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WILDFIRE EFFECTS ON SOIL EROSION DYNAMICS: THE CASE OF 2021 MEGAFIRES IN GREECE

SUMMARY

In recent decades, the frequency and severity of wildfires have increased, especially in the Mediterranean Basin. Aside from their direct effects, accelerated soil erosion is observed in fire-affected areas due to the destruction of vegetation. The 2021 Greece megafires were one of the country's major ecological disasters, destroying over 125,000 hectares of forest and agricultural land. The present study aims to quantify the effects of selected wildfire events on erosion dynamics over the 2021 fire season. To accomplish the goals of the current research the RUSLE erosion prediction model was implemented using readily available earth observation (EO) data. The results demonstrated a shift to the erosion hazard from very low and low (pre-fire) to severe and very severe (post-fire), in all cases. In particular, the increase in potential erosion, expressed in t ha^{-1} y^{-1}, was found to be equal to 98.5, 65.9, 57.0, 56.3, 51.6 and 35.6 for the Gytheio (Laconia), Schinos (Corinthia – West Attica), Northern Evia, Ancient Olympia – Gortynia (Ilia), Vilia (Western Attica) and Varympompi (Attica) regions, respectively. Moreover, the spatial distribution of post-fire soil erosion rates provides sufficient information for the identification of the erosion prone-areas and the corresponding emergency rehabilitation treatments.

Keywords: Megafires, Soil erosion, RUSLE, Earth Observation, Mediterranean Basin.

INTRODUCTION

The prevention of soil erosion and reduction of its damage requires reliable knowledge of the whole processes and effective factors (Bilasco *et al*., 2021; Dragicevic *et al*., 2017; Katebikord *et al*., 2017; Vujacic *et al*., 2017) including many natural and human-induced environmental factors. Fire is one of the

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effective factors on soil characteristics such as organic content, structure and infiltration which can change the runoff and erosion conditions on the soil surface. Climate change has the potential to influence many aspects of wildfire behaviour and risk. Wildfires constitute the most severe abiotic disturbance in the Mediterranean forest ecosystems. Although fire is an integral part of these ecosystems (Pausas *et al*., 2006), its frequency, duration and severity have significantly increased during the last decades (Fernandez-Anez *et al*., 2021). The prevailing burning conditions (fuel, weather, topography) under which a wildfire occurs synthesize the pyric environment that influences fire behaviour and suppression tactics (Dimitrakopoulos *et al*., 2011).

In Southern Europe, the Mediterranean-type climate with the prolonged dry and warm summer period, the flammable vegetation, the complex topography, as well as human activities, favors both the ignition and the spread of wildfires. Furthermore, warmer and drier conditions in the Euro-Mediterranean region are expected over the next decades under future climate projections (Cos *et al*., 2022; Hysa *et al*., 2021; Hysa & Spalevic, 2020; Zittis *et al*., 2019; Nemeth, 2015). Hence, there will be increases in fire extent, intensity and duration of the fire season (Amatulli *et al*., 2013; Mitsopoulos *et al*., 2016; Kotroni *et al*., 2020) leading to an increased likelihood of large wildfires, known as megafires.

Megafire is called an extraordinary fire that devastates a large area. They are notable for their physical characteristics including intensity, size, duration, and uncontrollable dimension, as well as their social characteristics, including suppression cost, damages and fatalities (Buckland, 2019). Megafires are not always a single wildfire, but sometimes a grouping or "complex" of inter-acting multiple fires across a large geographic area (Williams *et al*., 2011). However, there is no single, consistent, quantitative definition of a megafire. In Europe, they are characterized as beginning at 1,000 hectares (ha), in size, while in the United States beginning at 10,000 ha. Disastrous megafires events have been reported in the recent history of Greece. The fire of August 2007 in Peloponnese (South Greece) resulted in a loss of 84 human lives and 177,000 ha of burned area (Gitas *et al*., 2008), the biggest number of burned area among European countries (San-Miguel-Ayanz *et al*., 2013). Additionally, in July 2018 (Eastern Attica), Greece experienced the deadliest event ever (102 casualties) which burned approximately 1250 ha (Lagouvardos *et al*., 2019). Another ecological disaster was the megafires that occurred in Greece during the 2021 summer period, where multiple fire events burned a total area of almost 100.000 hectares, setting a new tragic record in the country's history (Papadopoulos *et al*., 2021).

It is well known fact that the land use change leads to changes in hydrologic response, soil erosion, and sediment dynamics characteristics (Spalevic *et al.*, 2021; Kuriqi & Hysa, 2021; Spalevic *et al.*, 2020; Spalevic *et al.*, 2013). Wildfires are taking significant part in this. In the aftermath of wildfires, significant changes occur on hydrological and erosion regimes (Shakesby 2011; Efthimiou *et al*., 2020; Curovic *et al*., 2021; Lecina-Diaz *et al*., 2021; Soulis *et al*., 2021). This is mainly due to the complete or partial loss of vegetation that decreases water infiltration rate and water storage capacity while surface runoff increases. Except for the damages to plant communities, fire affects the texture and the physico-chemical properties of the surface soil layer, turning it into a hydrophobic layer and thereby leading to higher soil erosion rates (Kokaly *et al*., 2007; McGuire and Youberg, 2021).

Quantitative soil erosion assessment in fire-affected areas is a crucial tool for policymakers to evaluate the magnitude of post-fire erosion risk and implement mitigation measures, such as emergency hillslope rehabilitation treatments and watershed stabilization measures (Myronidis and Arabatzis, 2009; Robichaud and Ashmun, 2012). The ever-growing availability of high-resolution earth observation data and the well-established use of geospatial technologies facilitate the large-scale quantitative analysis of soil erosion, in a short period.

During the last decade, Greece has experienced large-scale wildfire phenomena with unprecedented fire behaviour and impacts (Kalabokidis *et al*., 2015). The present study aims to quantify the erosion dynamics changes immediately after the megafires in 2021 over Greece. The analysis was not limited to a single event, but multiple destructive wildfires were studied. To that end, pre-fire and post-fire erosion dynamics were assessed, exploiting the combined use of freely EO data and the RUSLE model.

MATERIAL AND METHODS

The study was conducted in selected fire-affected areas of Greece territory from the destructive megafires in 2021. The analysis included the areas that suffered the greatest ecological disaster with burned areas of more than 5.000 ha. The location map of the selected megafires and the associated burned areas are given in the following figure (Figure 1).

Figure 1. The location map of the selected megafires over Greece in 2021: i) Northern Evia, ii) Varympompi (Attica), iii) Vilia (Western Attica), iv) Schinos (Corinthia – West Attica), v) Ancient Olympia - Gortynia (Ilia) and vi) Gytheio (Laconia).

The spatial extent of the burned areas was retrieved from the Copernicus Emergency Management Service (EMS)[2]. This service consists of the on-demand and fast provision (hours-days) of geospatial information in support of emergency management activities immediately following a disaster. The service is based on the acquisition, processing and analysis, in rapid mode, of satellite imagery and other geospatial raster and vector data sources. Analytical details of the start date and the burned area (ha) for the selected wildfire events based on the EMS data are given in the table (Table 1).

Table 1. Characteristics of the wildfire event based on EMS rapid mapping activations

A/A	Location	Start Date	EMS (Act. Code)	Burned Area (ha)
i	Northern Evia	03/08/2021	EMSR527	51245
ii	Varympompi (Attica)	03/08/2021	EMSR527	8454
iii	Vilia (Western Attica)	16/08/2021	EMSR540	10175
iv	Schinos (Corinthia – West Attica)	19/05/2021	EMSR510	7005
v	Ancient Olympia - Gortynia (Ilia)	04/08/2021	EMSR528	18400
vi	Gytheio (Laconia)	03/08/2021	EMSR531	11209

RUSLE Model

According to the various reports of the European Soil Bureau Institute for Environment and Sustainability and the European Environment Agency, the Universal Soil Loss Equation model (USLE) is extensively used in the following European countries: Austria, Bosnia, and Herzegovina (including the Republic of Srpska), Bulgaria, Greece, Italy, Hungary, Norway, Romania, Slovakia, Finland, Czech Republic, Spain, and Switzerland. The Revised Universal Soil Loss Equation (RUSLE) is used in Belgium; the UK, Germany, and France are using their domestic/national models (Spalevic *et al.*, 2019). In the countries of Balkan Peninsula, the Erosion Potential Method (EPM) for mapping the intensity of water erosion is the preferred model (Volk *et al.*, 2009; Spalevic, 2011; Kostadinov *et al.*, 2018; Gocic *et al.*, 2020; Tosic *et al.*, 2019; Nikolic *et al.*, 2021), and recently Globally the IntErO model, based on the EPM (Sabri *et al.*, 2019; Chalise *et al.*, 2019; Sakuno *et al*., 2020; Ouallali *et al.*, 2020; Mohammadi *et al.*, 2021).

In this research we used the revised (R) Universal Soil Loss Equations (USLE), known as RUSLE, is an empirical model that computes mean annual soil loss by sheet and rill water erosion (Renard *et al.*, 1991). The mathematical description of the model is expressed as a linear combination of five factors, related to climate, topography, vegetation cover, pedology and land management (Lense *et al.*, 2021).

The equation is presented as following:

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[2] https://emergency.copernicus.eu/mapping/list-of-activations-rapid

$$A = R \times K \times LS \times C \times P \quad (1)$$

where A is the computed annual soil loss (t ha^{-1} y^{-1}), R is the rainfall erosivity factor (MJ mm ha h^{-1} y^{-1}), K is the soil erodibility (t ha h ha^{-1} MJ^{-1} mm^{-1}), LS is the combined effect of slope length (L) and slope steepness factor (S) (dimensionless), C is the cover management factor (dimensionless) and P is the conservation practice factor (dimensionless).

In the current approach, the RUSLE model was implemented in a GIS framework using open available geospatial data. These datasets include gridded precipitation, satellite imagery, and digital elevation model (DEM) and soil properties. The data were organized in GIS thematic layers. Subsequently, the determination of each factor during the implementation of the soil loss model is described in the following sub-sections. The conservation practice factor was not considered in this study and a constant value equal to 1 was assigned to each case study. This was done for two reasons. Firstly, there were no reliable available data to define its values. Secondly, the conservation practices (P-factor), including contour farming, stone walls and grass margins has profound effects on cropland and rangeland. However, these types of practices are generally limited in forest ecosystems, as the examined burned areas.

The footprint of megafires on erosion dynamics was achieved by comparing the RUSLE values before and after the vegetation destruction from the fire events.

Rainfall Erosivity Factor (R)

The rainfall erosivity factor (R) is the model's climate component, accounting for the effect of rainfall amount and intensity on soil loss. It is defined as the average annual sum of the kinetic energy of storm events having a maximum rainfall intensity of 30 minutes. However, sub-hourly rainfall rate records from ground-based meteorological stations are rarely available in Greek territory. Therefore, in the present study average monthly precipitation data from the CHELSA (v2.1) dataset (Karger *et al*., 2017) for the period 1979-2018 were used. CHELSA (Climatology at high resolution for the earth's land surface areas) is a very high resolution (30 arcsec, ~1km) global downscaled climate data set currently hosted by the Swiss Federal Institute for Forest, Snow and Landscape Research WSL. It is built to provide free access to high-resolution climate data for research and application, and is constantly updated and refined.

To calculate the annual R-factor, a simplified mathematical equation developed by Arnoldus (1980) was applied. The mathematical description of the formula is given below:

$$R = \sum_{i=1}^{12} 1.735 \times 10^{\left(1.5 \log\left(\frac{P_i^2}{P}\right) - 0.08188\right)} \quad (2)$$

where R is the rainfall erosivity factor (MJ mm ha h^{-1} y^{-1}), P_i is the monthly rainfall (mm) and P is the annual rainfall (mm).

Soil Erodibility Factor (K)

The soil erodibility factor describes the susceptibility of soil types to detachment and transport as a result of the raindrop and runoff process. It depends on physical and chemical soil properties such as soil texture (contents of silt, sand, clay, and organic carbon), permeability, shear strength, organic matter and chemical composition. The K factor is rated on a scale from 0 to 1, where lower values indicate soils less prone to erosion.

Herein, the K-factor was estimated according to the Renard *et al* (1997) approach based on the soil's sand, silt and clay contents. The necessary data were retrieved in raster format from ISRIC-World Soil Information SoilGrids250m dataset (Hengl *et al* 2017) with a spatial resolution of 250m. Soil grids is a system for digital soil mapping based on a global compilation of soil profile data (WoSIS) and environmental layers using machine learning techniques. Afterward, the following mathematical equations were used to estimate K-factor in each grid cell:

$$K = 7.594\left\{0.0034 + 0.0405 \times \exp\left[-0.5\left(\frac{\log D_g + 1.659^2}{0.7101}\right)\right]\right\} \quad (3)$$

$$D_g = \exp\left(0.01 \sum f_i \ln m_i\right) \quad (4)$$

where K is the soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1}), D_g is the geometric mean particle diameter (mm), for each size class (clay, silt, sand), f_i is the primary particle size fraction in percent and m_i is the arithmetic mean of the diameter limits for each particle size class (mm) based on the USDA classification.

Topographic factor (LS)

The combination of slope length (L) and slope steepness (S) individual factors describe the effect of topography on the erosion process. The slope length is the distance from the origin of overland flow along its flow path to the location of either concentrated flow or deposition, while slope steepness is the segment or site gradient slope, expressed as a percentage. The higher values of LS-factor represent steeper relief, where erosion and sediment yield increase due to an increase in the runoff.

The LS-factor was calculated in the System for Automated Geoscientific Analyses (SAGA) GIS software package which incorporates the multiple flow algorithm (Pilesjö and Hasan, 2014). In this module, a digital elevation model (DEM) is required as an input parameter for the calculation of the LS-factor. The FABDEM (Forest and Buildings removed Copernicus DEM) was selected for this analysis. This is a global DEM at 30 m grid-spacing, with artefacts from forests and buildings removed (FABDEM). FABDEM has notable benefits compared to existing global DEMs, resulting from the use of the new Copernicus GLO-30 DEM and a machine learning correction of forests and buildings. This makes it preferable for many purposes where a bare-earth representation of terrain is needed (Hawker *et al*., 2022).

The S-factor is calculated, considering the slope gradient, in degrees (ϑ) based on the mathematical equation provided by McCool *et al.* (1989)

$$S = \begin{cases} 10.8 \times \sin\vartheta + 0.03, \vartheta < 0.09 \\ 16.8 \times \sin\vartheta - 0.5, \vartheta > 0.09 \end{cases} \quad (5)$$

Regarding the L-factor, it is calculated using the proposed equation by Desmet and Govers (1996). This approach takes into account that the slope steepness is not uniform for the whole area and introduces the concept of the unit-contributing area. The mathematical formula given below:

$$L = \frac{(A_{i,j-in} + D^2)^{m+1} - A_{i,j-in}^{m+1}}{D^{m+2} \times x_{i,j}^{m} \times 22.13^{m}} \quad (6)$$

where $A_{i,j,-in}$ is the contributing area (m^2) at the inlet of grid pixel (*i*,*j*), D is the grid pixel size (m), $x_{i,j}$ is the summation of the sine and cosine of aspect direction ($\alpha_{i,j}$) of grid pixel ($x_{i,j} = \sin \alpha_{i,j} + \cos \alpha_{i,j}$), and *m* is a coefficient related to the ratio β of the rill to inter-rill erosion. The *m* values range between 0 and 1 and ϑ is the angle of slope in degrees. The equation for the *m* coefficient is:

$$m = \frac{\beta}{\beta + 1} \quad (7)$$

$$\beta = \frac{\frac{\sin\vartheta}{0.0896}}{[0.56 + 3 \times \sin\vartheta^{0.8}]} \quad (8)$$

Cover Management Factor (C)

The C-factor reflects the effect of surface cover and cover management practices on erosion rates. It is defined as the ratio of soil loss from a certain area with specific vegetation coverage to a constantly barren region. The C-factor ranges between 0 and 1, while the lowest values indicate the well-protected land.

There are several methods in the literature for calculating the C-factor using vegetation indices derived from satellite images (Phinzi and Ngetar, 2019). The most well-known approaches analyzed the linear correlation between C-factor and NDVI (Van der Knijff *et al*., 2000; Durigon *et al*., 2014). Also, the NDVI is sufficient for change detection (Polykretis *et al*., 2020; Tariq *et al*., 2021). The NDVI was calculated considering the near-infrared (NIR) and red (RED) spectrums of a multispectral satellite image using the following mathematical formula:

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (9)$$

Subsequently, the following equations were used to calculate the C-factor based on NDVI vegetation index.

$$C = \exp\left[-\alpha\left(\frac{NDVI}{\beta - NDVI}\right)\right] \tag{10}$$

where a and b are unitless parameters and equal to 2 and 1, respectively. The C-factor ranges from 0 to 1, with closeness to 0 indicating well-protected land.

NDVI index derived from Sentinel-2A imageries, which provides optical data with atmospheric and radiometric corrections. The spatial resolution on the red (RED) and near-infrared (NIR) spectral bands that are required for the NDVI calculation has a spatial resolution of 10 m. In the current approach, pre-fire and post-fire Sentinel-2A images (single-date) were obtained for each fire event. The images were acquired from the European Space Agency (ESA) Copernicus Access Hub (https://scihub.copernicus.eu) and a universal cloud coverage threshold <10% for all the images was used. Dates of the selected images per fire event can be seen in the next table (Table 2).

Table 2. Dates of the Sentinel 2-2A imageries per fire event.

Fire event	**Sentinel-2 image pre-fire**	**Sentinel-2 image post-fire**
Northern Evia	1/8/2021	18/8/2021
Varympompi (Attica)	3/8/2021	8/8/2021
Vilia (Western Attica)	28/7/2021	26/8/2021
Schinos (Corinthia - West Attica)	13/5/2021	23/5/2021
Ancient Olympia - Gortynia	2/8/2021	17/8/2021
Gytheio (Laconia)	1/8/2021	11/8/2021

RESULTS AND DISCUSSION

The erosion prediction model of RUSLE was implemented in a GIS environment under pre-fire and post-fire conditions for the selected natural ecosystems. Unfortunately, no actual measurements are available to validate the model's accuracy. However, the performance of RUSLE in quantifying soil loss rate has been found to be satisfactory in the neighbouring Mediterranean basin (Efthimiou, 2016; Napoli *et al*., 2016; Porto *et al*., 2022). Significant changes in erosion dynamics were found in the fire-affected areas (Figure 2). It is worth noting that the soil loss rate in the most pre-fire case was quite low. On the contrary, the megafires increased potential erosion by nearby 10 times compared to the pre-fire conditions. Particularly, the magnitude of the erosion dynamic changes, expressed in t ha^{-1} y^{-1}, was equal to +98.5, +65.9, +57.0, +56.3, +51.6 and +35.6 for the Gytheio, Schinos, Northern Evia, Ancient Olympia – Gortynia, Vilia and Varympompi region respectively. Similar increases in the post-fire erosion potential have been documented in Mediterranean ecosystems (Mallinis *et al*., 2009; Myronidis *et al*., 2010).

Subsequently, the obtained values of soil loss were grouped into six classes according to the Reneuve and Galevsky (1955) classification scheme. This classification approach is effective for the identification of areas threaten by accelerated erosion (Myronidis *et al*., 2010).

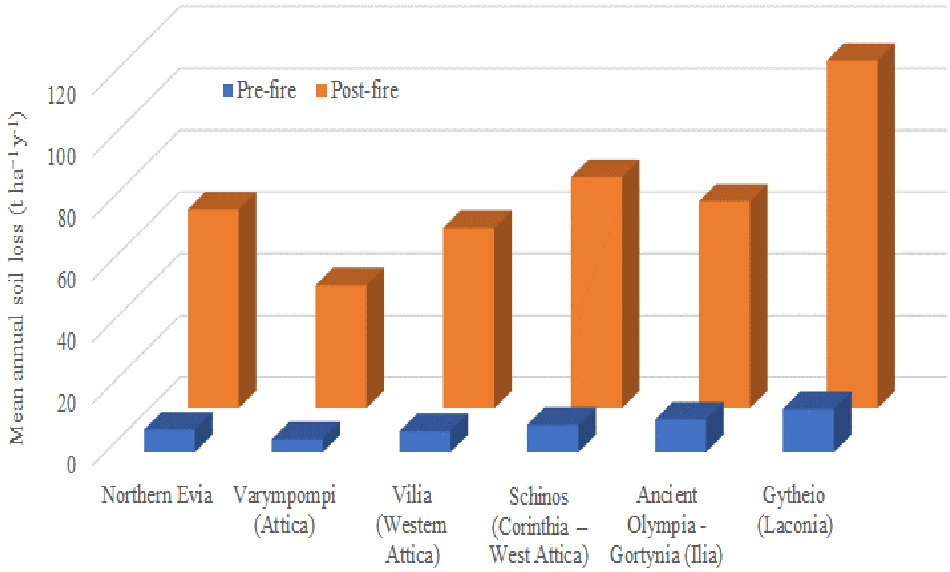

Figure 2. Soil loss rate in the study areas under each condition

The erosion hazard classes and their corresponding break values (t ha^{-1} y^{-1}) are as follow: Very Low (<5), Low (5-12), Moderate (12-50), Severe (50-100), Very Severe (100-200) and Extreme (>200). In the pre-fire scenario, all the examined areas had very low and low erosion hazard for more than 70% of their entire area. On the contrary, severe, very severe and extreme hazard classes are negligible except in Laconia, where they account for around 6.5% of the total area. The coverage distribution of the erosion hazard classes is directly affected by the megafires. In general, there was a transition from very low and low hazard (pre-fire) to severe and very severe (post-fire). Additionally, a remarkable rise in the moderate and extreme hazard classes has been noted. Detailed results on the coverage rates for each erosion hazard class category, between the pre-fire and post-fire conditions, are presented in the next figure (Figure 3).

The analysis highlighted the footprint of the 2021 megafires on erosion regulation ecosystem service. Beyond the numerical statistics concerning soil loss rate, the spatial mapping of erosion dynamics provides critical information to policymakers. These maps could be a useful tool for selecting the appropriate erosion mitigation strategy. The emergency hillslope rehabilitation treatments and watershed stabilization measures could be determined in a cost-effective way based on the identified erosion prone areas, proximity to the stream network and settlements, and geomorphological conditions. The spatial distribution of erosion hazard after the megafires events were given in the following figure (Figure 4).

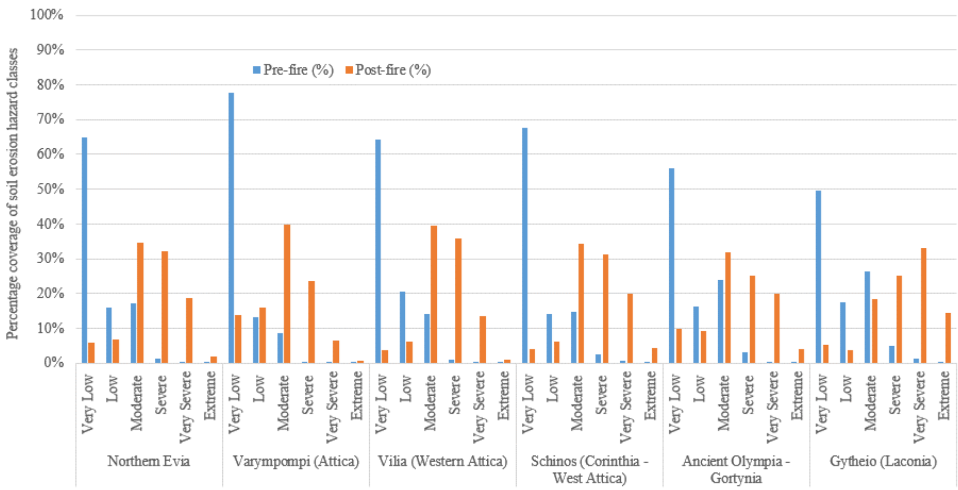

Figure 3. Erosion hazard classes coverage rate in the examined areas

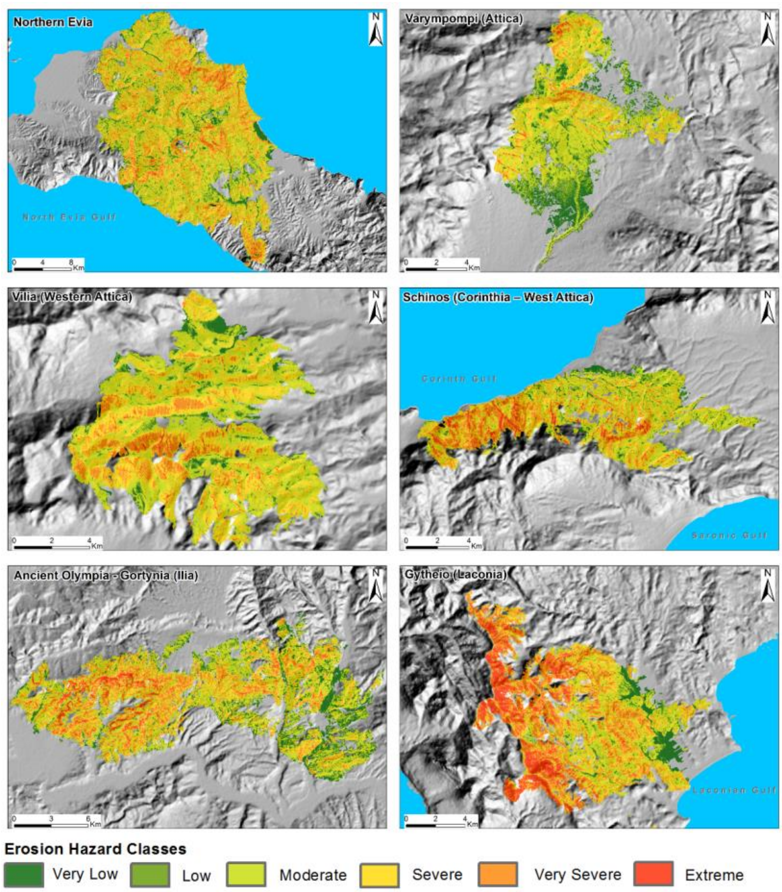

Figure 4. Post-fire erosion hazard mapping in the fire-affected ecosystems

CONCLUSION

This paper quantifies the spatiotemporal changes in soil erosion dynamics driven by Greece's megafires in 2021. Our approach integrates freely accessible EO data and the empirical RUSLE model for the estimation of the potential soil loss. Aside from its practical usefulness, the proposed methodology is simple, easy to use, has minimal input data requirements and low computational demands. To that end, quantitative and spatial distribution of erosion hazard was achieved at high spatial resolution. The developed methodology can easily transfer to any region and scaled at national or even Pan-European level.

Significant increases in soil loss rates have been reported in fire-affected regions, based on a comparison of pre-fire and post-fire RUSLE model outputs in each case. The investigation also highlighted the footprint of multiple destructive fire occurrences on natural ecosystems' erosion regulation services. Furthermore, the produced erosion hazard maps provide helpful information for identifying the erosion prone areas. It may also be employed by policymakers for targeted management and planning of post-fire erosion mitigation strategy. Controlling accelerated erosion following wildfires is a primary concern for stabilizing soils and enhancing natural regeneration in Mediterranean pinewoods. Future research could focus on the development of an automated workflow for the spatial determination of emergency erosion control works based on the previously described erosion hazard maps.

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