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Methodology for the identification of priority areas for post-fire restoration: study of the Sierra Bermeja forest fire 2021

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INTRODUCTION AND CONTEXT

The 2021 Sierra Bermeja wildfire in Málaga, Spain, was one of the most devastating forest fires in recent decades, consuming 8,401 hectares in a unique serpentine ecosystem. This study aims to develop a systematic and replicable methodology to identify priority areas for post-fire restoration, with a focus on mitigating soil erosion, facilitating vegetation regeneration, and addressing long-term ecosystem vulnerabilities.

Forest fires, particularly in Mediterranean ecosystems, pose significant threats not only during the event but also in the aftermath. Post-fire effects, including hydrological disruptions, sediment transport, landslides, and soil degradation, often have a more lasting impact than the fires themselves. The combination of climate variability, the high sensitivity of Mediterranean soils, and the increasing frequency of large-scale fires necessitate innovative management strategies. The Sierra Bermeja fire highlights the urgency of identifying vulnerable zones and implementing effective restoration measures.

OBJECTIVES

The objectives of this study are: (i) to evaluate the post-fire effects, including erosion risk and regeneration capacity, and (ii) to identify specific areas requiring intervention. Additionally, the proposed methodology aims to be adaptable to similar events, considering the unique characteristics of each case. This approach is grounded in the use of readily accessible tools and data.

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METHODOLOGY

The study utilized vector layers from the "Red de Información Ambiental de Andalucía" (REDIAM) and the "Datos Espaciales de Referencia de Andalucía" (DERA) databases. Satellite images from the Sentinel-2A satellite, acquired between 2021 and 2023, were employed to assess fire severity and vegetation regeneration in affected areas. Spectral indices such as ΔNBR (Normalized Burn Ratio) and NDVI (Normalized Difference Vegetation Index) were applied to evaluate the impact of the fire on vegetation, with images processed to Level 2A (Bottom of Atmosphere, BOA) to ensure high-quality, atmospheric-corrected data.

Soil properties were analyzed using samples collected from different fire severity levels, both pre- and post-fire. A total of 110 soil samples were collected to assess key edaphic factors, including organic carbon content, pH, electrical conductivity, structural stability, porosity, and texture. Statistical analyses, including ANOVA and Tukey's test, were performed to identify significant differences in these properties across varying fire severity levels.

To estimate soil erosion rates before and after the fire, the Revised Universal Soil Loss Equation (RUSLE) was applied. The RUSLE model is widely used for estimating soil erosion and incorporates five main factors:

- **Rainfall Erosivity (R):** This factor measures the potential of rainfall to cause erosion. It was derived from 26 years of rainfall data (1992–2018) from the REDIAM database. The rainfall erosivity was calculated at a 25-meter resolution to enhance the spatial accuracy of the estimates.
- **Soil Erodibility (K):** This factor reflects the susceptibility of soil to erosion, influenced by its texture, organic content, and other physical properties. The K factor was estimated based on field measurements of soil properties (including texture and organic carbon content) and interpolated across the study area using Kriging to create a spatial map of soil erodibility.
- **Topography (LS):** The topographic factor accounts for the effects of slope length and steepness on water runoff and soil erosion. Using a Digital Elevation Model (DEM) with a 5-meter resolution, the LS factor was calculated according to the methodology of Moore and Burch (1986), which models how topography affects water flow and erosion potential.
- **Vegetation Cover (C):** The C factor reflects the protective role of vegetation in reducing soil erosion. In this study, vegetation cover was assessed using NDVI (Normalized Difference Vegetation Index), derived from satellite images taken before and after the fire. The C factor was calculated by correlating NDVI values to soil erosion, using a well-established equation.
- **Conservation Practices (P):** This factor accounts for soil conservation measures that reduce erosion. Since no specific conservation practices were implemented in the area, the P factor was set to 1, indicating no erosion control.

These factors were combined to estimate soil erosion rates for both pre- and post-fire conditions, highlighting areas at risk for increased erosion. The analysis indicated significant increases in erosion after the fire, particularly in areas with sparse vegetation cover and steeper slopes.

Priority areas for restoration were identified by combining ΔNBR (fire severity), NDVI (vegetation health), and the post-fire soil loss estimates. Areas with values above 180 were designated as high-priority zones for intervention, ensuring that the most vulnerable regions were addressed first.

RESULTS

The analysis of the Sierra Bermeja wildfire in 2021 showed significant variation in the severity of the fire across different areas, based on the ΔNBR index. The most affected regions were the slopes near the Infierno stream and Horno de los Almárgenes, which recorded ΔNBR values exceeding 0.66, indicating very high fire severity. These areas, along with others like the slopes between the Castor and Velerín rivers, San Manuel Mines, and the southeastern sector of Canalizo, represented regions where the fire had a devastating impact on vegetation and soil. A total of 57% of the burned area was categorized under high severity (ΔNBR = 0.44-

0.66), while 36% of the area experienced low to moderate fire severity (ΔNBR = -0.25 to 0.44). Only 7.3% of the burned land showed no fire damage (ΔNBR < -0.25), highlighting the widespread nature of the wildfire's impact.

Vegetation recovery, measured through NDVI, showed a stark contrast between pre- and post-fire conditions. Before the fire, 91% of the area had medium-high to high photosynthetic activity (NDVI > 0.25), which significantly decreased after the fire, with only 13.18% of the area retaining medium-high photosynthetic activity. Most of the affected area (87%) displayed very low to low photosynthetic activity (NDVI < 0.15), indicating that the fire had drastically reduced the vegetation's ability to carry out photosynthesis, especially in areas with low moisture content that burned more intensely. These results point to the severe transformation and degradation of the vegetation cover in Sierra Bermeja.

Soil properties also showed marked changes, particularly in areas with high fire severity. The post-fire analysis indicated a significant decrease in soil aggregate stability and an increase in soil porosity, with values of 59.45% in the most affected areas. The soil texture also changed, with a reduction in clay content and an increase in coarser particles like sand and silt. Furthermore, significant increases were observed in electrical conductivity and pH in these areas, indicating alterations in soil chemical properties due to the intense heat of the fire.

The impact of the wildfire on soil erosion was dramatic, as estimated using the Revised Universal Soil Loss Equation (RUSLE). Prior to the fire, the region exhibited relatively low soil erosion rates, with 60.1% of the area having erosion rates below 25 t ha^{-1} $year^{-1}$. However, post-fire estimates showed a substantial 47.5% increase in erosion rates, with total soil loss rising to 381.44 t ha^{-1} $year^{-1}$. The most affected areas, such as those around Horno de los Almárgenes and Pico Canalizo, saw erosion rates exceed 150 t ha^{-1} $year^{-1}$, indicating severe soil degradation. This dramatic rise in soil loss is primarily attributed to the loss of vegetation cover, which normally helps stabilize the soil and prevent erosion.

Priority Areas for Intervention

By combining satellite indices and the RUSLE model, three priority areas for intervention were identified. These zones exhibited the highest levels of fire severity, soil loss, and vegetation damage:

- **Zone 1:** Slopes between the Infierno stream and Horno de los Almárgenes, exhibiting the highest fire severity, significant soil impact, and limited recovery.
- **Zone 2:** Areas near Peña Blancas pass and the Alto Porrejón peak, which, while less severe, also face soil erosion issues and vegetation damage.
- **Zone 3:** Areas around Canalizo, with similar impacts on soil and vegetation.
- These areas, with values exceeding 180 in the combination of indices and RUSLE results, must be prioritized for intervention and restoration due to their vulnerability and the risk of further degradation.

CONCLUSIONS

This study underscores the importance of fire severity in identifying priority areas for post-fire restoration. The analysis revealed that regions with high fire severity experienced significant vegetation loss, drastic changes in soil properties, and increased soil erosion. Specifically, Sierra Bermeja showed considerable soil vulnerability, with alterations in physical, chemical, and hydrological properties, which could lead to decreased infiltration capacity, higher runoff, soil nutrient loss, and reduced organic carbon content in the first few years post-fire.

The NDVI analysis demonstrated that the fire effects persisted for several months, indicating prolonged exposure of the soils to the risk of erosion, particularly during the spring rains. The results were consistent with prior studies that showed a delayed recovery of vegetation in areas with low precipitation. These findings highlight the critical role of vegetation in protecting the soil and regulating the local climate, especially in Mediterranean regions like Sierra Bermeja, which are already under pressure from climate change.

Using the RUSLE model within a GIS framework, the study quantified the increase in soil erosion post-fire, particularly in areas with high fire severity and low vegetation cover. This model proved effective in identifying areas with high erosion risks, despite the tendency for some overestimation in soil loss, which has been noted in previous research. The results indicated that areas with the highest fire severity are especially vulnerable to soil erosion, further stressing the need for immediate restoration efforts.

By integrating fire severity, soil vulnerability, and vegetation data, the study successfully identified three priority restoration zones. This GIS-based methodology offers a data-driven, cost-effective approach for managing post-fire recovery, enabling targeted interventions in the most affected areas. The tool can help optimize the use of resources in post-fire management and restoration, particularly in regions that lack standardized protocols for addressing post-fire impacts.

The methodology presented here offers a significant advancement in the post-fire management of forested areas. It provides environmental managers with a robust tool for planning restoration strategies based on validated data. The combination of remote sensing technology and GIS allows for a more accurate and efficient assessment compared to traditional field methods, reducing both costs and time. Furthermore, the methodology's adaptability makes it suitable for application in other fire-prone ecosystems, not only in Mediterranean regions but also globally. By fostering ecosystem resilience and sustainable land management, this approach contributes to the long-term recovery and stability of areas affected by forest fires.