Targeted placement of soil erosion prevention works after wildfires

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Abstract. Anthropogenic activities and climate change have accelerated soil erosion in the Mediterranean. In the region, erosion rates are further exacerbated due to frequent wildfires and flash floods. Soil bioengineering works and nature-based solutions need to be placed in targeted areas to provide the greatest erosion control in the burnt areas. The purpose of this study was to provide a targeted approach by utilizing spatial software along with field measurements to place optimally soil erosion prevention works. Specifically, the Gavrilovic soil erosion equation was implemented within the Geographical Information System (GIS) to estimate the areas of greatest erosion potential. The study area was Prinos Watershed of Thasos Island in Greece that was burnt in the summer of 2017. To run the soil erosion equation in GIS, different layers of data were collected or developed. Visual field measurements were taken to estimate the erosion potential factor. The results indicated the areas with the greatest soil erosion and allowed to pinpoint the location for the soil bioengineering works. The recommended works were wooden dams and log erosion barriers. This method could be used by the Greek Forest Service to promote the sustainable restoration of burnt areas.

1. Introduction
Agriculture, deforestation, urbanization and other anthropogenic activities have significantly increased soil erosion rates in the last two-three centuries [1]. This increase has led to soil loss rates, today, that are 10–40 times greater than the natural rates [2] and have led to the degradation of the landscape. Soil loss and degradation are considered, today, threats with potential impacts as severe as climate change, to human societies [3]. Nonpoint source pollutants from soil erosion have negative impacts on surface water bodies because they can: a) reduce water quality, b) degrade aquatic habitats, c) diminish recreational opportunities, and d) reduce reservoir storage [4, 5, 6]. Global and EU initiatives such as
“the Bonne Challenge”, “Convention on Biological Diversity” and “Water Framework Directive” have been developed and are being implemented to accomplish the UN’s Sustainable Development Goals in order to prevent soil loss and landscape degradation, restore these degraded areas and minimize nonpoint source pollutants from reaching water bodies [7].

The Mediterranean region is one of the most sensitive in Europe, to soil degradation and land desertification [8]. The semi-arid climatic conditions, the frequent wildfires and the existence of civilizations for thousands of years in the region, are the reason why it is so susceptible to erosion [9, 10]. Many plants of the Mediterranean ecosystems have adapted to wildfires that act as an evolution trigger mechanism, which is necessary for their survival. Unfortunately, after wildfires, the bare landscape along the steep slopes of the region is extremely prone to the autumn and winter rains and create intense erosion and floods, which can even cause the appearance of the parent material [11]. To achieve the restoration of these burnt areas, sustainably, cost-effective measures need to be implemented at large scales, that are environmentally friendly and based on ecosystem principles. Such a method, to reduce surface and stream erosion, is soil and water bioengineering that recently, in the scientific community, is widely accepted and adopted [12].

Climate change is increasing temperatures that will lead to higher intensity and more frequent wildfires, within the Mediterranean region. Extended periods of drought, particularly towards the end of the dry period (summer), lead to catastrophic wildfires that are one of the major natural disturbances of the region [13]. In Greece, the increase of the frequency and intensity of wildfires, in the last decades, has brought this problem to the forefront. The Greek Forest Service recorded, for the period from 1983 till 2006, that there were 38085 forest fires and 13613121 acres burnt during these fires. The main culprits were the intense dry climate, during the summer period, along with the increased accumulation of the understory biomass, as a result of poor forest management and decreased agricultural activities in rural areas [14].

In Greece, researchers and authorities, typically at the local level, have studied soil erosion but a holistic national management plan is required that should incorporate climate change implications [15]. To mitigate soil erosion sustainably, Europe needs to establish a common policy and a monitoring system, particularly for Greece and other countries of the Mediterranean region [15]. The purpose of this study was to design a targeted approach in the implementation of bioengineering works to reduce soil erosion after wildfires. Targeted approaches have been quite successful in reducing soil erosion, because by placing conservation measures in the areas that produce the top 10% of sediment, 20% of the watershed stream sediments was reduced [16]. Specifically, a soil erosion equation within the Geographical Information System (GIS) was utilized to determine the areas that have the greatest risk to be eroded. This study focused on Prinos Watershed of Thasos Island in Greece whose majority was burnt in the summer of 2017.

2. Materials and Methods

2.1. Study Area
Prinos Watershed of Thasos Island (40° 34’-40° 48’ N, 24° 30’-24° 46’ E) was the study area. Thasos is Greece’s most northern island and it belongs to Eastern Macedonia Region (Figure 1a). Since the 1980s the island has experienced multiple catastrophic wildfires [11]. The climate of the island is considered as hot-summer Mediterranean along the coasts and as warm-summer Mediterranean in the inlands. The mean annual temperature is 15.8°C, and the mean annual precipitation is 800 mm. The shape of the island is circular with the coastline length approximately 102 km. The area of the island is 378 km². The inland of the island has mountains with the highest peak reaching 1203 m. Emphasis was given to the Prinos Watershed (Figure 1b) because most of the watershed was burnt in August of 2017 (Figure 1c). Finally, it must be noted that, in many cases, many of the wildfires start as a result of human actions.

2.2. Gavrilovic Equation
The Gavrilovic formula was preferred to calculate the amount of sediment for the following reasons:
The Gavrilovic method is a semi-quantitative model based on empirical data [17].
Field research measurements were utilized to develop the method.
The method has been successfully implemented to estimate surface and torrent erosion in the Balkans.

The description of the Gavrilovic equation follows:

\[ W = T \times P \times \pi \times \sqrt{Z^3} \times F \]

- \( W \) = annual eroded soil (m\(^3\) yr\(^{-1}\))
- \( T \) = coefficient of temperature, given by \( T = \sqrt{\frac{t^0}{10}} + 0.1 \)
- \( t^0 \) = average annual temperature (°C)
- \( P \) = average annual precipitation (mm)
- \( Z \) = coefficient of erosion, given by \( Z = Y \times X \times (\Phi \times \sqrt{J}) \)
- \( F \) = study area (km\(^2\))
- \( Y \) = coefficient of soil erodibility
- \( X \) = coefficient of soil protection
- \( \Phi \) = coefficient of erosion type and extent
- \( J \) = mean slope of the study area (%)

**Figure 1.** a) Prinos Watershed of Thasos Island was the study area (red line). b) A close up of the Prinos Watershed with its contour lines (black lines) and hydrologic network (blue lines). c) A close up of the burned area in the summer of 2017 (green area).

2.3. Field Measurements
Field measurements were taken, primarily to be able to estimate the coefficient of erosion (\( Z \)) used in the Gavrilovic equation. Specifically, in sixty different points (Figure 2), the coefficient of soil protection (\( X \)) and the coefficient of the erosion type and extent (\( \Phi \)) were estimated. The coefficient \( X \) of soil protection, when the point was considered completely bare received a value of 1, while, when the point was considered completely covered with vegetation the coefficient \( X \) received a value of 0.
For the coefficient \( \Phi \) of the erosion type and extent, signs of recent erosion and/or rilling were investigated. When extensive rilling was present it received a value of 1. Finally, the coefficient \( Y \) of soil erodibility was determined based on the geology maps of the island. In addition, for each point, a GPS was used to have the exact coordinates of the sampled locations. Having the coordinates would allow the easy transfer of these data into GIS.

Figure 2. The 60 field measurement points within the Prinos Watershed boundary.

2.4. Gavrilovic Equation in G.I.S.
The topographic map of Thasos had a 1:50000 scale, originated from the Army Geographic Service and was inserted and geo-referenced in the ESRI’s ArcGIS 10.2.2 software environment. The projection system was defined as the Greek Geodetic Reference System of 1987 (EGSA 87), which has been used in practice in Greece since 1989.

Afterwards, the following layers were digitized:
- 20-meter contour lines (line feature)
- Hydrographic network (line feature)
- Watershed boundary (line feature)
- Watershed area (polygon feature)
- Vegetation cover based on satellite images (polygon feature)

In addition, the following data were inserted:
- Type and extent of erosion, revegetation present (point features)
- Precipitation and temperature data from weather of Thasos (point features)
- Geologic map of Thasos (polygon features)

Based on the contour lines, the Digital Elevation Model (DEM) was created. The DEM and the other layers were used within the Raster calculator to run the Gavrilovic equation. The equation was run for each pixel, and based on the values of the parameters of the equation, the annual eroded soil \( W \) was calculated for each pixel. The different stages of the methodology are shown in Figure 3.
3. Results and Discussion

The map in Figure 4 shows the annual erosion that is expected in Prinos Watershed after the wildfire. For the entire watershed, annual losses of 97059 m$^3$ yr$^{-1}$ were expected although all areas were not contributing the same amounts. Specifically, some pixel areas (Figure 4), whose dimensions where 103 m by 103 m, had expected erosion rates as low as 0.8 m$^3$ yr$^{-1}$ while others had as high as 571.5 m$^3$ yr$^{-1}$. This clearly indicates that some parts of the watershed will contribute larger amounts of sediments during erosional events and should be prioritized. These are the areas that should be targeted and soil bioengineering works should be implemented.

Typically, after wildfires, because of the availability of wood (burned trees), log erosion barriers and wooden dams are utilized by the Greek Forest Service (Figure 5). Based on the erosion map (Figure 4) and our field measurements, seven wooden dams and approximately 12 km of log erosion barriers were recommended (Figure 6). The log erosion barriers are located in the area with the highest erosion. In regard to the wooden dams, four are located in the area with the highest erosion, while the other are upstream to reduce the stream water velocity of the sub-watersheds. Log erosion barriers are concentrated in the areas in which we expect the most surface erosion.
Figure 4. Annual eroded soil (m$^3$/yr) in Prinos Watershed of Thasos Island based on the Gavrilovic equation that was run in GIS.

Figure 5. Typically, wooden dams (right) and log erosion barriers (left) are used after wildfire to reduce sediment transport capacity.

4. Conclusions
Utilizing GIS and quick field measurements based on the Gavrilovic equation, highlights the areas that have the greatest erosion potential. This allows implementing targeted approaches of soil bioengineering works, reducing the decision-making time for their placement and results in the most cost-effective way to reduce soil loss after wildfires. This could be a great tool for the Greek Forest Service that would help in the faster recovery of the ecosystems after wildfires. Of course, for the final location of the bioengineering works, an additional field visit and assessment is required. Finally, the visualization of the areas of erosion and the location of bioengineering works would be attractive to decision makers and the general public that would make these works more easily adopted and accepted.
Figure 6. The recommended location of wooden dams and log barriers based on soil loss map of Prinos Watershed of Thasos Island.

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