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WILDFIRE IMPACTS ON FLOOD REGULATION AND WATER PURIFICATION

Impacto de los incendios forestales en la regulación de las inundaciones y la depuración del agua

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ABSTRAC: Wildfires are global phenomena with positive and negative impacts on ecosystems. They are a natural ecosystem element that shaped several biomes. However, for some time, they may disturb the ecosystems, reducing their capacity to supply several services. The objective of this article is to resume the impacts of wildfires on flood regulation and water purification and discuss the use of some restoration measures to mitigate the wildfire impacts. Wildfires, especially in the immediate period after, reduce the ecosystem's capacity to regulate floods and purify water due to vegetation removal and ash that can degrade water quality. The magnitude of the impacts depends essentially on wildfire severity and post-wildfire precipitation intensity. Restoration measures must be applied, especially after high-severity wildfires and if the recurrence is high. In the context of climate change, the interval between fires is expected to be shorter, and the severity will be high. Therefore, restoration measures may be more needed.

KEYWORDS: Wildfires; flood regulation; water purification; severity; restoration.

RESUMEN: Los incendios forestales son un fenómeno global con repercusiones positivas y negativas en los ecosistemas. Estos son un elemento natural de los ecosistemas que dio forma a diversos biomas. Sin embargo, durante algún tiempo, pueden perturbar los ecosistemas, reduciendo su capacidad para suministrar diversos servicios. El objetivo de este artículo es resumir los impactos de los incendios forestales en la regulación de las inundaciones y la depuración del agua y discutir el uso de algunas medidas de restauración para mitigar los impactos de los incendios forestales. Los incendios forestales, especialmente en el periodo inmediatamente posterior al evento, reducen la capacidad del ecosistema para regular las inundaciones y depurar el agua debido a la eliminación de vegetación y cenizas que pueden degradar la calidad de ese agua. La magnitud de los impactos depende esencialmente de la severidad del incendio forestal y de la intensidad de las precipitaciones posteriores al mismo. Deben aplicarse medidas de restauración, especialmente después de incendios forestales de gran severidad y si la recurrencia es elevada. En el contexto del cambio climático, se espera que el intervalo entre incendios sea más corto y que la severidad sea mayor. Por lo tanto, las medidas de restauración pueden ser más necesarias.

PALABRAS CLAVE: Incendios forestales; regulación de inundaciones; depuración de aguas; severidad; restauración.

1. Background

Fire is a natural element of the ecosystems that, except the polar zones, shaped global biomes at different intensities (e.g., Holz *et al.*, 2012; Muñoz-Rojas *et al.*, 2021). In recent decades, as a consequence of land use (e.g., land abandonment, industrial plantations, urban sprawl) and climate change (e.g., drought), there has been an increase high the severity of fires. Such fires can have a long-term effect on different ecosystem components such as air, water, biodiversity or soils (Pereira *et al.*, 2021). Land abandonment promoted vegetation encroachment and the increase of biomass in several parts of the world (e.g., Mantero *et al.*, 2020; Khorchani *et al.*, 2021). This rewilding trend increases the ecosystem services supplied by the abandoned areas, such as carbon sequestration, air quality regulation, erosion regulation, flood regulation, water purification and recreation (Pereira *et al*., 2022). Nevertheless, this fuel accumulation is also responsible for the increasing wildfire risk (Zazali *et al*., 2019; Davies *et al*., 2022). Also, the proliferation of highly flammable monoculture plantations (e.g., pines or eucalyptus trees), generally without management, is increasing the vulnerability of these environments drastically to severe wildfires (e.g., Pereira *et al*., 2018a). Urban sprawl and the negligence of people are increasing the risk of wildfire. The sprawl of new houses and people with careless habits (e.g., vegetation and fire management) into wildland areas is increasing the risk and vulnerability of these communities to wildfire effects. With such vulnerability due to human landscape management and behaviour, the occurrence of wildfires during drought periods is expected to increase (Bento-Gonçalves & Vieira, 2020; Gonzalez-Mathiesen *et al*., 2021).

The wildfire's impact depends on the severity. Usually, low and medium-severity wildfires do not have long-term impacts on the ecosystems, contrary to high-severity wildfires (e.g., Blandon *et al*., 2014; Dove *et al*., 2020). Nevertheless, this dynamic does not depend only on wildfire severity but what happens after. Vegetation recuperation and the hydrological response also depend on soil properties (e.g., vulnerability to erosion, water repellency), fire history (e.g., recurrence), ecosystem affected (e.g., more or less resilient) and post-fire meteorological conditions (e.g., heavy rainfall). Fire severity and the factors mentioned will determine the impacts of wildfire (e.g., Pereira *et al.*, 2018a; Etchells *et al.*, 2020). In the short and long term, it is well known that wildfires negatively affect several ecosystem services (e.g., carbon sequestration, air quality regulation, erosion regulation, flood regulation, water purification, pollination, food, fibre, cultural heritage, recreation). Flood regulation is one of the most critical ecosystem services affected by wildfires, especially in the immediate period (Pereira *et al*., 2021). Vegetation removal, root system destruction, bare soil and water repellency increase the risk of floods. This will increase the development of flash floods depending on the amount of precipitation intensity, topography and the capacity of the soil to retain water (e.g., Mueller *et al.*, 2018; Ebel & Moody, 2020). In case of high hydrological response, water bodies quality is also usually affected (e.g., Hohner *et al*., 2019; Emerton *et al*., 2020). Although there are previous works focused on wildfire impacts on ecosystem services (e.g., Sil *et al*., 2019; Robinne *et al*., 2020; Pereira *et al*. 2021; Taboada *et al*., 2021), a synthesis focused on the effects on flood regulation and water quality is lacking. The objective of this perspective paper is to make a synthesis of the effects of wildfires on flood regulation and water purification and propose several restoration strategies.

2. Flood regulation

In the immediate period after a wildfire, vegetation removal (e.g., soil cover, interception) reduces soil protection against rainfall kinetic energy, increasing sediment detachment, erosion and overland flow (Shakesby, 2011; Cole *et al*., 2020). Also, the high temperatures on the soil surface can create a hydrophobic layer and reduce water infiltration (e.g., Doerr *et al*., 2006). Ash may reduce or increase water retention, depending on the temperature of combustion. Black ash can be highly repellent and increase the hydrological response. On the other hand, white ash has a higher capacity to retain water during the first rainfalls. Nevertheless, white ash can produce an impermeable layer after drying due to carbonate particle crystallization. This also depends on the type of forest affected and the species composition. Some are more flammable than others, affecting ash properties (Pereira *et al*., 2018b). Overall, the flood regulation capacity is reduced immediately after a fire and is especially damaged in areas affected by high-severity wildfires (Brogan *et al*., 2019; Alexandra & Finlayson, 2020) (Figure 1) or

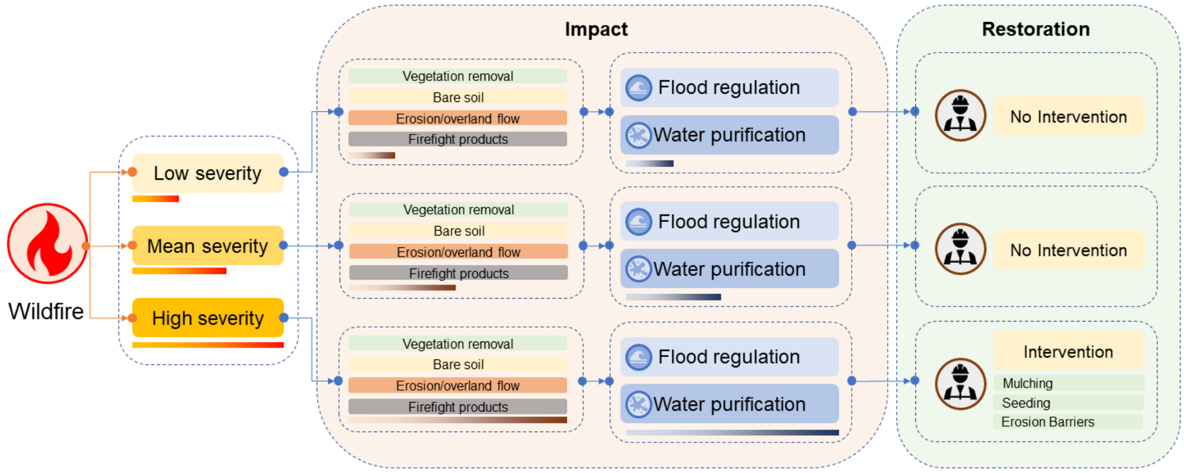

Figure 1. Different wildfire severities impact on ecosystems, services and restoration required.
Figura 1: Impactos de las diferentes severidades de los incendios forestales en los ecosistemas, servicios y la restauración necesaria.

hyper-dry conditions (Moody & Ebel, 2012). In these circumstances, if a high rainfall intensity occurs in sloped areas, flash floods are highly likely (e.g., Liu *et al.*, 2022). Climate change will increase the probability of flash floods in wildfire-affected areas, as observed elsewhere (e.g., Touma *et al.*, 2022). Previous works identified the occurrence of flash floods immediately after wildfires in Australia (Nyman *et al.*, 2011), the United States (Vieira *et al.*, 2004), Italy (Coscarelli *et al.*, 2021), Greece (Filis *et al.*, 2020), Spain (Ortega-Becerril *et al.*, 2022) or Uganda (Jacobs *et al.*, 2016). Therefore, it is a recurrent problem in several areas of the world. The extension of wildfire impacts on flood regulation depends on the fire severity (Figure 1). In areas where wildfire severity is low, the impact is reduced, while when the wildfire severity is high, the effect on flood regulation capacity is larger (e.g., Dahm *et al.*, 2015). The timing of precipitation is key to producing floods after wildfires. For instance, in Mediterranean areas, fire season can last until August/September (e.g., Francos *et al.*, 2016; Turco *et al.*, 2017). In the last years, even in October (e.g., Portugal), wildfires with high severity occurred (Figueiredo *et al.*, 2021), likely due to climate change. During summer and Autumn (October and November), isolated thunderstorms and intense rainfall periods are frequent (e.g., Roye *et al.*, 2018; Henin *et al.*, 2021). If intense rainfall periods occur in recently burned areas, the probability of flash floods increases substantially. The increased fire season length and extreme rainfall due to climate change may create "the perfect storm" for flash flood development in wildfire-affected areas.

The burned area flood regulation capacity increases with increasing vegetation coverage (Pereira *et al.*, 2021). Several biomes (e.g., Mediterranean) are adapted to fire disturbance (e.g., Santana *et al.*, 2018). Nevertheless, wildfire recurrence has detrimental impacts on soil properties (e.g., Pereira *et al.*, 2018a) and delays vegetation recuperation (e.g., Moghli *et al.*, 2022). This may severely affect the restoration of burned areas' flood regulation capacity, especially in a climate change context where short-term wildfire recurrence is expected to increase (Elia *et al.*, 2020).

3. Water purification

Vegetation removal decrease the ecosystem capacity to purify water (Figure 1). Also, wildfire ash has many potentially toxic elements, such as metals and metalloids (Murphy *et al.*, 2020) or Polycyclic Aromatic Hydrocarbons (PAHs) (Silva *et al.*, 2015). Previous works also observed that firefight products released toxic elements into the environment (e.g., fluorosurfactants or perfluorosurfactants) (Peshoria *et al.*, 2020). After the first rainfalls, these elements can be incorporated into the soil matrix and pollute groundwater (Fernandez-Marcos, 2022) or transported in overland flow and polluting rivers (Meneses *et al.*, 2019), lakes (Pelletier *et al.*, 2022) and estuaries (Barros *et al.*, 2022) (Figure 1). Numerous studies found negative impacts of toxic materials from burned areas on fauna (e.g., Gomez-Isaza *et al.*, 2022) and flora (e.g., Thompson *et al.*, 2019). This increase in pollution affects drinkable water (e.g., Robinne *et al.*, 2020), affecting the supply to large cities. Examples of this were found in urban areas located in California (Proctor *et al.*, 2020), Colorado (Hohner *et al.*, 2019) or Canada (Emelko *et al.*, 2016). Generally, after a wildfire, there has been observed an increase in freshwater turbidity (Rust *et al.*, 2019), major cations and ions, and metallic elements or PAHs (Mansilha *et al.*, 2019). The factors that affect post-fire water purification are similar to the ones mentioned in flood regulation. Previous works observed that these impacts could be medium (5 years after) (Rust *et al.*, 2018) or long-term (10 years after) (Yu *et al.*, 2018).

4. Restoration measures

Post-wildfire restoration needs to be considered carefully because several innervations can be more damaging to the soil than the wildfire itself. They are usually appropriate when the wildfire has high severity and there are goods to protect from floods or landslides in downstream areas (Pereira *et al*., 2018a). Several works identified that several post-fire managing strategies (e.g., Savage logging) induce a very high soil degradation and erosion (e.g., Francos *et al*., 2019; Fernandez *et al*., 2021). If some intervention measure is planned, the best option is to do when the vegetation covers the soil. This will minimize the degradation (Pereira *et al*., 2018a).

When the wildfire has a low or medium severity, the best approach is not to intervene and leave the vegetation to recover naturally. In several ecosystems (e.g., the Mediterranean), vegetation can recover fast after a wildfire. However, in areas where wildfires are more recurrent, the vegetation capacity to recover is low (e.g., Smith-Ramírez *et al*., 2021). In this case, some intervention may be needed. Nevertheless, it is crucial to analyze case by case. Several strategies are applied to restore fire-affected areas, such as mulching (e.g., hydromulching, straw, wood chips), site preparation (e.g., tree plantation, ripping and post-fire mounding), channel treatments, erosion barriers, seeding or salvage logging. Mulching and seeding techniques can serve as a nature-based solution to improve the soil condition in the immediate period post-wildfire. Erosion barriers reduce soil erosion Therefore, if some restoration practices are needed, these practices are the best for soil restoration (Pereira *et al*., 2018a) (Figure 1). Overall, they reduce the impact of wildfire on flood regulation and water purification since they reduce sediment transport and water transport that can trigger flash floods or water quality degradation in rivers and lakes.

Although restoration measures need to be applied in areas affected by high-severity fires, it is important to rethink their application in the future. The use of nature-based solutions cannot be discarded. The current land abandonment trend (responsible for the biomass increase) (e.g., Piccinelli *et al*., 2020) and the increase in droughts, frequency, length and severity (Chiang *et al*., 2021) will affect the wildfire regime extending the wildfire season and the vulnerability of the ecosystem. In this context, previous works showed that it is expected an increase in wildfire severity and recurrence (Halofsky *et al*., 2020; Moghli *et al*., 2022). In this case, ecosystem restoration to mitigate the impacts of wildfire on flood regulation and water purification may be more needed since they may be more fragile and the post-wildfire recuperation more problematic. This is also essential to reduce the impacts on water availability. According to previous works, extreme wildfire risks may threaten the water supply (Robinne *et al*., 2021).

5. Conclusions

Although wildfires are a natural element of ecosystems, they may cause some negative temporal impacts, especially if they have a high severity. Wildfires decrease the ecosystem's capacity to regulate floods and water purification in the immediate period after. Normally until the vegetation recover. The risk may increase if the wildfire reaches a high severity and occur intense precipitations. The combination of these factors may trigger the development of flash floods and water quality degradation. The risk of floods and water quality degradation depends on the capacity of the ecosystems to recover and the post-wildfire meteorological conditions. In some cases, the impacts of wildfires can be long-term. The burned ecosystems restoration may be needed if wildfires reach high severity, are recurrent, or there is a risk of flooding or landslides. Normally ecosystem restoration in low and medium-severity wildfires is not needed. However, in a global change context (e.g., land abandonment and climate change), wildfire recurrence and severity are increasing. In this context, restoration measures may be more needed to mitigate the impacts of wildfires on flood regulation and water purification

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