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Article

The Footprint of Wildfires on Mediterranean Forest Ecosystem Services in Vesuvius National Park

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Abstract: Wildfires are one of the most important natural disturbances in vegetation biomes. In recent decades, both the number and severity of fires have significantly increased in Mediterranean forests, frequently resulting in catastrophic events. In this scenario, we aimed to explore the flow of ecosystem services and their related economic value that was disrupted by human-induced megafires in the Mediterranean forest of Vesuvius National Park in the summer of 2017. We adopted an innovative approach by merging two methodologies: an ecological approach to evaluate the status of the forest ecosystem after the wildfires and an economics methodology to estimate the monetary value of the interruption to ecosystem services. Losses related to the following six services were estimated: woody biomass, soil erosion control, habitat maintenance, pollination, carbon stock, and ecotourism. In 2017, 3350 ha of forest (88% of the total forested area of Vesuvius National Park) burnt over a period of 49 days. The total estimated monetary loss amounted to €14.363 M, 56.9% of which comprised of provisioning ecosystem services, while 34.7% encompassed maintenance and regulation services, and 8.5% were so-called cultural services. Suppression costs accounted for 16% of the total estimated economic loss of ecosystem services. Our results provide useful insights for decision-makers when allocating financial resources, suggesting that they should invest in fire prevention rather than fire suppression and post-fire restoration. This explicit valuation of the footprint of the wildfires, although not exhaustive, can also lead to greater awareness among the public regarding the benefits conferred by Mediterranean forest ecosystems. This is the first study to economically evaluate the interruption of ecosystem services after megafires in the Mediterranean basin.

Keywords: burn; economic loss; Mediterranean pines; megafire; monetary values; protected area

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1. Introduction

Wildfires constitute the strongest natural disturbance in Mediterranean biomes in both space and time [1]. Although fire is an integral part of such ecosystems [2], in recent decades, both the number and severity of fires have significantly increased in the Mediterranean basin. While many southern European countries have experienced severe forest fire damage within the last 20 years, the year 2017 was particularly extreme. Huge areas were affected by fires in several Mediterranean countries [3], and human lives were also lost, e.g., in Portugal, 112 forest-fire-related deaths were recorded in 2017 [4]. Against this background, this study investigates the ecological and economic consequences of the 2017 summer fire events in Vesuvius National Park in southern Italy, when several human-induced wildfires occurred (Figure 1), involving an extensive forest area of approximately 3350 ha.

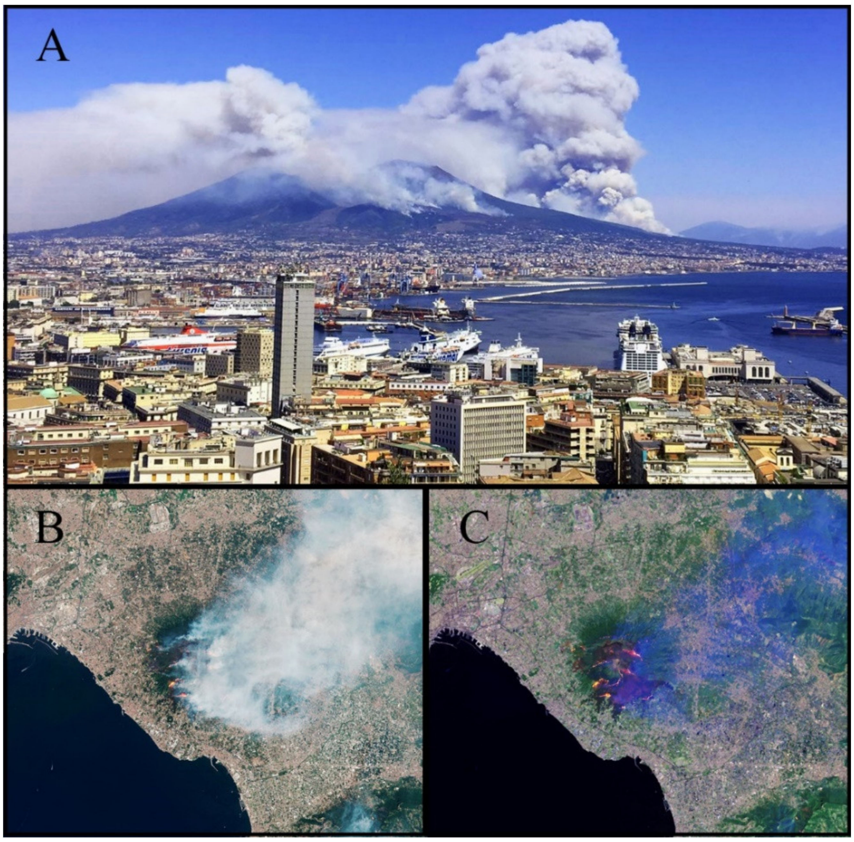

Figure 1. Forest fires in Vesuvius National Park on 12 July 2017. (**A**) Photograph courtesy of Caroline von der Tann, taken from the Bay of Naples. (**B**,**C**) Modified (cropped) remote-sensing images from Copernicus Sentinel data (2017), processed by ESA, CC BY-SA 3.0 IGO.

In ecological terms, as a disturbance, a wildfire can be considered "*a relatively discrete event in time that disrupts [the] ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment*" [5]. From an economic perspective, a wildfire can be defined as "*an event that interrupts or impedes the flow of goods and services provided by forest ecosystems that are desired by people*" [6].

The Mediterranean basin is characterised by climate seasonality, and the native vegetation is adaptive and prone to fire, which plays a leading role in preserving ecosystem health and stimulating rejuvenation [7]. Nevertheless, each ecosystem is adapted to a specific fire regime, defined as the spatio-temporal occurrence patterns and ecological impacts of fire on the ecosystem; when the fire regime deviates from expected patterns, the resilience of the ecosystem to fire may be exceeded [8]. In this regard, the word "megafire" was coined to describe particularly extensive, severe fires in North America [9]. The EU MEGAFIREs project (https://cordis.europa.eu/project/rcn/31836/factsheet/en) (accessed on 18 March 2020) proposed a threshold of 500 ha for Europe. However, because of the differences in landscape characteristics worldwide, it is not feasible to establish a universal fixed-size threshold of burnt surface area to define a megafire [10]. Although such a metric does not, in itself, provide a clear and complete description of the wildfire regime, we consider it a good proxy to discriminate, in a specific landscape, a wildfire that has assumed extreme characteristics (i.e., fire intensity and severity, size, frequency, etc.) [11].

Once a large wildfire has been defined, the challenge is to quantify the effects of the fire on the disruption of forest ecosystem functions. The assignment of "value to ecology" is a cross-disciplinary and controversial concept, being differently interpreted by ecologists, natural scientists, and economists [12–15]. Despite this, the study of post-fire ecosystem conditions and the related disruptions in ecological processes represents the first step in translating the loss of biophysical supply service into the loss of benefits to people, thereby assessing the associated value of the ecosystem service (ES) benefits in areas affected by fire [11]. Forest ecosystems provide a suite of ESs for human well-being, which can provide them with economic value [14,16]. The challenge of ES evaluation lies in the absence of a market for some such goods. To address this, current theories are founded on both economic and non-economic methods [17]. These insights have implications in the decision-making process of post-fire vegetation restoration and for future economic resource allocation, encouraging investment in the prevention, rather than the suppression, of fires.

Although large wildfires simultaneously impact the biotic and abiotic components of ecosystems, loss of human life, suppression costs, and direct damage to infrastructure receive the most media attention and capture most of the information flow [18–20]. Thus, a quantitative description of fire effects could lead to a better understanding of wildfires by urban populations, who often have a negative perception of wildfires based on incomplete media information [18,19,21], and help the decision-makers and managers of forest areas to select optimal pre- and post-fire actions. Therefore, beyond the mere costs of fire suppression, it is also critical to consider the value lost in terms of depleted ES supplies.

The aim of the present study was to quantify the impact of ES losses immediately after the large wildfires that occurred in the Mediterranean forests of Vesuvius National Park in the summer of 2017. Starting with a spatial assessment of the wildfire effects, the lost ES value was spatially computed by merging economics, ecological, and forestry methodological approaches. Within this framework, we specifically investigated whether: (A) the multiple wildfire events that occurred in Vesuvius National Park can be classified as a megafire; (B) ES delivery losses vary spatially according to the burn severity and the forest community's resilience to wildfires; and (C) ES delivery losses are economically more consistent than suppression costs. We hypothesised that mixed-severity megafires amplify the spatial variability in ES losses, according to both the burn severity and the recovery of Mediterranean forest communities to wildfire disturbances. Finally, we propose appropriate post-fire management actions aimed at both re-establishing the safe functioning of the park and increasing the biodiversity and fire resilience of the forests.

2. Materials and Methods

2.1. Study Area

Vesuvius is a stratovolcano in continental Europe that has been active for the past 25,000 years and is still active [22]. Vesuvius National Park was officially established in 1995 (National Law n. 394/1991) to preserve and promote the geological singularities and biological communities in the area. Currently, this volcano is an iconic symbol of the Bay of Naples and a "green lung" in one of the most urbanised and densely populated areas of Italy. Moreover, the shrubland and forest canopy cover of the volcano slopes offer effective protection against hydrogeological hazards. The native vegetation on the slopes of Vesuvius was recurrently destroyed by eruption events, the last one occurring in 1944, and in many cases, it was replaced by plantations of alien trees and shrubs.

The Vesuvian landscape is characterised by a great variety of land use, including volcanic geo-sites (lava fields and cones), forest, farmland, and high-density urban areas. The park forests cover an area of 3800 ha. The pre-fire forest vegetation was dominated by pure and mixed broadleaved stands (1542 ha) and even-aged monospecific and mixed coniferous stands (1504 ha), followed by shrubland (754 ha). The stone pine (*Pinus pinea*) is the most abundant planted species and is locally mixed with other Mediterranean coniferous species (mainly *Pinus pinaster*). Some coniferous stands are currently listed as sites of community importance for Habitat 9540–"Mediterranean pine forests with endemic Mesogean pines" (https://eunis.eea.europa.eu/habitats/10235) (accessed on 18 March 2019).

2.2. Burn Severity and Megafire Determination

In fire ecology, severity is defined as the loss or destruction of above- and below-ground organic matter [23]. In Mediterranean landscapes, wildfires generate considerable spatial variation in burn severity owing to the heterogeneity of the physiognomy and forest community species. In the present study, severity was assessed using a remote-sensing bi-temporal approach, and the validation and accuracy of the resultant burn-severity estimation map are illustrated in Saulino et al. [24].

To determine whether the 2017 summer fire events can be described as a megafire, we applied the criterion that the fire must be >2 standard deviations above the average size of other fire events in a specific region during a specified period [25]. Statistical records of fires that occurred in the park from 1997–2017 were extracted from the reports of the Italian Ministry of the Environment [26] and integrated with missing 2016 data extracted from the National Geoportal (http://www.pcn.minambiente.it/mattm/en) (accessed on 22 November 2020).

2.3. Suppression Costs

Suppression costs were assessed by considering the number of interventions by both land and air personnel and their related vehicles involved in the 2017 wildfires. Effort data were provided by the Carabinieri Corps (Department of Forest Protection of Campania region), the average cost of specialised operators was obtained from SMA Campania (http://www.smacampania.info/) (accessed on 14 January 2019), and the average hourly costs of vehicles from Ciancio et al. [27]. For details, see Section S2 in Supplementary Material S1 and the related sheet 'suppression costs' in Supplementary Material S2.

2.4. Ecosystem Services, Beneficiaries, and Categorisation

To determine a partial spectrum of the economic footprint of the wildfires, we selected six ESs, based on the Common International Classification of Ecosystem Services [28], and associated them with the severity of the 2017 wildfires (Table 1). The monetary value of each selected ES was based on data retrieved during fieldwork (see Sections S3–S5 in Supplementary Material S1 and related Supplementary Material S2 for details). First, we determined the post-fire forest ecosystem status and the related processes disrupted by the fire, using fire severity as a proxy. Then, the losses of biophysical supplies were translated into monetary losses for each ES, and the social beneficiaries of each ES were also assessed [11]. The most suitable economic estimation method was selected for each ES, as detailed in Sections S3–S5 of Supplementary Material S1.

Table 1. Overview of different valuation methods and social beneficiaries used in the study for each ecosystem service, described according to Haines-Young and Potschin [28].

Ecosystem Services	Short Description	Method	Recipient
Provisioning	Biomass (i.e., timber and chips) for direct use or processing	Residual value	Local bio-based industry
Regulation and maintenance	Control of erosion rates and habitat restoration	Replacement price	Local inhabitants
	Pollination	Market price	Local tomato farms
	Carbon stock	Permit prices/Benefit transfer	Local inhabitants
Cultural	Physical and experiential interactions with the natural environment	Direct-use value	Local ecotourists

2.5. Provisioning Services

Woody Biomass

Woody biomass represents one of the main provisioning services of forests, and wildfires interrupt the wood products and ES delivered by unburnt forests. The magnitude of such biomass loss differs significantly according to the burn severity experienced by the vegetation communities. After wildfires, one point of near-consensus is the removal of scorched trees adjacent to roads and trails for safety reasons. Additionally, in severely burnt forest stands, in which restoration efforts are needed to re-establish the stand and protect the vulnerable soil substrate from erosion, the harvesting of burnt trees represents a mandatory management action (see also Section 2.6.1, below).

To evaluate above-ground woody biomass losses owing to burnt trees in moderate–high burn-severity areas, as reported by Saulino et al. [24], we considered the volume of trees extracted from the forests, selecting two wood products: timber and chips. The above-ground volume was assessed using 40 experimental plots in 2018, approximately one year after the fire events. Data on the market prices of the wood products were extracted from the web page of the Italian National Institute of Statistics (https://www.istat.it/en) (accessed on 14 January 2019), distinguishing between coniferous softwood (*Pinus* spp.) and broadleaf hardwood (i.e., *Quercus* spp.) assortments.

Roundwood volume losses were estimated by applying the stumpage price, defined using the residual value (RV) method [29,30]. To estimate the RV of the roundwood volume of the trees killed by the fire, we considered the cost of wood management operations, logging, harvesting, extraction, and transport to the roadside. Considering local market requirements, we evaluated chip RV for both coniferous and broadleaf stands and timber RV for only coniferous stands (see Section S3.1 in Supplementary Material S1 for details).

2.6. Regulation and Maintenance Services

2.6.1. Control of Erosion Rates and Habitat Restoration

A key forest function is the maintenance of suitable habitats for wildlife and biodiversity. Large wildfires generally result in major habitat loss or degradation, directly and indirectly affecting biotic communities and their activities. Moreover, as almost one million people live in the areas surrounding Vesuvius National Park, forests provide the volcano's slopes with the most effective protection against the hydrogeological hazards associated with the erosion-prone andic soils. If these crucial functions in regulating the water system inflow and outflow and maintaining slope stability are disrupted by fire [31], we are forced to find alternative solutions to guarantee the safety of the local population. Both habitat maintenance and erosion control are beneficial, and their restoration is costly.

The values of both habitat restoration and erosion-rate control were estimated by applying the replacement cost method [32]. In stands of *Pinus pinea* affected by high-severity wildfires, salvage logging is conducted because the species is unable to regenerate by seed after the fire and to ensure safe conditions in the most tourist-frequented areas of Vesuvius Park. Consequently, to ensure efficient restoration, a trusted bioengineering technique, coupled with the planting of native shrub and tree species, was chosen to restore hydrological functionality and the forest habitat simultaneously. Owing to their multiple interconnected functions, the estimation of these two ESs were pooled. A major constraint in vegetation restoration was the presence of Habitat 9540, as the ancient Mediterranean *P. pinea* plantations needed to be restored. Therefore, in our case, planting *P. pinea* in open stands, mixed with native evergreen sclerophyllous Mediterranean trees and shrubs and sub-Mediterranean deciduous tree species, is mandatory. Implementation and maintenance costs were obtained from the official environmental engineering price list of Campania (http://www.regione.campania.it/assets/documents/drd-281-26-10-10.pdf) (accessed on 14 January 2019). Overall, the value of habitat restoration and soil erosion control was determined as the product of the implementation and maintenance costs and the forest surface area affected by a high burn severity.

2.6.2. Pollination

As an ES, pollination can be delivered by organisms that depend strictly on forest habitats. Approximately one-third of crop production depends on animal pollinators, and 60–90% of plant species require an animal pollinator [33,34]. Although the services provided by wild pollinators are globally recognised, valuing the benefit of this service necessarily entails a contextual approach at a specific spatial scale. Indeed, the value of the resulting goods and benefits may be assessed via market-based feedback, considering that some agricultural production is directly dependent on animal-mediated pollination [35]. The main commercial crops around the forested area in Vesuvius National Park consist of grapevines and tomatoes, but only the tomatoes are insect-pollinated. The Piennolo Cherry Tomato of Vesuvius is a protected designated-origin product (EU regulation NO1151/2012) and is the most profitable agricultural product in the area. Considering the mean annual production, the total cultivated area, and the product market price obtained from the official website of the regional authority (www.regione.campania.it/) (accessed on 18 March 2020), we evaluated the annual production value. Given that insect pollination is an essential condition for tomato (re)production, the proportion of the annual production value attributed to wild insect pollination can be assumed to be 8% [36]. The value of production losses owing to reduced wild pollination was estimated to be equal to the share of production that depends directly on insect pollination [37]. Following this approach, we estimated a decrease in tomato production resulting from a decrease in the population of bumblebees (*Bombus* spp.—the main wild insect pollinator of Vesuvius cherry tomatoes) caused by the destruction of nest sites (i.e., tussocks and underground cavities) in burnt forest areas [38].

2.6.3. Carbon Stocks

Damage to carbon stocks was calculated as a combination of two factors: the number of carbon emissions released during the wildfire and the social costs of carbon. Fire affects biomass carbon stocks at different spatial scales, depending on the fuel type and fire intensity [39]. In the field, we observed that, in stands affected by high fire severity, the leaves and fine branches of the crown, the outer bark, and the litter and duff were combusted. Consequently, we estimated the carbon fraction of the canopy leaves and forest floor (litter and duff) to be 50% of the total biomass [40] (for detail, see both Sections S4.3.1. Carbon content of canopy leaves and S4.3.2. Forest and shrub floor (litter and duff) in Supplementary Material S1). The total biomass was calculated from the field assessment of 40 circular plots (20 m radius) in oak, pine, chestnut, and *Genista aetnensis* stands, using species-specific allometric equations (see Section S4.3 in Supplementary Material S1).

The price range for carbon credits was determined from the average 2017 permit price in the European Emissions Trading System (EU ETS), using the carbon price viewer available on the official website of Quandl Inc. (https://www.quandl.com/data/CHRIS/ICE_C1) (accessed on 23 September 2021).

CO_2, released as smoke from burning vegetation, is the dominant component across biomes. It is a permanent gas that can be transported over vast distances, threatening human health [41] and contributing substantially to climate change [42]. CO_2 emissions from studied wildfires are generally monetised using market prices [43,44]. Consequently, we considered the social cost of carbon as the monetised value of its contribution to climate change, derived from the emission of an additional tonne of CO_2 (Mg CO_2) into the atmosphere [45,46]. As this value was tested for external validity, it can be directly applied to the study at hand without any further adaptation, according to the benefit transfer method [14].

2.7. Cultural Services

Ecotourism

Vesuvius represents a world-renowned tourist attraction. It is included in many tours with neighbouring attractions such as the Roman ruins of Pompeii and Herculaneum.

We quantified the cost of the temporary inaccessibility of the park to tourists during the wildfires and until service was restored. Given that the park footpaths are free, visitor statistics, which are often available in other protected areas, represent a knowledge gap [47]. A representative value of the benefits conferred by interaction with the Mediterranean forests in the park could only be loosely represented by a marketable good: entry tickets to the "Gran Cono" tour of Vesuvius, led by a specialised guide.

The estimation procedure started by calculating the annual tourism income for 2016 and 2017 (see Section S5 in Supplementary Material S1 and the related sheet 'Ecotourism' in Supplementary Material S2 for details). The year 2016 was used as a benchmark since the park was able to offer all its services without any disturbance and interruption. A comparison between the number of visitors in 2016 and 2017 allowed the likely decrease in tourists induced by the megafire to be quantified: Vesuvius National Park recorded about 90,000 fewer visitors in 2017 than in the previous year.

2.8. Normalisation of the Economic Loss of Ecosystem Services

A standard data normalisation procedure was applied to express the magnitude of monetary ES loss as a metric of the ecological and economic footprint of forest wildfires. For each combination of forest physiognomy *j* (broadleaved, conifers, and shrubland) and burn severity class *k* (low, moderate–low, moderate–high, and high), all monetary estimates of ES loss ($ES_{j,k}$, € ha^{-1}) were calculated as follows:

$$ES_{j,k} = \sum_{i=1}^{n} ES_i \quad (1)$$

where n is the number of estimated ES. Subsequently, the normalised ES economic loss ($NLoss_{j,k}$) was calculated by scaling each cumulated monetary value of $ES_{j,k}$ to a fixed range [0, 1], as follows:

$$NLoss_{j,k} = \frac{ES_{j,k} - \min\left(ES_{j,k}\right)}{\max\left(ES_{j,k}\right) - \min\left(ES_{j,k}\right)} \quad (2)$$

When the value of $NLoss_{j,k}$ approaches zero, the loss in ES is minimal, whereas when $NLoss_{j,k}$ approaches one, the ES loss increases consistently toward the maximum value.

3. Results

The event can be considered a megafire (Figure 2B), according to the criterion of DellaSala and Hanson [25] (burnt forest area > 2 SD of the average size of burnt forest areas within a specific period). In the summer of 2017, the total burnt forest area amounted to 3350.23 ha (88% of the total forested area of Vesuvius National Park), which burnt over a period of 49 days, starting on 2 July. The burn severity was generally high, with the moderate–high and moderate–low classes most widely represented across the total burnt area (Figure 2A). Of the total burnt area, 1067.45 ha (35.55%) were even-aged Mediterranean pine stands, with the non-fire-resilient *P. pinea* being the most representative species.

The estimated suppression costs accounted for €2.751 M, 94.8% of which was generated by aerial operations involving aircraft such as Canadairs and helicopters. However, it accounted for only ~16% of the total estimated loss of value, in terms of ESs (see Section 3.1 below).

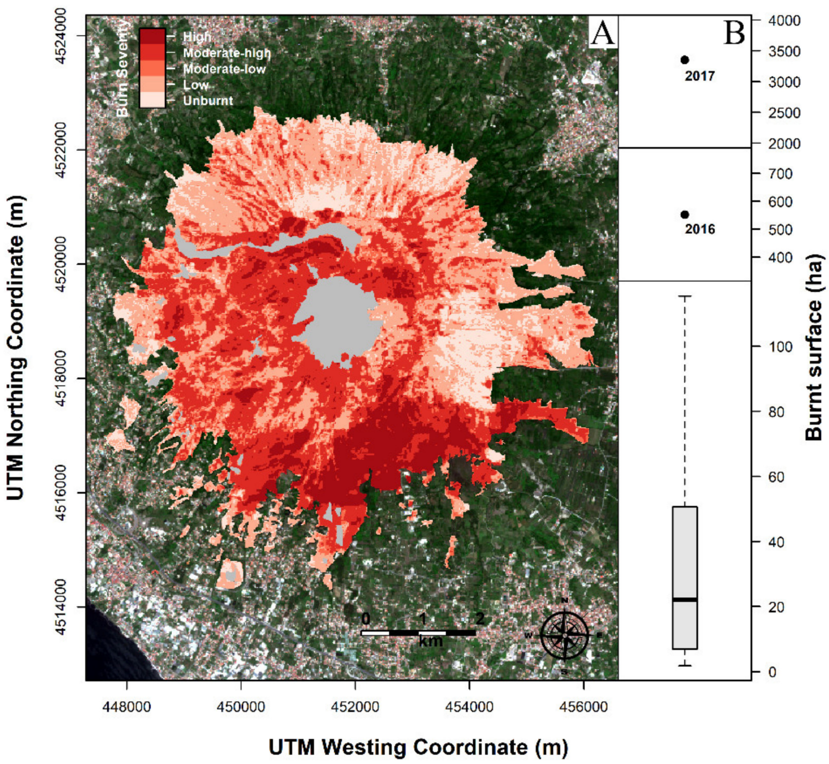

Figure 2. Burn severity map of the wildfires that occurred in summer 2017 (panel (**A**)). On the right box plot of 20-year historical data for the annual burnt surface area from 1997–2017 in the forest area of Vesuvius National Park (panel (**B**)). The outliers in 2016 and 2017 can be classified as megafires, according to DellaSala and Hanson [25]. Grey polygons represent non-forested areas (i.e., the main volcano cone, secondary adventitious cones, and lava fields).

3.1. Ecosystem Services

The total estimated loss in terms of ESs after the 2017 megafire was €14.363 M (Figure 3). Although provisioning ESs in this study were represented only by roundwood biomass, they accounted for 56.9% of the total estimated cost. Maintenance and regulation services, consisting of habitat maintenance, erosion control, pollination, and carbon stocks, accounted for 34.7% of the estimated cost, while cultural services, represented only by losses in tourist inflow, accounted for 8.5% of the total estimated cost (Figure 3).

3.2. Provisioning Services

The estimated total loss of potential profit from roundwood production was €8.166 M. Due to the large stem size of the Mediterranean conifer stands distributed across the extensive burnt surface area, the softwood timber assortments accounted for 93%, while broadleaf chips (shoots of burnt coppices) and conifer chips (branches of conifer trees killed by fire) accounted for only 17% of the total potential profit.

3.3. Regulation and Maintenance Ecosystem Services

3.3.1. Habitat Restoration and Mitigation of Surface Soil Erosion

The total cost of restoring Habitat 9540 and concomitantly mitigating post-fire surface soil erosion on volcano slopes affected by a high fire severity was €3.416 M. Considering the topography, geomorphology, post-fire properties of the andic soil, and vegetation features of the high-severity burnt surfaces, the bioengineering system consisted of a combination of two operations. First, a temporary log dam structure was built to lessen hydrological risks by reducing surface water velocity, promoting soil water infiltration and sediment deposition, and preventing the spatial shift of soil seed banks post-fire. Then, native trees and shrubs were planted (Figure 4).

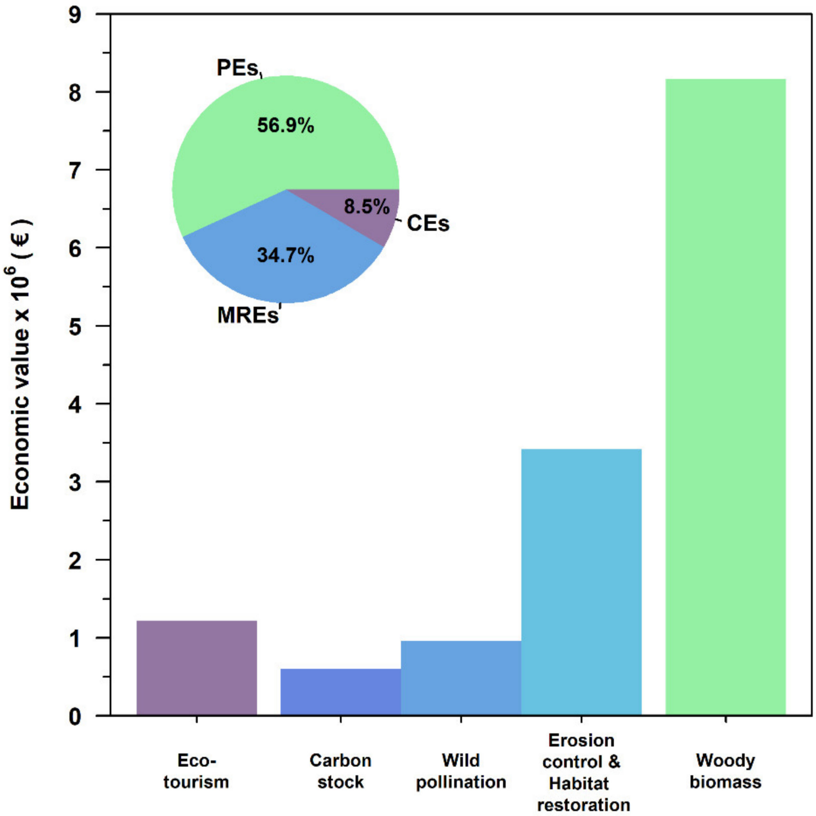

Figure 3. Value of economic losses resulting from wildfire-related damage to ecosystem services. In the inset graph, PEs correspond to provisioning services, MREs to regulation and maintenance services, and CEs to cultural services.

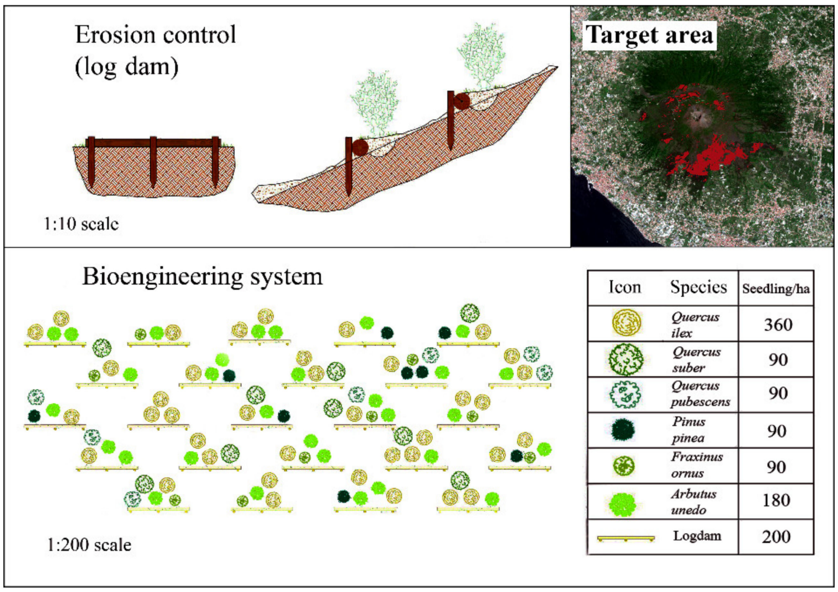

Figure 4. Bioengineering system applied to control the erosion rate, and native shrub and tree species prescribed to re-establish a suitable forest habitat.

3.3.2. Wild Bumblebee Pollination

The estimated loss of profit arising from missing wild pollinators during and after the wildfire was €960,000.00. This value corresponds to the income losses of the Vesuvius cherry tomato agricultural industry, which is directly dependent on wild bumblebee pollinator populations.

3.3.3. Carbon Stocks

The estimated value of the carbon emissions, based on the carbon price traded in the EU ETS, was €600,677.00. Coniferous stands, which represented the largest fraction of the total burnt area, accounted for 65.7% of the total carbon loss, while oak and chestnut stands accounted for 14.6% and 19.7%, respectively. Importantly, when considering the social cost of this carbon, the estimated cost was higher, amounting to €2.002 M.

3.4. Cultural Ecosystem Services

Ecotourism

The estimated loss of income owing to closing the burnt areas during and after the wildfires was €1.219 M. Tourist visits to the cone of Vesuvius were suspended for safety reasons from the beginning of the wildfire in July and in the last week of August 2017, which were statistically the months with the highest numbers of visitors (Figure 5). In September, after post-fire logging and other safety measures had been performed along the main access routes, public access was restarted, and it reached numbers comparable with the September data of the previous year.

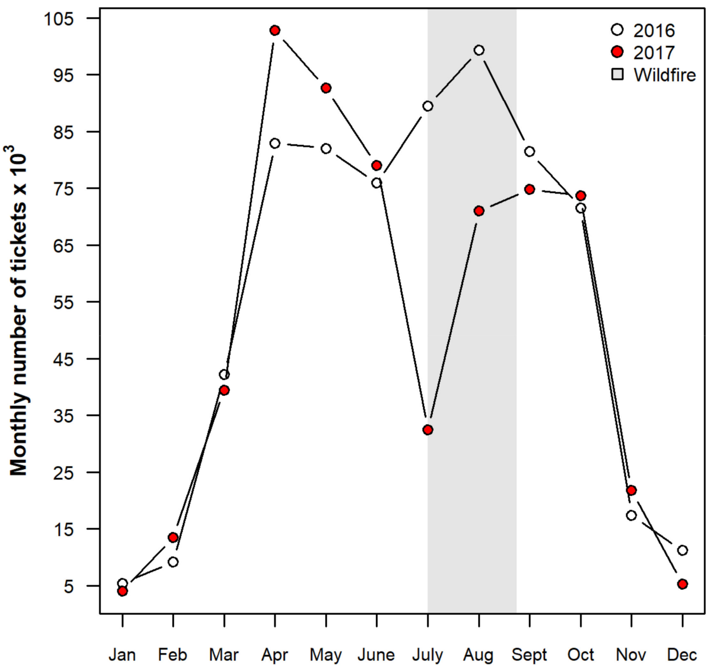

Figure 5. Trends in the monthly number of entry tickets to the "Gran Cono" tour of the Vesuvius volcano in 2016 (white circles) and 2017 (red circles). In 2017, the sharp decrease of visitors in July, and the gradual increase in August–September, are related to limitations in public access owing to wildfire occurrence and post-fire logging safety operations along the main access routes, respectively.

3.5. Spatial Distribution of ES Economic Losses

The spatial distribution of the normalised ES monetary losses was patchy (Figure 6), according to the different degrees of burn severity experienced by each forest physiognomy (Figure 7). High ES losses (NLoss > 0.9) were mainly localised on the southern slopes of Vesuvius, accounting for 10.0% (385.12 ha) of the total forest surface area (including unburnt forests). These high ES losses were chiefly detected in highly burnt conifer forests, in which the monetary losses amounted to 19,300.00 € ha^{-1}.

The forest cover, for which the normalised ES loss ranged between 0.5–0.7, was spatially distributed around the borders of the areas with high normalised ES monetary losses (NLoss > 0.9). This surface area accounts for 647.44 ha, which is equal to 17.0% of the total forest cover. In these burnt forests, the monetary loss was 12,000.00 € ha^{-1} in the highly burnt broadleaved stands, a value slightly higher than that in the highly burnt shrubland physiognomy, which amounted to 10,200.00 € ha^{-1}. However, the same range of the normalised ES loss (0.5–0.7) also encompassed the moderate–high burnt conifer forests, accounting for a monetary loss of 10,000.00 € ha^{-1}.

However, most of the forest cover, 61.0% (2317.67 ha) of the total forested surface, showed a normalised ES loss value < 0.2. These areas were mainly localised on the western, northern, and eastern slopes of Vesuvius and mixed with unburnt forest surfaces. Such surface areas consisted of both shrubland and broadleaved physiognomies affected by burn severities ranging from low to moderate–high, and conifer forests affected by low or moderate–low burn severities. In these areas, a high ES monetary loss of 2711.61 € ha^{-1} was detected in the broadleaved forests with moderate–high burn severities, followed by conifer forests with moderate–low burn severities, which had a cumulative ES loss of 1033.82 € ha^{-1}. In the broadleaved forests with moderate–low burn severities and shrubland with moderate–low and moderate–high burn severities, the ES monetary losses varied between 808.30 and 907.53 € ha^{-1}. The minimum monetary ES loss value of 725.73 € ha^{-1} was detected in all the forest areas with low burn severities.

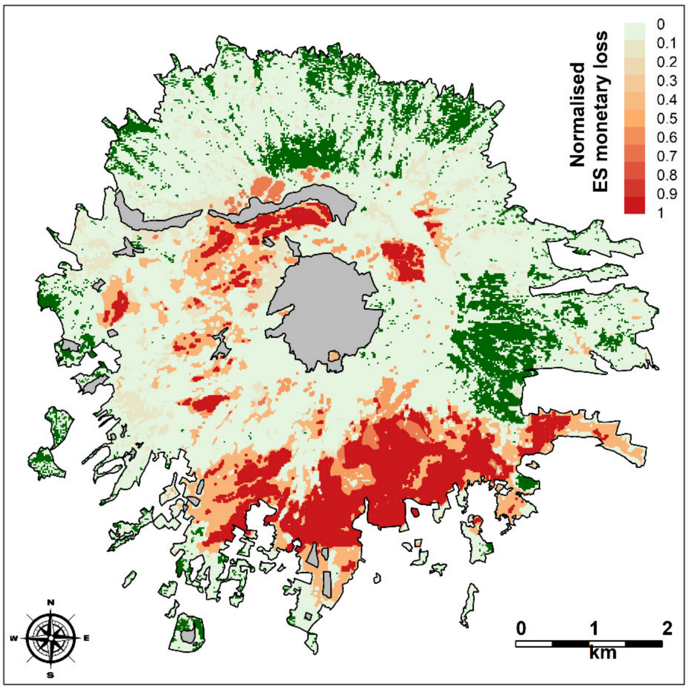

Figure 6. Normalised ES loss map. Gradient colours from light green to dark red represent the normalised monetary loss. The dark green polygons are unburnt forest surface whereas the grey polygons represent non-forested areas (i.e., the main volcano cone, secondary adventitious cones, and lava fields).

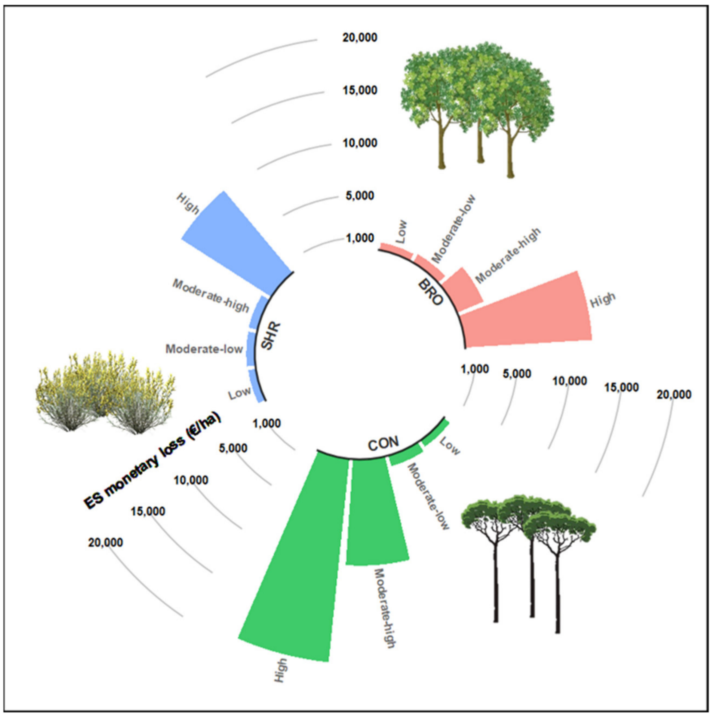

Figure 7. ES monetary loss (€/ha) according to the severity of wildfires (from low to high severity) experienced by each vegetation physiognomy (BRO–broadleaved forest, CON–conifers, and SHR–shrubland).

4. Discussion

Because the megafire events in our case did not injure any people or cause considerable damage to infrastructure, the high suppression cost dominated the information in the media. As we pointed out previously, the suppression costs represented only ~16% of the value of the disruption of ESs that provide social and human well-being. Consequently, it seems reductive to use only the suppression cost as a descriptor of the megafire, potentially misleading the public. Indeed, from the perspective of post-fire impacts, megafires have considerable and long-lasting social and economic impacts (e.g., a decline in habitat quality, loss of amenity, and loss of aesthetic value), making them a disaster rather than an incident [10,48–50].

4.1. From Ecology to Economics

Aside from policy-makers, society, in general, is forced to make decisions and trade-offs about ecosystems every day. This entails a valuation process that is either implicit or explicit [13]. In this scenario, we considered that giving appropriate weight to the ES provided by the Mediterranean forests of Vesuvius National Park could promote more equitable, cost-effective, and sustainable biodiversity conservation policies.

In Italy, the economic impact of wildfires usually only encompasses the costs of fire suppression and forest rehabilitation, but catastrophic wildfires have direct and indirect impacts on the environment and socio-economic systems [51], which propagate spatially [49,52]. To fill this gap, we provide an additional assessment of other components of fire damage that, in our opinion, can increase public awareness and represent valuable information to society, stakeholders, and policy-makers. Economic losses are usually considered in decision-making when choosing whether to implement actions to mitigate the risk of wildfires. Thus, by considering only suppression costs rather than all the costs suffered by the environment and society, misguided decisions could be made [53]. Indeed, decision-makers and society can make better choices about ecosystems if the valuation of their ES is made as explicit as possible [14,54]. In this regard, Ekayani et al. [55] pointed out the crucial role of scientific production in promoting efforts to make forest and wildfires a policy priority and a global concern. This evaluation was performed with the ultimate goal of fostering a rapid change of perspective in Mediterranean forest fire management to promote fire prevention actions on a local scale rather than focusing on suppression strategies. Indeed, until the economic, social and environmental losses associated with wildfires are unknown, policies and strategies incorporating wildfire information cannot be fully planned [51]. We strongly believe that these explicit valuations and the processes involved can help to develop better ways to evaluate ESs. To achieve this goal, we discuss our results below and highlight the issues and limits faced for each considered ES, before deriving our conclusions regarding post-fire management.

Megafires have long-lasting impacts and induce substantial changes in forest ecosystems [50]. Subsequently, as previously noted by Pausas et al. [56], natural post-fire regeneration in Mediterranean forest ecosystems can vary substantially in space and time. This uncertainty, and the circumstance that only some target areas are subject to post-fire management, led us to consider only immediate post-fire losses in our calculations, rather than considering a multi-year time span.

Provisioning ESs, represented in the present work only by roundwood biomass, accounted for the highest fraction of the loss of benefit after the megafire. Nevertheless, some considerations regarding the estimated monetary losses caused by the fire are necessary. In national parks, the primary goal is to protect unique geological and ecological processes, as well as landscape features. When severe fire damage occurs in protected areas surrounded by densely populated areas and with a high rate of touristic and recreational use, as in our case, salvage logging is ineluctable and generates an unexpected surplus income that would not exist without the wildfire disturbance. Currently, the management actions in these forest areas focus on habitat conservation and ensuring the safety of visitors, excluding timber-based production purposes. Furthermore, the Italian Minister for the Environment, Land and Sea Protection established sustainable forest management criteria for national parks, and salvage logging after stand-replacing disturbances must be authorised, especially if the proposed logging area is large. The estimated volume collected during salvage logging from charred standing trees is highly realistic because it was based on sampling in several field plots and the price of low-quality salvage roundwood products in local markets. It refers to the salvage period in the first two years after the fire events.

The Vesuvian landscape comprises a mosaic of natural habitats that support several ecological communities. As already mentioned, fire severity is heterogeneous in space, leading to habitat fragmentation. Indeed, a direct consequence of fire events is that they may jeopardise biodiversity [57]. The new open spaces created by fires could be colonised by more competitive alien species (e.g., *Robinia pseudoacacia*, *Ailanthus altissima*, and *Genista aetnensis*), historically introduced to regulate hydrological processes and mitigate soil erosion on the slopes of Vesuvius [58]. Post-fire vegetation dynamics can shift successional trajectories but have a positive effect on controlling accelerated surface soil erosion immediately after the wildfire, owing to basal resprouting or regeneration from subsurface root sprouts and rapid post-fire above-ground regrowth [59]. The logging actions described in the present work were intended only for areas where the standing trees were charred. Although the ecological consequences of salvage logging are still under debate in the scientific community among others [60,61], in our site-specific case, such management practices were considered mandatory, both to mitigate the high risk of soil erosion and to ensure safety along the hiking and nature trails in the park. Nevertheless, the estimated cost may be considered exhaustive because, through the replacement cost approach, the values of both ESs (i.e., habitat maintenance and erosion control rate) were estimated only for the areas affected by a high-severity stand-replacing fire. Although a decline in habitat quality can also occur in moderately burnt surfaces, these areas are currently dominated by evergreen Mediterranean shrub and tree species able to resprout after a fire. This suggests that, although habitat maintenance is one of the primary conservation objectives in the protected area, after a stand-replacing fire, the ES provided by continuous forest cover, in terms of erosion control and slope stability (soil protection) are more relevant than habitat conservation, especially in the wildland–urban interface of the southern slopes. In this context, Vesuvius National Park can be considered a remnant natural area embedded in a human-dominated landscape, making risk mitigation actions for humans mandatory after severe wildfire disturbances.

The forests of the park provide services that functionally support the primary production of the surrounding agricultural crops. The current land uses of the slopes of this volcano and the surrounding areas are the result of thousands of years of cultivation of fertile andic soil [62]. Traditionally valuable agricultural production is intimately connected with, and dependent upon, the foraging activity of wild pollinator colonies that live in or spread into the forest habitats. To incorporate this important aspect, we estimated the extent to which changes in the wild bumblebee population affected the profitable production of Piennolo cherry tomatoes. Equating the value of pollination to the proportion of total cherry tomato production value dependent on wild bumblebee pollinators led to the interpretation of this ES as pollination flow; that is, the productive success attributable to the action of wild pollination at a farm-scale [63,64]. Although the proportional production value method is known to generate a flawed evaluation of wild pollination services, it is conventionally applied because it reflects practical considerations regarding the accessibility and availability of consistent data [64]. Alternatively, an appropriate monetary evaluation of pollination service loss would require information on the damage caused to wild pollinator populations by the wildfires, which is often not available and is difficult to measure, especially in burnt forest habitats. Nevertheless, given that only the market price of raw material production was computed, without added value from processing, the estimated value represents a minimum income loss for the Piennolo cherry tomato production industry at a farm scale.

Although in the final estimation the value derived from the market price of carbon was considered, in the context of the present work, the social cost appears more representative to estimate the value of the losses after the occurrence of the megafire. The social cost of carbon is defined as the marginal present-value cost imposed by the emission of an additional tonne of CO_2 (Mg CO_2) in the atmosphere. This concept does not reflect the market price (which can be misleading owing to the elasticity of demand and country/international regulations of the CO_2 market) and has emerged as a key concept in the economics of climate change [45,46,65]. Therefore, assessing the social costs appears to be a more appropriate approach to estimating the CO_2 emission disservices generated by multiple wildfire events. Indeed, the atmospheric release of CO_2 from the burnt carbon stock and the modification of aerosol properties by the fire exacerbate climate regulation and air quality, affecting both local proximal and global non-proximal spatial scales [41,66,67].

Vesuvius represents a world-renowned tourist attraction, epitomised by the "Gran Cono" tour and, among other geological and landscape features, the lava flows of the previous century eruption, the most recent colonised by the endemic lichen *Stereocaulon vesuvianum* [68]. The 1944 lava flow represents an excellent scientific and educational case study of primary succession, where annual herbs, shrubs, and pioneer tree species succeed each other diachronically after initial lichen colonisation. Given that the park footpaths are free, visitor statistics, which are available in many other protected areas, represent a knowledge gap. A representative proxy value of the benefit conferred by physical and experiential interactions with the Mediterranean forests in the park can be appropriately estimated using the admission fees for entry tickets to the "Gran Cono" tour, led by specialised guides. There is general agreement that cultural ESs suffer from poor quantification and integration within management plans [47,69]. As we were unable to achieve comprehensive quantification of cultural services, we included in this computation the only tangible direct-use value available for Vesuvius National Park. Nevertheless, this estimation does not consider the potential reduction of monetary income from all the commercial activities (e.g., accommodation, small business activities such as restaurants, cafeterias, souvenir shops, etc.) related to the visit to the "Gran Cono". However, in the highly urbanised landscape, the present-day forests of Vesuvius represent a key resource for leisure activities and for direct contact with the forest environment. Clearly, using merely the number of tickets for access to the "Gran Cono" tour as a means of valuing all cultural services provided by the Vesuvius forests results in appreciable undervaluing of the amenity.

4.2. Post-Fire Management Actions

After a wildfire, forest managers and stakeholders face the dilemma of whether a reforestation plan should be carried out and, consequently, if it is worth waiting for natural regeneration. Such questions may not have easy or universal answers, especially if we do not explore the purpose of the proposed action. Post-fire management measures should generally have two objectives: (I) preventing the further loss of certain goods and services and (II) shortening the vegetation recovery period. In the post-fire rehabilitation of Mediterranean-type woodlands, Vallejo et al. [70] suggested that the main priorities should be soil and water conservation, improving the resistance and resilience of the vegetation to fire, promoting biodiversity, and fostering the re-introduction of key and native species. According to the guidelines of Wittenberg et al. [71], in our fire landscape, charred and severely scorched trees are promptly removed in a 30 m buffer on both sides of public roads, official hiking trails, and structures supporting tourism to guarantee safe conditions for tourists. Salvage logging is also applied in stands affected by high fire severity, mainly on the southern slopes. At these sites, salvaging was coupled with the construction of a log dam using downed wood and logging slash, with the intent of reducing soil erosion and debris flow, retaining coarse and fine burnt biomass in situ, and promoting biodiversity. In Mediterranean environments, it is well documented that post-fire rainfall intensity affects the magnitude of soil erosion and nutrient loss [72–74]. Therefore, these multifunctional structures not only provide a beneficial erosion restraint on steep slopes but also support biodiversity by halting the downward spatial shift of soil seed banks, at the same time assuring safe sites for the recruitment of new post-fire vegetation communities [75]. Consequently, it is obvious that these good practices provide ESs that are intimately interlaced and cannot be estimated separately. To summarise, the long-term objectives of restoring burnt areas are to support biodiversity and simultaneously improve the fire resistance and resilience of stands. Mediterranean-type ecosystems are highly resilient to fire when dominated by shrub and tree species that can resprout or regenerate from seeds after fire. Thus, these traits should be considered during post-fire restoration.

5. Conclusions

This paper aimed to provide current information on the Vesuvius National Park forest resources and estimate the value of some ESs that were lost after the multiple wildfire events in summer 2017. We first evaluated the post-fire ecosystem status throughout the burnt area, using a burn-severity metric, and then estimated the economic and ecological footprint of the wildfires using a set of ESs. The available data narrowed the range of ESs used in the monetary valuation and it was carried out using different methods, depending on each ES. Consequently, the 2017 wildfire-related damage is underestimated because it does not capture all the ESs disrupted by the megafire. Valuation of the ecosystem goods and services offered by Mediterranean forests can promote public awareness regarding the welfare benefits derived from such ecosystems. Moreover, such contextual analyses can provide useful insights for decision-makers. While many studies have assessed the value of existing forests, few estimations have been conducted after the value was lost owing to fire disturbance events [49,52]. Thus, the results can inform stakeholders of the actual extent of the damage caused by the wildfires in the summer of 2017. At the national level, the economic impact of wildfires usually only comprises the costs of fire suppression and forest rehabilitation. Although we did not evaluate the cost of fire prevention operations, we provided an additional assessment of damaged components which, in our opinion, constitutes novel information of value to society, stakeholders, and policy-makers. Such data are usually considered by decision-makers when choosing whether to implement actions to mitigate the risk of forest fires. Thus, when the costs are underestimated by considering only the suppression costs rather than all the connected costs to the environment and society, misguided decisions may be made [53]. Our results clearly show that even considerable suppression costs represent only a small fraction of the high-value losses in terms of ESs. The main objective of the present work was to redirect the attention of policy decision-makers, forest managers, the media, and society toward the ecological consequences of extreme or recurrent wildfires, using the support of economic quantification. The climate change scenario for the Mediterranean area predicts increases in the size, frequency, and severity of wildfires [76–78]; thus, forest fire management requires a rapid change in perspective.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/fire4040095/s1, Supplementary Material S1: Details on the methodological approach used to estimate the wildfire suppression costs and to obtain the economic valuation of ecosystem service (ES); Supplementary Material S2: Details on the data and calculations of the wildfire suppression costs and the detriment of ecosystem service (ES).

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