sediment sources that correspond to the Picuezo watershed [26,27].

The transport of sediment to streams occurs through various mechanisms:

- Sheet erosion and rilling on hillslopes
- Dry ravel in steep terrain
- Channel incisions
- Debris flows

These activities fill channels with unstable silt, increasing the likelihood of debris flows after a fire. Sediment is moved through convergent terrain related to channel creation by rain splashing, and entrainment of loosened surficial soils, ash, and debris within overland flows [28].

The impact of wildfires on sediment delivery can be substantial and long-lasting. For instance, research revealed that suspended sediment loads eight years after a fire were more than twice as high as pre-burn projections. In certain instances, channel bank erosion may be responsible for up to half of the yearly sediment load [26].

Downstream impacts

The increased erosion and sediment transport following wildfires have significant downstream impacts on water quality, aquatic ecosystems, and human infrastructure.

1. **Water quality:** Significant increases in runoff and erosion can have an impact on irrigation systems, water treatment facilities, and supplies of drinking water [25]. greater sediment loads in surface waterways may result in greater prices for downstream customers to receive water treatment [28].
2. **Aquatic ecosystems:** Elevated sediment loads can impact aquatic habitats, food webs, and fish spawning grounds in aquatic ecosystems. In extreme situations, they can directly lead to the death of fish. The sediment frequently contains additional pollutants like phosphorus, which have the potential to cause eutrophication in aquatic environments [25].
3. **Reservoir sedimentation:** Increased levels of sediment can lead to reservoirs used for drinking water becoming filled, ultimately decreasing their capacity and shortening their lifespan [25].
4. **Water temperature:** By directly heating and eliminating riparian vegetation, wildfires can elevate surface water temperatures, in the short and long run. These rising temperatures can cause oxygen levels in the water to decrease, posing a threat to fish populations [25].
5. **Nutrient pollution:** Nitrogen that is emitted from plant tissues during and after a fire can drain out as nitrate from burnt regions and get transported to adjacent water sources. Elevated levels of nitrates in drinking water sources may pose a risk to human health [25].

In conclusion, the erosion and sediment transport processes triggered by wildfires have complex and long-lasting effects on watersheds. Understanding these dynamics is crucial for developing effective post-fire management strategies and mitigating the impacts on downstream ecosystems and human communities.

Water Chemistry Alterations

Wildfires significantly alter the chemistry of water bodies in affected areas, leading to complex changes in major ion concentrations, trace element mobilization, and organic carbon fluxes. These alterations have profound implications for water quality, aquatic ecosystems, and downstream water resources.

Major ion concentrations

Wildfires generate the combustion of organic soil and biomass, with the concomitant release of exchangeable cations (Ca^{2+}, Mg^{2+}, and K^{+}) into the environment. As a result, the ions are transported to streams and lakes rather than retained on soil particles as is normal and cause an increase in the pH of surface waters through cation exchange. Calcium and potassium concentration in water bodies compared to reference conditions may be elevated by as much as 300% (with some cases having increases above 60,000%) [29,30]. The return period of these high levels is typically <5 years after a fire event.

Conversely, many studies have reported post-fire peaks in anions such as sulphate (SO_4^{2-}), chloride (Cl^{-}), and nitrate (NO^{3-}). These increases are attributed to a combination of release from soil and reduced biological demand, particularly for nitrate. The dominance of acid anions over base cations can result in the acidification of downstream waters, especially in areas with higher concentrations of stored sulphur or nitrogen from historic deposition or a high proportion of peatlands [29].

Conductivity, which is closely related to ion concentrations, also tends to increase after fires, with a median increase of just over 100%. These changes in conductivity generally follow burn severity patterns due to greater ash production and mineralization at higher temperatures [30].

Trace element mobilization

Wildfires can mobilize various trace elements, including heavy metals, which can have significant impacts on water quality and aquatic ecosystems. The combustion of vegetation and soil organic matter releases these elements, which are then transported to water bodies through erosion and runoff [31].

Toxic and other metal concentrations in downstream water resources can increase due to enhanced erosion rates and sediment loads following wildfires. This mobilization of contaminants, including metals, occurs particularly during or immediately after the first major post-fire rainfall events [31]. The impact is especially pronounced in landscapes with already elevated contaminant levels.

Wind may also have a major impact on the movement of metals, potentially spreading pollutants across vast areas. The enhanced movement of metals could greatly affect the water quality of forest catchments, rivers, and water storages, posing potential health hazards to humans and ecosystems [31].

Organic carbon fluxes

Wildfires affect DOC concentrations in water bodies, but the overall responses to wildfire vary depending on what components of DOM are incorporated and how this combines into one pool. Surprisingly, some studies found that DOC concentrations can even be higher after a fire than previously, although the organic matter load should have decreased due to

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burning. This pyrogenic dissolved organic matter (PyDOM) bears unique chemical signatures relative to many other forms of DOM originating from unburned parent materials [32,33].

Pyrogenic DOM typically has a lower average molecular weight but higher aromatic and nitrogen content levels than nonpyrogenic DOM. This variation in makeup impacts how it acts in water treatment procedures. PyDOM is usually less efficiently removed from water (20-30% removal) compared to nonpyrogenic DOM (typically 50-60% removal or higher) [33].

The increased levels and altered characteristics of PyDOM in water bodies following wildfires have significant implications for water treatment. Higher chemical dosages are needed for treatment, and there is an increased likelihood of disinfection by-product (DBP) formation during treatment. PyDOM is more reactive, promoting the formation of potentially harmful oxygenated DBPs, such as haloacetic acids during chlorination and N-nitrosodimethylamine during chloramination [33].

These changes in water chemistry following wildfires pose challenges for water resource management and treatment, highlighting the need for adaptive strategies to mitigate the impacts on water quality and aquatic ecosystems.

Ecosystem Recovery Trajectories

Factors influencing recovery rate

Ecosystem recovery after wildfires is a complex, multifactorial process. The significance of post-fire climate is particularly important for the regeneration of vegetation in Mediterranean forests, as longer gaps between severe droughts could hinder their ability to bounce back in the future. The duration of drought after disturbance is crucial for vegetation recovery in semi-arid and wet regions, and it also impacts scaling factors like tree size distribution across the area. [34].

The degree of fire severity affects the initial growth of plants post-fire but to a lesser extent than drought. Interestingly, the impact of fire severity varies based on the degree of aridity in the study region. In areas with high humidity and moderate humidity, vegetation regrowth is more pronounced with higher fire severity, but in dry areas, the opposite trend is observed. Topographic characteristics like slope direction and height have been shown to slightly influence post-fire recovery in arid regions [34].

Vegetation regrowth patterns

The growth of vegetation following wildfires shows varying trends that are hard to predict over time. The NBR recovery rate peaks a few years after the fire before gradually declining. Burned patches with high severity usually experience the best recovery, especially in forests with a mix of conifer species. However, it wasn't until 13 years post-fire that areas of ponderosa pine forests that experienced moderate to high severity burns began to show slower recovery rates compared to those that were lightly burned [35].

The NBR recovery rate differs among different types of forests, with the lowest in ponderosa pine forests, moderate in mixed conifer forests, and highest in conifer-oak-chaparral forests [30]. It is crucial to mention that the majority of areas do not fully return to their pre-fire NBR levels even after 9 to 16 years post-fire. Out of the fires studied, only a small proportion of low, moderate, and high-severity areas had recovered their pre-fire NBR levels: 6 to 28%, 4 to 26%, and 1 to 22%, in that order [35].

Soil-Plant feedback

Wildfires significantly impact plant-soil feedback (PSF) processes, which play a crucial role in ecosystem recovery. Immediately after a fire, PSF processes are expected to be nullified, with average neutral PSF responses being more common in the short term. This is due to the selective reduction in abundance and biomass of associated groups of soil microbes and soil fauna, which reduces the strength of both positive and negative feedback effects [36].

Prompt changes in soil characteristics cause fire's long-term consequences on PSF, especially intense fires. In addition to changing the PSF's intensity, these indirect effects can reset and reroute it since different taxa or groupings of soil microbes and soil animals have varying post-fire recovery strategies and rates. For example, fire has been demonstrated to reduce the positive PSF for Eucalyptus trees, presumably as a result of severing ties with ectomycorrhizal and arbuscular mycorrhizal fungi [36].

The recovery of soil-borne pathogens after fire remains poorly documented, creating a gap in understanding how fire can delay the return of negative PSF. However, in pyro-diverse dry-sclerophyll forests, some research has discovered that infections are comparatively more prevalent soon after fire than other soil microbial groups [36].

Intense fires are expected to result in abrupt and significant changes in the PSF's strength and direction in environments where woody plants predominate. In ecosystems that support fire-adapted mutualistic microbes (such as N_2-fixing bacteria), a near-complete reversal of PSF direction is anticipated, along with a significant decline in soil-borne diseases [36].

Conclusions

Wildfires have a profound impact on biogeochemical cycles, altering soil and water quality in complex ways. These events trigger significant changes in soil organic matter, nutrient availability, and sediment transport, leading to far-reaching consequences for both terrestrial and aquatic ecosystems. The effects on water chemistry, including changes in major ion concentrations and organic carbon fluxes, pose challenges for water resource management and treatment.

The recovery of ecosystems after wildfires is an intricate process influenced by various factors such as post-fire climate, fire severity, and local topographic conditions. Vegetation regrowth patterns show non-linear trends over time, with recovery rates varying among forest types. Understanding these dynamics is crucial to developing effective post-fire management strategies and to mitigate the long-term impacts on ecosystems and water resources.

Disclosure Statement

No potential conflict of interest was reported by the authors.

References

1. Badía D, Martí C, Aguirre AJ, Aznar JM, González-Pérez JA, De la Rosa JM, et al. Wildfire effects on nutrients and organic carbon of a Rendzic Phaeozem in NE Spain: changes at cm-scale topsoil. Catena. 2014;113:267-275. https://doi.org/10.1016/j.catena.2013.08.002

https://doi.org/10.61577/jgi.2024.1000010

2. Miesel JR, Hockaday WC, Kolka RK, Townsend PA. Soil organic matter composition and quality across fire severity gradients in coniferous and deciduous forests of the southern boreal region. J Geophys Res Biogeosci. 2015;120(6):1124-1141. https://doi.org/10.1002/2015JG002959
3. Santín C, Doerr SH, Preston CM, González-Rodríguez G. Pyrogenic organic matter production from wildfires: a missing sink in the global carbon cycle. Glob Chang Biol. 2015;21(4):1621-1633. https://doi.org/10.1111%2Fgcb.12800
4. Hu Y, Zhan J, Zhou G, Chen A, Cai W, Guo K, et al. Fast forest fire smoke detection using MVMNet. Knowledge-Based Systems. 2022;241:108219. https://doi.org/10.1016/j.knosys.2022.108219
5. Thomas SC, Gale N. Biochar and forest restoration: a review and meta-analysis of tree growth responses. New For. 2015;46(5): 931-946. https://doi.org/10.1007/s11056-015-9491-7
6. Gao C, Lin H, Hu H. Forest-fire-risk prediction based on random forest and backpropagation neural network of Heihe area in Heilongjiang province, China. Forests. 2023;14(2):170. https://doi.org/10.3390/f14020170
7. Nave LE, Vance ED, Swanston CW, Curtis PS. Fire effects on temperate forest soil C and N storage. Ecol Appl. 2011;21(4): 1189-1201. https://doi.org/10.1890/10-0660.1
8. Caon L, Vallejo VR, Ritsema CJ, Geissen V. Effects of wildfire on soil nutrients in Mediterranean ecosystems. Earth-Sci Rev. 2014;139:47-58. https://doi.org/10.1016/j.earscirev.2014.09.001
9. Fendorf S, Lopez A, Lezama-Pacheco J. Unforeseen metal toxin produced in particulates of wildland fires. https://doi.org/10.21203/rs.3.rs-2177622/v1
10. Wang Y, Xu Z, Zhou Q. Impact of fire on soil gross nitrogen transformations in forest ecosystems. J Soils Sediments. 2014;14:1030-1040. https://doi.org/10.1007/s11368-014-0879-3
11. Adkins J, Sanderman J, Miesel J. Soil carbon pools and fluxes vary across a burn severity gradient three years after wildfire in Sierra Nevada mixed-conifer forest. Geoderma. 2019;333:10-22. https://doi.org/10.1016/j.geoderma.2018.07.009
12. Hinojosa MB, Albert-Belda E, Gómez-Muñoz B, Moreno JM. High fire frequency reduces soil fertility underneath woody plant canopies of Mediterranean ecosystems. Sci Total Environ. 2021;752:141877. https://doi.org/10.1016/j.scitotenv.2020.141877
13. Liu Z, Ballantyne AP, Cooper LA. Biophysical feedback of global forest fires on surface temperature. Nat Commun. 2019;10(1):214. https://doi.org/10.1038/s41467-018-08237-z
14. Rodriguez-Cardona BM, Coble AA, Wymore AS, Kolosov R, Podgorski DC, Zito P, et al. Wildfires lead to decreased carbon and increased nitrogen concentrations in upland arctic streams. Sci Rep. 2020;10(1):8722. https://doi.org/10.1038/s41598-020-65520-0
15. Schoch P, Binkley D. Prescribed burning increased nitrogen availability in a mature loblolly pine stand. For Ecol Manag. 1986;14(1):13-22. https://doi.org/10.1016/0378-1127(86)90049-6
16. Maksimova E, Abakumov E. Wildfire effects on ash composition and biological properties of soils in forest-steppe ecosystems of Russia. Environ Earth Sci. 2015;74:4395-4405. https://doi.org/10.1007/s12665-015-4497-1
17. Jhariya MK, Singh L. Effect of fire severity on soil properties in a seasonally dry forest ecosystem of Central India. Int J Environ Sci Technol. 2021;18(12):3967-3678. https://doi.org/10.1007/s13762-020-03062-8
18. Li XY, Jin HJ, Wang HW, Marchenko SS, Shan W, Luo DL, et al. Influences of forest fires on the permafrost environment: A review. Adv Clim Change Res. 2021;12(1):48-65. https://doi.org/10.1016/j.accre.2021.01.001
19. Franco MG, Mundo IA, Veblen TT. Field-validated burn-severity mapping in North Patagonian forests. Remote Sens. 2020;12(2):214. https://doi.org/10.3390/rs12020214
20. Verma S, Singh D, Singh AK, Jayakumar S. Post-fire soil nutrient dynamics in a tropical dry deciduous forest of Western Ghats, India. For Ecosyst. 2019;6:1-9. https://doi.org/10.1186/s40663-019-0168-0
21. Chungu D, Ng'andwe P, Mubanga H, Chileshe F. Fire alters the availability of soil nutrients and accelerates the growth of Eucalyptus grandis in Zambia. J For Res. 2020;31(5):1637-1645. https://doi.org/10.1007/s11676-019-00977-y
22. Zhang Y, Biswas A. The effects of forest fire on soil organic matter and nutrients in boreal forests of North America: a review. Adaptive soil management: from theory to practices. 2017;465-476. https://doi.org/10.1007/978-981-10-3638-5_21
23. Fernández-García V, Fulé PZ, Marcos E, Calvo L. The role of fire frequency and severity on the regeneration of Mediterranean serotinous pines under different environmental conditions. Forest Ecology and Management. 2019;444:59-68. https://doi.org/10.1016/j.foreco.2019.04.040
24. Raison RJ, Khanna PK, Woods PV. Mechanisms of element transfer to the atmosphere during vegetation fires. Can J For Res. 1985; 15(1):132-140. https://doi.org/10.1139/x85-022
25. Paige G, Zygmunt J. The science behind wildfire effects on water quality, erosion. Living With Wildfire in Wyoming. University of Wyoming Extension. Available at: https://www.uwyo.edu/barnbackyard/_files/documents/resources/wildfire2013/waterqualityerosion2013wywildfire.pdf
26. Ryan SE, Dwire KA, Dixon MK. Impacts of wildfire on runoff and sediment loads at Little Granite Creek, western Wyoming. Geomorphology. 2011;129(1-2):113-130. https://doi.org/10.1016/j.geomorph.2011.01.017
27. Ortega-Becerril JA, Suarez C, Vázquez-Tarrío D, Garrote J, Gomez-Heras M. Sediment response after wildfires in mountain streams and their effects on cultural heritage: the case of the 2021 Navalacruz Wildfire (Avila, Spain). Fire. 2024;7(2):52. https://doi.org/10.3390/fire7020052
28. Ice GG, Neary DG, Adams PW. Effects of wildfire on soils and watershed processes. J For. 2004;102(6):16-20. https://doi.org/10.1093/jof/102.6.16
29. Granath G, Evans CD, Strengbom J, Fölster J, Grelle A, Strömqvist J, Köhler SJ. The impact of wildfire on biogeochemical fluxes and water quality in boreal catchments. Biogeosciences. 2021; 18(10):3243-3261.
30. Paul MJ, LeDuc SD, Lassiter MG, Moorhead LC, Noyes PD, Leibowitz SG. Wildfire induces changes in receiving waters: A review with considerations for water quality management. Water Resour Res. 2022;58(9):e2021WR030699. https://doi.org/10.1029/2021WR030699
31. Abraham J, Dowling K, Florentine S. Risk of post-fire metal mobilization into surface water resources: A review. Sci Total Environ. 2017;599:1740-1755. https://doi.org/10.1016/j.scitotenv.2017.05.096
32. Crandall T, Jones E, Greenhalgh M, Frei RJ, Griffin N, Severe E, et al. Megafire affects stream sediment flux and dissolved organic matter reactivity, but land use dominates nutrient dynamics in semiarid watersheds. PLoS One. 2021;16(9):e0257733. https://doi.org/10.1371/journal.pone.0257733
33. Chow AT, Karanfil T, Dahlgren RA. Wildfires are threatening municipal water supplies. Eos, Science News by AGU. 2021. https://eos.org/science-updates/wildfires-are-threatening-municipal-water-supplies
34. Blanco-Rodríguez MÁ, Ameztegui A, Gelabert P, Rodrigues M, Coll L. Short-term recovery of post-fire vegetation is primarily limited by drought in Mediterranean forest ecosystems. Fire Ecol. 2023;19(1):68. https://doi.org/10.1186/s42408-023-00228-w
35. Bright BC, Hudak AT, Kennedy RE, Braaten JD, Henareh Khalyani A. Examining post-fire vegetation recovery with Landsat time series analysis in three western North American forest types. Fire Ecol. 2019;15(1):1-4. https://doi.org/10.1186/s42408-018-0021-9
36. Kardol P, Yang T, Arroyo DN, Teste FP. Plant-soil feedback in the 'real world': how does fire fit into all of this ?. Plant and Soil. 2023;485(1):91-102. https://doi.org/10.1007/s11104-022-05778-7

https://doi.org/10.61577/jgi.2024.1000010