

Article

Development of Comprehensive Fuel Management Strategies for Reducing Wildfire Risk in Greece

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Received: 11 June 2020; Accepted: 18 July 2020; Published: 22 July 2020



Abstract: A solution to the growing problem of catastrophic wildfires in Greece will require a more holistic fuel management strategy that focuses more broadly on landscape fire behavior and risk in relation to suppression tactics and ignition prevention. Current fire protection planning is either non-existent or narrowly focused on reducing fuels in proximity to roads and communities where ignitions are most likely. A more effective strategy would expand the treatment footprint to landscape scales to reduce fire intensity and increase the likelihood of safe and efficient suppression activities. However, expanding fuels treatment programs on Greek landscapes that are highly fragmented in terms of land use and vegetation requires: (1) a better understanding of how diverse land cover types contribute to fire spread and intensity; and (2) case studies, both simulated and empirical, that demonstrate how landscape fuel management strategies can achieve desired outcomes in terms of fire behavior. In this study, we used Lesvos Island, Greece as a study area to characterize how different land cover types and land uses contribute to fire exposure and used wildfire simulation methods to understand how fire spreads among parcels of forests, developed areas, and other land cover types (shrublands, agricultural areas, and grasslands) as a way to identify fire source–sink relationships. We then simulated a spatially coordinated fuel management program that targeted the fire prone conifer forests that generally burn under the highest intensity. The treatment effects were measured in terms of post-treatment fire behavior and transmission. The results demonstrated an optimized method for fuel management planning that accounts for the connectivity of wildfire among different land types. The results also identified the scale of risk and the limitations of relying on small scattered fuel treatment units to manage long-term wildfire risk.

Keywords: fuel treatment optimization modeling; Calabrian pine; *Pinus brutia*; European olive; FlamMap; fire behavior modeling; minimum travel time algorithm; Lesvos Island

1. Introduction

Mediterranean areas are experiencing rapid expansion of communities into rural areas with multiple adverse impacts in terms of invasive species, deforestation, and human activities that increase fire ignitions [1]. The expanding intermix of flammable vegetation and low density development along with a warming climate and more ignitions [2,3] has created a wicked wildfire problem due to the significant economic burden of wildfire management, incomplete knowledge, the number of people and opinions involved, and the interconnected nature of these problems with other governance challenges [4–6]. Risk governance systems have failed to keep pace with the change in these

anthropogenic fire regimes and new policies [7–13] proposed to address the wildfire problem have yet to be implemented. These policies aim to improve landscape fuels management but stop short of identifying specific spatial strategies and their outcome in terms of reducing future losses [3]. The core issue is identifying the scale of risk to ensure that fire management activities consider the source and key values exposed to large wildfire events. Overlaying the spatial context of risk are the multiple and complementary strategies that address the pinch points from ignition to containment. Increasingly, literature from North America [14–19] and Southern Europe [20–22] has shown that investing more in fuel management and pre-fire planning is critical to mitigate upcoming challenges that emerge from climate change and land abandonment effects on fuel patterns.

In Greece, different stakeholders see the wildfire issue as a symptom of a higher order problem but tend to focus on specific solutions rather than a broad-spectrum strategy. For example, some point to poor forest and fuels management, while others argue that wildfire problems could be solved if there were only more resources for fire suppression. Greece implements minimal levels of fuel treatments in terms of extent, size, and intensity, and the government funds a broad mix of fire prevention with local governments with a 2020 budget of 17 million euros, with an additional 2 million euros for fire protection in the Forest Service [23,24]. However, only a fraction of this funding is applied to treat fuels in forested areas. Rarely do forest management agencies combine forest and fuel treatments on management units at a scale comparable to the burned area of predicted fire events. Thus, risk management is entirely dependent on fire suppression to protect people, private property, and other values-at-risk. Managing fuels in Greece has multiple challenges such as rapid re-growth of fuels with vegetation that exceeds the flammability of what was removed, and restrictions that exclude fuel management with prescribed fire. The bulk of the fuel treatments are fuel breaks around communities and are located without strategic assessment of the likely wildfire paths from wildlands [25]. Around the fuel breaks, the vegetation has the potential to burn in crown fires that generate spot fires kilometers ahead of the fire perimeter [26]. By contrast, many studies have shown that landscape scale programs that are strategically allocated are effective at changing wildfire behavior before fires arrive at community boundaries [22,27–32]. Much of the evidence is experimental, obtained through use of scenario planning tools to evaluate alternative management strategies and estimation of potential trade-offs [28,33–37]. For instance, previous studies have shown that reduction in large fire growth is obtainable through the collective effect of many treatment units occurring on the landscape with specific patterns and densities [27,38,39]. Random treatment patterns are inefficient in changing large fire growth rates compared with strategic designs, because they permit fire to easily move laterally around treatments, unless large portions of the landscape are treated [40]. Several alternative fuel treatment methods exist that can be applied as prescriptions in pre-selected units on the landscape, including silvicultural tending with mechanical means (e.g., thinning, pruning), prescribed burning, and grazing for reducing surface and ladder fuels.

In this study, we first used wildfire simulation methods to assess the relative contribution of different land cover types to the overall fire problem on a large and diverse fire prone landscape on the island of Lesbos, Greece. The goal was to show the connectivity in terms of fire spread and exposure among the major land types in a typical, highly fragmented Greek landscape. We then used wildfire and fuel treatment simulation methods to develop an optimized fuel treatment program in the extensive, fire prone conifer forests. The objective of the fuel treatments design was to effect broad landscape fire risk reduction in terms of fire severity and control by suppression forces, rather than fuel breaks focused in a specific location. Fuel treatments consisted of the removal of small trees and saplings by thinning and cleaning the understory to reduce fuels. We assumed these treatments would be achieved through grazing or mechanical means since prescribed fire is not legal in Greece. Forest canopy fuels would be treated with silvicultural improvement methods including thinning and pruning to increase tree canopy base height and reduce ladder fuels. We assess how the varied land uses and associated vegetation interact and spread fire and examine how investments in forest and fuel management can bring about landscape improvements in fire resiliency in the pine forests. We discuss

how the current practice of relying on fuel breaks will not significantly alter the growing wildfire risk problem without coupling with more extensive and intensive forest and fuel management.

2. Materials and Methods

2.1. Study Area

The study area covers 46,800 ha located in the central part of Lesvos Island, Greece (Figure 1), encompassing the largest continuous Calabrian pine (*Pinus brutia*) forest among the Aegean Sea islands (21,000 ha). In terms of forest structure, about 16,500 ha are dense, 2700 ha are sparse, and 1800 ha are young forests. The species typically burns at high severity and regenerates by seed from serotinous cones [41]. Calabrian pine has a short juvenile phase that leads to an early cone and seed production that ensures regeneration in cases where fire frequency is relatively high [41]. Factors like poor soils, steep slopes, post-fire flash floods, grazing, and new wildfires substantially reduce post-fire regeneration success.

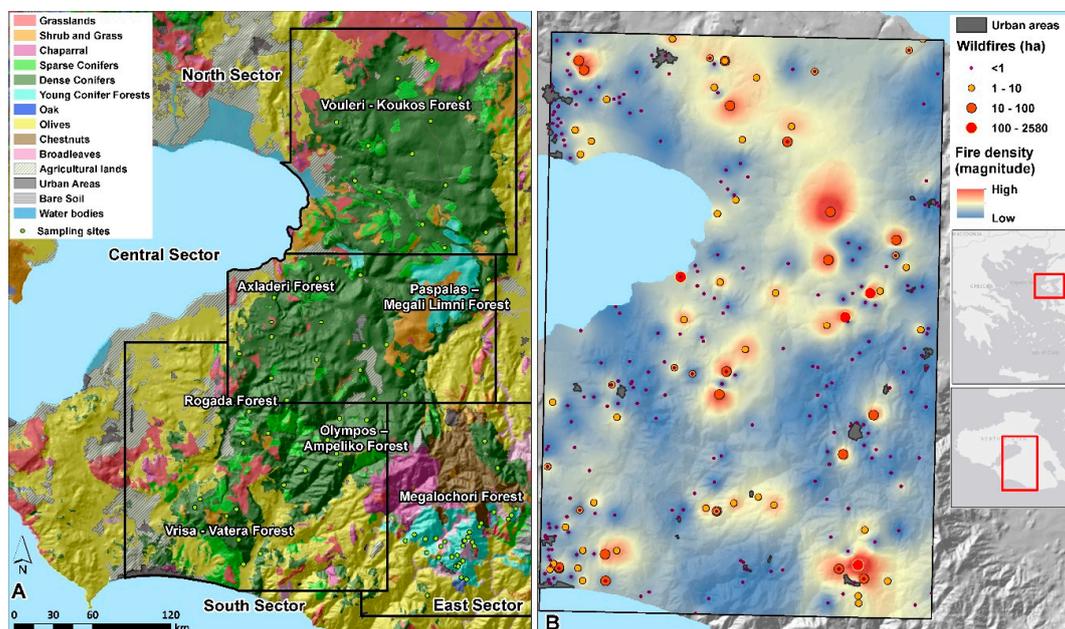


Figure 1. (A) Land cover types and forest sectors of the study area; (B) wildfire events and fire density based on the magnitude of the event (in hectares), estimated with the inverse distance weighting interpolation for the period 1971–2015.

A large portion of the study area is covered with olive trees (13,000 ha) or other agricultural areas (i.e., permanent crops or orchards) (3100 ha), with the remaining covered with typical Mediterranean fuels such as grasslands (2500 ha), chaparral (2100 ha), mixed grass and shrubs (2000 ha), and broadleaved trees (1700 ha) (Figure 1A) [42]. The land cover surrounding the 25 communities inside the study area (1 km buffer—7500 ha) is comprised mostly of olive groves (51%), cultivations (16%), dense conifers (13.5%), young conifers (3%), and grasslands (3%). Significant parts of the island face land abandonment with subsequent reforestation, and since conifer forests are mostly unmanaged and privately owned, i.e., not industrial or commercial type ownerships, no official fuel management exists on most of these lands. Approximately 300 fire events have been recorded since 1974 in this area, resulting in about 6000 ha of burned area (Figure 1B). The largest wildfire ever recorded occurred in 1994 and burned 2600 ha, equivalent to 5% of the study area.

Lesvos is characterized by traditional olive grove monoculture. Olive fields are “partially abandoned”, meaning that the olives are collected and fuel management is applied only during years with satisfactory production [43]. This is mainly because only 17% of the people owning olive fields are

full-time farmers, with 42% being pensioners who practice farming as extra income, and the remainder with a second occupation [44]. Regarding the size of the agricultural area, the average unit is 8.2 ha, with half used for olive plantations. Previous studies [45] framed the typology of olive cultivation in Lesvos (Figure 2). The abandoned plantations are former olive fields without cultivation and without harvest for several years with a mixed fuel model comprised of annuals, litter, and short shrubs that create dense understories (Figure 2C) and produce fast moving fires with moderate intensity. The neglected plantations (Figure 2B) are shifting between abandonment and cultivation based on the production of each year. The olive plantation fuel model is comprised of annuals and short shrubs and produce low-intensity, fast-moving fires. Labor-intensive plantations (Figure 2A) are managed cultivations using herbicides, pile burning, or grazing, typically planted on terraces with pruned trees and clear understories limiting available fuels to allow a fire to spread. This state can be considered as the predominant landscape of Lesvos before the 1920s. Finally, housing plantations (Figure 2D) are former olive fields, usually with high real estate value, where one or more buildings are found. Grassy fuels are the primary carrier of fire in housing plantations, but these are usually non-transmitted fires that are rapidly extinguished. Changes between these types are continuous, as cultivated or abandoned fields are cleared for housing, fields are abandoned or neglected, and abandoned or neglected fields are cleared for cultivation [45], and thus all four types were lumped into a single fuel model.



Figure 2. The typology of the four types of olive plantations [45]: (A) labor-intensive plantations; (B) neglected plantations; (C) abandoned plantations; (D) housing plantations (photos by the authors).

There are four dominant types of dense Calabrian pine forests on Lesvos (Figure 3). First, the very dense conifers aged between 20–45 years old with deep litter layers and an absence of other tree or understory species (Figure 3A). These forests are formerly burned forests that regenerated and reached maturity, but without receiving any type of management. In these stands, mortality due to severe competition results in natural thinning and reduced understory vegetation [46]. In addition, dead branches of living trees reduce the crown base height that adds to the vertical continuity of the fuelbed. Finally, pine needle litter accumulation in thick undecomposed layers is evident, with a storage of dead

pine needles upon the dead branches of trees or upon understory woody vegetation [46]. The most frequent dense conifer type is the short shrub understory mixed with litter (Figure 3B). These are the most frequently burned forests during the past decade. Large parts of the landscape are dominated by mature conifers where agroforestry or past fires reduced the quantity of fuels, creating a relatively fire-resilient forest (Figure 3C). Thirty-year-old Calabrian pine are quite resilient to prescribed burning of understory vegetation since their rhytidome is at an age such that it is thick enough to protect the cambium from the released heat [46]. Finally, dense mature conifer forests with tall shrubs (>2 m) are expected to produce high-intensity fires if burned. In this older forest structural stage, the stands are thinned naturally, and their density is decreasing. The understory is formed by a very dense layer of live herbaceous and woody fuels mixed with conifer litter with very low moisture content. Although we find all four types in our study area, the most common are those in Figure 3B,C. In our previous studies [47] we used field inventory data [48] (see next section for more details) to create four custom fuel models to accurately model the fire behavior in the abovementioned conifer types. A detailed discussion on the four custom fuel model properties can be found in Appendix A.



Figure 3. The typology of the four types of dense pine forests: (A) litter understory; (B) short shrub understory with litter; (C) low-fuel understory; (D) tall shrub understory with litter (photos by the authors).

2.2. Field Inventories on Conifer Forests

The main conifer forested complex was divided into four study sectors: north, central, south, and east (Figure 1A). Wildfires and human-related activities such as grazing, resin collection, infrastructure construction, and farming influenced the development and conditions of each sector. During our previous studies [48], we conducted field inventories (circa 2009) on 52 plots (405 m² each) inside mature conifer forests capturing the range of existing vegetation and fuel conditions, with an additional 30 plots inside post-fire conifer regeneration sites (circa 2011), to measure or estimate tree height, diameter at breast height (DBH), canopy base height (CBH) and crown bulk density (CBD), along with several other surface and canopy stand level attributes (Table 1) based on well-established field

inventory and sampling protocols [49,50]. No major disturbances like fire, insects, disease, or weather damages occurred on the sampled locations or across the study area since the time of field inventories. On each plot, we measured all overstory dominant trees with their crown part of the stand canopy, and understory trees or shrubs with DBH > 10 cm, including suppressed or young trees or shrubs with heights lower than the stand canopy layer.

Table 1. Average vegetation and fuel conditions for the seven forests of the study area, as derived from the field inventory on 82 plots. n.a.: not available. Basal area was estimated for the dominant species (Calabrian pine).

Forest	Plots	Basal Area	Mean Tree Height	Mean Canopy Base Height	Canopy Cover	Overstory/Understory Tree Density	Mean DBH	Litter Depth	Dead Fuel Load
units	n	m ² ha ⁻¹	meters		%	n ha ⁻¹	cm	tons ha ⁻¹	
Vouleri-Koukos	10	38.3	10.6	4.2	59	1034/733	28.4	4	6.72
Paspalas-Megali Limni	10	45.0	11	5	60	1077/533	23.7	10	8.96
Axladeri	9	44.5	11	5	57	790/584	28	4	5.82
Olympus-Ampeliko	8	80.6	13	5.6	58	858/599	35	12	18.83
Rogada	8	57.5	14.3	6.1	58	633/469	35	5.5	8.51
Vrisa-Vatera	7	26.5	13	5	64	490/346	33	8.0	6.51
Megalochori	30	5.1	5.3	2.0	40	1480/n.a.	9.2	n.a.	n.a.

The north sector has one forest (Vouleri-Koukos) with dominant olive plantations east and west of it, while to the north, grasslands and shrubs prevail. Over 90% of all recorded trees were conifers; the litter layer was thin, while herbaceous vegetation and the most common shrub species found elsewhere were absent due to grazing (Figure 3C). The central sector contains two forests (i.e., Paspalas-Megali Limni and Axladeri). The first forest is located on a flat landscape dominated by young conifers mixed with chaparral and shrubs, resulting from repeated wildfires during the years 1984 and 1992 (Figure 3A). The forest of Axladeri is located on the east side of the gulf of Kalloni, with elevations spanning from 40 to 350 m, composed of either single story mature (Figure 3B) or young conifer stands.

Forests in the south sector are comprised of tall and mature conifers (400–800 m), forming multi-story stands with early successional regeneration in canopy openings. Olympus-Ampeliko forest stands had an average DBH of 35 cm, and due to past management from resin collection activities, we found stands with average DBH greater than 100 cm. Rogada forest is comprised of a mixture of mature single or multi-story conifer stands and farming areas. The Vrisa-Vatera forest in the south sector extends to the coastline with either young or mature multistory stands comprised of pine trees, oak (*Quercus macrolepis*) and shrubs (*Quercus coccifera*) (Figure 3D). This forest receives pressure from urban development and touristic activities, resulting in more than 40 fire incidents during the past 40 years, but fire size was small for each incident, i.e., <10 ha and only one with 100 ha. Finally, the east sector is situated on an elevation gradient between 450 and 810 m, dominated by a regenerated conifer forest resulting from the large wildfire of 1994. Young conifers were usually mixed with oaks, shrubs (*Quercus coccifera*), and small shrubs (*phrygana*). Other large areas were dominated by chestnut trees, tall shrubs, and olive trees.

2.3. Design of Fuel Treatment Prescriptions

Table 2 provides information about the proposed treatments (prescriptions) for each conifer forest type. For sparse conifer stands, the goal was to: (a) change the current fuel model (FM) to TU1 (timber understory), which characterizes conditions with low grass load and/or shrubs with litter producing low spread rate and flame length fires [51]; (b) reduce canopy cover and CBD for trees < 5 m height; and (c) increase CBH for trees >5 m height. Canopy treatments (i.e., pixel values that meet the abovementioned criteria) could extend to 1300 ha out of the 2700 ha, i.e., 48%. This percentage is translated to the fraction of area covered with sparse conifers that meets the conditions we set as a prerequisite to receive fuel treatments, i.e., height, canopy cover, CBD, and CBH. For dense conifer

stands, the goal was to: (a) change the FM to TL1 (timber litter), which characterizes conditions with compact forest litter of light to moderate load producing low spread rate and flame length fires [51]; (b) reduce CBD and canopy cover by 50% for areas with CBD values $>0.2 \text{ kg m}^{-3}$; and (c) increase low CBH sites to 4.4 m for areas with CBD $>0.2 \text{ kg m}^{-3}$. Canopy treatments could extend to 8300 ha out of the 16,500 ha, i.e., 50%. Finally, for young conifer and regeneration stands, the goal was to identify areas with high canopy cover ($>50\%$) and reduce it, along with CBD, by 50%, while increasing CBH to 2 m. Canopy treatments could extend to 630 ha out of the 1800 ha, i.e., 35%.

Table 2. Proposed fuel treatments (prescriptions). Numbers in parentheses denote the current average values of each variable. n/t denotes that no treatments were proposed.

Vegetation	Fuel Model [51]	Canopy Cover (%)	CBD (kg/m^3)	Height (m)	CBH (m)
Sparse Conifer	TU1	If height $< 5 \text{ m}$, reduce by 50% (37.9%)	If height $< 5 \text{ m}$, reduce by 50% (0.16 kg/m^3)	n/t (8.34 m)	If $< 3.3 \text{ m}$ and height $> 5 \text{ m}$, set to 3.3 m (3.79 m)
Young Conifer/Regeneration	TU4	If $> 50\%$ reduce by 50% (41.8%)	If $\text{CC} > 50\%$, reduce by 50% (0.01 kg/m^3)	n/t (5.05 m)	If $\text{CC} > 50\%$, increase to 2 m (1.04 m)
Dense Conifer	TL1	If CBD > 0.2 , reduce by 50% (50.3%)	If $> 0.2 \text{ kg/m}^3$, reduce by 50% (0.2 kg/m^3)	n/t (10.7 m)	If CBD $> 0.2 \text{ kg/m}^3$ and $< 4.4 \text{ m}$, increase to 4.4 m (4.43 m)

2.4. Fuel Treatment Optimization

We used the FlamMap fire simulation system to design an optimal fuel treatment scenario [29,52,53]. FlamMap simulates two-dimensional fire growth using the minimum travel time (MTT) algorithm [54] under constant weather. FlamMap uses eight grid themes that describe surface and canopy fuel characteristics and topography that are combined into a binary landscape (LCP) file. Canopy fuel is measured by crown bulk density, canopy closure, height to live crown, and average stand height. Surface fuel is described by fuel models [51,55] that quantify loading of live and dead fuels, surface-area-to-volume ratio for live and dead fuels, the fuelbed depth, moisture of extinction, and heat content. Fuel models are classified depending on the dominant carrier of fire (grass, grass and brush, brush, timber with vegetative understory, timber litter, and slash). The required inputs for the study area were created in previous work using data from field inventories [48]. We used the Treatment Optimization Model (TOM) within FlamMap [29] to design optimal fuel treatments locations. TOM uses a specific weather scenario to analyze the fastest fire travel routes and then uses fuel treatments to block the paths [29]. The process uses two landscape files—one representing the existing condition and the other where treatments are implemented in all possible stands (e.g., ideal landscape). In each scenario, the total area available for treatment is specified and the potential treatment areas are defined. Testing and application of TOM has been discussed in detail elsewhere [56]. In the current study, we specified a maximum of 20% of the landscape was available for treatment, as suggested by Finney [56], and the treatments (Table 2) could be placed without restrictions. We set the maximum treatment dimension of 300 m, consistent with the relatively small size of the typical treatments in Greece.

Weather inputs were derived from a Remote Automatic Weather Station installed in the southern part of the study area [57]. We extracted weather conditions for the month of July 2014 when a severe wildfire burned in the northern part of the study area. We identified the dominant wind direction at northeast (45 degrees), and an average maximum gusting wind speed at 56 km h^{-1} (35 miles h^{-1}). For the TOM process, we used WindNinja [58] within FlamMap to compute local wind vectors for the existing and ideal landscape. Fuel moisture values used in FlamMap were computed from the 10-hr sensor at the weather station and averaged over the 06:00–21:00 time period (base values: 1-hr = 5%, 10-hr = 6%, 100-hr = 7%). Fuel moistures for each fuel model (FM) were adjusted for solar exposure; i.e., grass/shrub FM with no overstory had a reduction of 2% for each dead fuel moisture class (live moistures were set as LH = 30%, LW = 60%), the chaparral FM was the same as base values, and for the timber, FM we added 1% to each dead fuel moisture class (LH = 60%, LW = 90%), similar to our previous studies [59]. Due to lack of the local fuels, all four types of olive plantations (Figure 2)

were assigned the low load, dry climate grass–shrub (GS1) FM (Figure A7A,B) [51]. We assigned the custom fuel model FM03 to conifer forests in Figure 3A (18.5% of all burnable pixels in the study area), FM02 for conditions similar to Figure 3B (13% of all burnable pixels), FM04 for Figure 3C (5% of all burnable pixels), and FM01 for Figure 3D (3% of all burnable pixels). Across the study area, 39.5% of all burnable pixels were assigned a custom conifer FM, 30% with a grass–shrub FM, 15.5% with a grass FM, 6% with a shrub FM, and the remaining 9% with other timber fuel models. Foliar moisture content was set at 90%, corresponding to very dry conditions.

Crown fires were estimated using the Scott and Reinhardt [60] method. Fire simulation validation revealed that modeling produced surface and crown fire rates of spread and other fire behavior characteristics consistent with historical conditions and with reliable estimates having low uncertainty [61] (see Appendix A).

2.5. Fire Simulations to Measure Fire Transmission among Land Use Classes

We used a command line version of FlamMap (FConstMTT Ager, et al. [62]) that was created to model multiple probabilistic weather scenarios [28,63]. In this way, multiple likely weather scenarios can be modeled as part of a single simulation experiment. A total of 10,000 ignitions were simulated with Monte Carlo sampling of three dominant weather scenarios. The scenarios used a simulation duration of 300 min and a wind speed of 48 km h⁻¹, but differed by dominant wind direction probability, i.e., NE (45 degrees; 0.7 probability), NW (330 degrees; 0.2 probability), and SW (225 degrees; 0.1 probability). Ignition location was determined from an ignition probability grid (Figure 1B) created by smoothing 300 historical fire events between 1971 and 2015 using inverse distance weighting [64].

Transmitted wildfire exposure was calculated by intersecting fire perimeters and ignition locations with the land cover layer, similar to our previous research [63,65,66]. We estimated the amount of incoming wildfire, which is the sum of area burned from ignitions on another land cover type; outgoing, which is the sum of all area burned outside the boundary of the ignition land cover type; and self-burning, which is the area burned within a land cover type from an ignition within the same type [67]. Annualized estimates were calculated by dividing the simulated fire size with the number of years of historical fire events records we used for the ignition probability grid (45 years). Incoming, outgoing, and self-burning area burned were estimated for each land cover type using all 10,000 simulated ignitions without differentiating among the three weather scenarios. Results were also used to create a network graph to show the connectivity of wildfire transmission among land cover types. Networks are comprised of nodes corresponding to land cover types, and edges corresponding to fire transmission. Finally, we estimated the spatial differences in burn probability and conditional flame length between the base and treatment landscapes.

3. Results

Simulations revealed that most fires burned in olive plantations (42.7%), followed by dense conifer forests (19.7%), agricultural lands (9.9%), and grasslands (8.1%) (Figure 4A and Table 3). The land cover types that received the most fire from self-burning ignitions were olives, dense conifers, agricultural lands, and grasslands (Figure 4B and Table 3). Sparse conifers received 4.6% of all fires, most of which came from dense conifers (25.5%), olives (25.1%), self-burning (11.6%), grasslands (11.2%), chaparral (10.2%), shrub/grass (7.8%), and agricultural lands (6.2%) (Figures 4C and 5A). Dense conifers burned mostly from self-burning fires (33.8%), followed by olives (31.8%), grasslands (9.1%), and chaparral (6.2%) (Figure 4C). Young conifers received 3.1% of all fires, with 30.8% self-burning, followed by dense conifers (17.4%), olives (16%), chaparral (13.8%), and shrub/grass (9.9%). In Figures 4A and 5B, we see that most outgoing fires came from olives (27.2%), affecting dense conifers, chaparral, grasslands, and agricultural lands. Dense conifers sent 18% of area burned, mostly to olives, grasslands, and chaparral. Chaparral and grasslands sent 12% of total outgoing area burned, followed by agricultural lands. Overall, the amount of area burned generated by ignitions on each land cover type was non-proportional to the cover type's total area, in particular for dense conifers that produced less fire

compared to their proportional area cover, i.e., 35% of the study area but produced 19.7% of total fire activity, olives (27.5% cover/42.7% of total fire activity), and grasslands (5.3% cover/8.1% of total fire activity).

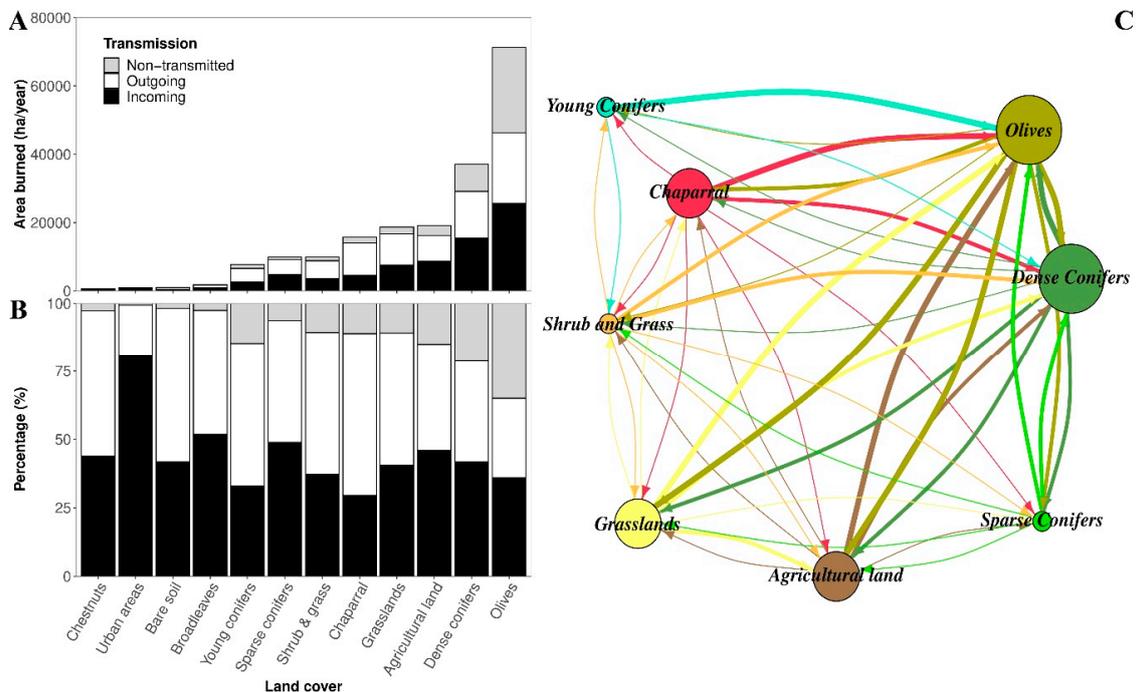


Figure 4. (A) Relative amounts of incoming, outgoing, and self-burning wildfire for the major land cover types in Lesvos Island, Greece by total simulated annual area burned; (B) percent within each land tenure; (C) wildfire transmission network among the land cover types. Network edges in (C) represent wildfire transmitted from one land tenure to another, as shown by the arrow and colored by its source. The size of each node corresponds to the amount of fire transmitted and received from that node.

Table 3. Burned area by land cover type and fire type (incoming or self-burning). Total burned area is the sum of incoming and self-burning area.

	Area (ha)	Incoming Fire (ha yr ⁻¹)	Self-Burning (ha yr ⁻¹)	Total Burned Area (ha yr ⁻¹)	Total Burned Area (%)	Incoming from Total Burned Area (%)	Self-Burning from Total Burned Area (%)
Olives	12,800	25,618	24,939	50,557	42.7	50.7	49.3
Dense conifers	16,500	15,481	7898	23,379	19.7	66.2	33.8
Agricultural land	3300	8796	2880	11,676	9.9	75.3	24.7
Grasslands	2500	7603	2030	9633	8.1	78.9	21.1
Sparse conifers	2700	4841	635	5476	4.6	88.4	11.6
Chaparral	2100	4649	1747	6397	5.4	72.7	27.3
Shrub & grass	2000	3698	1064	4762	4.0	77.7	22.3
Young conifers	1800	2574	1145	3720	3.1	69.2	30.8
Broadleaves	550	954	47	1001	0.8	95.3	4.7
Urban areas	400	743	6	749	0.6	99.2	0.8
Bare soil	330	432	18	451	0.4	95.9	4.1
Water	660	267	0	267	0.2	99.8	0.2
Chestnuts	1120	264	16	281	0.2	94.2	5.8
Oak	40	92	2	94	0.1	98.1	1.9
SUM	46,800	76,013	42,428	118,441	100		

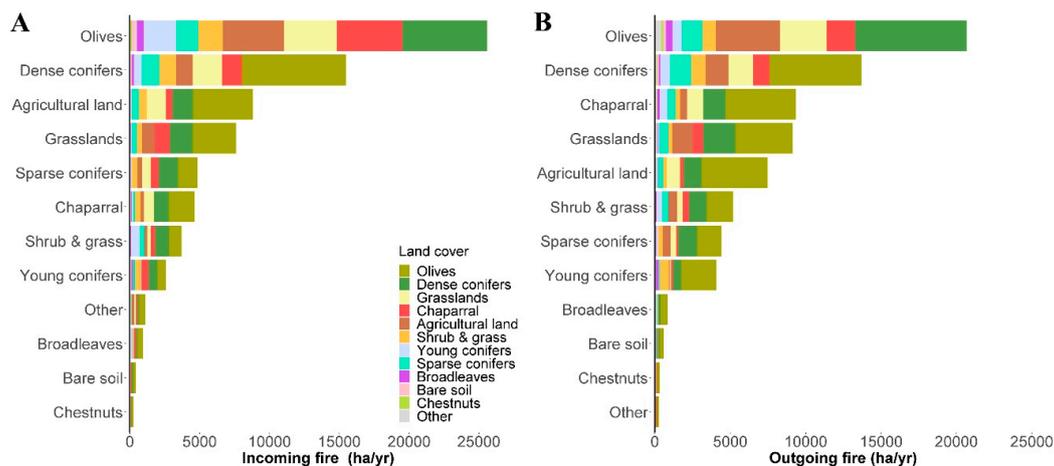


Figure 5. (A) Predicted annual area burned from fires ignited elsewhere by source of ignition (bar colors indicate fire source); (B) Outgoing area burned on other land cover types (*y*-axis labels indicate fire source; bar colors indicate recipient of fire).

The proposed combined surface and canopy fuel treatment units inside conifer forests, as described in Table 2 and derived from TOM simulations, spanned 7600 ha, with 6000 ha located inside dense, 770 ha inside sparse, and 500 ha inside young conifer forests (Figure 6A). This can be translated as 35% of all conifer covered lands and 16% of the total simulation landscape (i.e., 46,800 ha). These treatment areas included 75 polygons with an area >10 ha and 64 polygons between 10 and 100 ha. Five treatment units were between 100 and 250 ha, four between 350 and 650 ha, and two between 800 and 900 ha. Two-thirds of all treatments were located on ten units, each with area greater than 200 ha. At the north and eastern parts of the Vouleri-Koukos forest, we found the largest and most continuous treatments sites. The Olympus-Ampeliko forest also had large candidate areas for fuel treatments. Smaller treatment units were established inside the Axladeri and Vrisa-Vatera forests, while the conifer forest east of the chestnut forests in the Megalochori forest had also great potential for successful fuel treatment application.

The percentage of burned area of each land cover type from the total area burned from each large (>50 ha) simulated fire was estimated using the outputs of the two stochastic MTT simulations (pre- and post-fuel treatments modeling), and was compared using boxplots (Figure A5 in Appendix B). The number of large simulated fires were 8470 for the baseline conditions and 5510 after fuel treatment modeling, with a notable reduction in the percent area burnt by large fires for dense conifers.

Under the assumption that we treated the entire landscape for the stochastic simulations with the MTT algorithm (Figure 6A), the decrease in burn probability (BP) was greater in the southern section of the study area and in parts of the Olympus-Ampeliko and Axladeri forests (Figure 7A), while conditional flame length (CFL) reduction was moderate for most of the dense conifer forests and higher in parts of the Olympus-Ampeliko and Vrisa-Vatera forests (Figure 7B). We noticed that conifer fuel treatments influenced the value of burn probability on different land cover types (Figure 7A), but regarding CFL, almost all pixels with a reduction greater than 1 m were inside conifer forests (Figure 7B). The greatest number of times a pixel could be burned on the base condition simulations was by 395 (out of the 10,000 fires simulated), and decreased to 319 on the ideal conditions simulation (burn probabilities were 0.0395 and 0.0319, respectively). Simulations after applying fuel treatments revealed that sparse conifer forests experienced on average 60 fewer fires and CFL was reduced by 1.17 m; dense conifer forests experienced 50 fewer fires and a CFL reduction of 1.47 m; and young conifer forests experienced 20 fewer fires and a CFL reduction of 0.09 m. We found that more than a third (7800 ha) of conifer forests had a minor reduction in CFL (<1 m), while 9500 ha had a moderate reduction (>1 m up to 2 m), 2300 ha moderate-high reduction (>2 m up to 3 m), and 1400 ha high to very high reduction (>3 m). About 14,500 ha of conifer forests were projected to show a moderate or

low decrease in burn probability, 3500 ha a moderate-high decrease, and 3000 ha a high to very high reduction. For the treatment sites selected by TOM, the reduction in both BP and CFL was high to very high for 20% of their area (approximately 1500 ha), while approximately 50% for both metrics showed a moderate reduction.

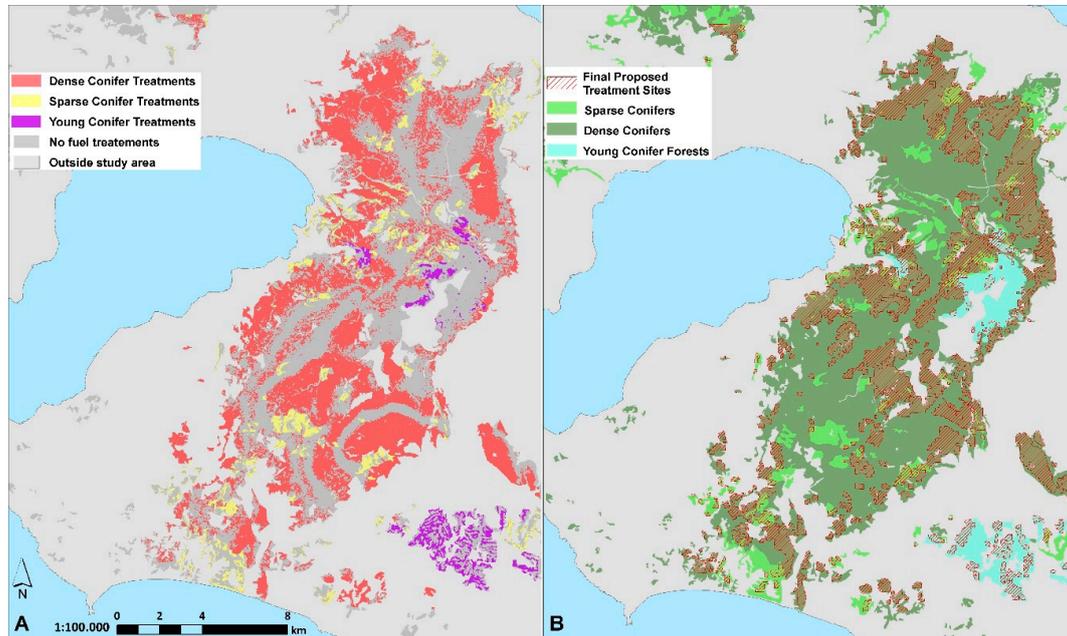


Figure 6. (A) Modifications of canopy cover characteristics for generating the ideal landscape on dense, sparse, and young conifer forests (red, yellow, and purple areas, respectively); (B) optimum fuel treatment areas (red dashed polygons) inside conifer forests where the combined canopy and surface treatments can reduce wildfire behavior, as calculated by TOM.

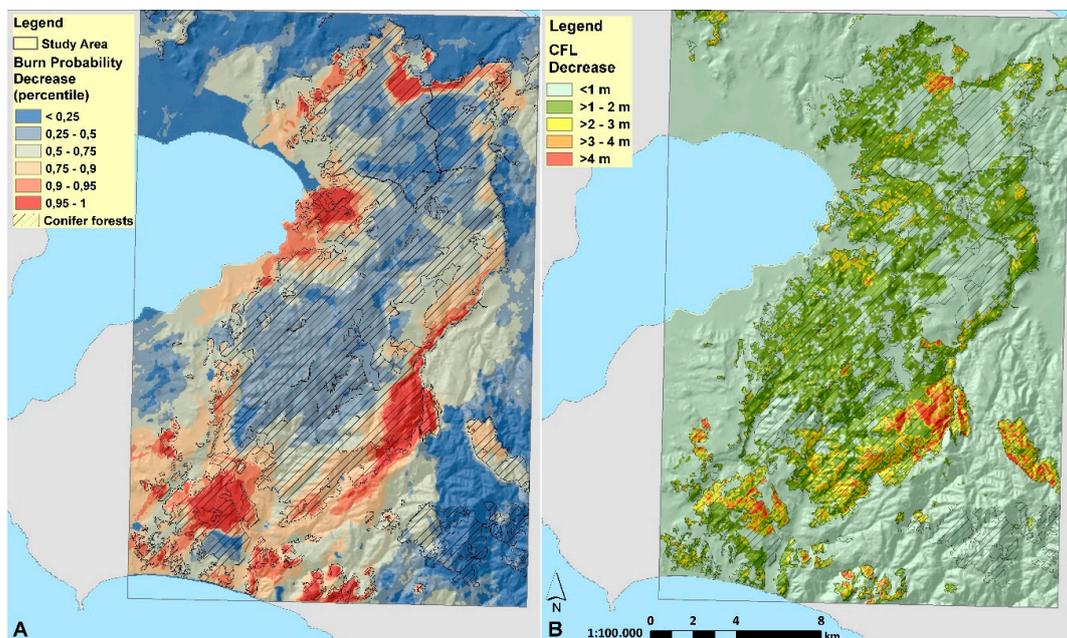


Figure 7. Decrease in: (A) burn probability (BP) and (B) conditional flame length (CFL), as calculated by stochastic fire simulations with MTT for the entire study area.

4. Discussion

Our results showed the how diverse land cover types and land use practices contribute to fire spread on a typical Greek landscape, and how a fuel management program targeting the conifer forests can reduce area burned and fire intensity. One key finding is that olive plantations were predicted to be a substantial contributor to fire exchange among the land cover types even though they cover 22% less area compared to the conifer forests. Olive plantations interspersed with abandoned agricultural lands and grasslands create a fuel mosaic with high rates of overall fire spread. All the major land cover types showed high fire connectivity as measured by fire transmission metrics, with more than half of the outgoing area burned originating from olive plantations and dense conifers. Olives received substantial fire originating on conifer forests, since formerly cultivated olive groves have been invaded by conifers, and on highly productive lands, farmers expanded their cultivations through conifer deforestation (Figure A6A in Appendix C). The result of these land transitions is an increase in shared boundary, and high interdependence in terms of fire spread.

When fuel treatments were located with the TOM optimization process, most of the treatments were placed near boundaries of conifer forests with olives, underscoring the importance of this intermixed land type in the management of fire. Most of the conifer forest was of low priority for receiving fuel treatments because past management practices (agroforestry, silvo-pastoralism, grazing, and resin collection) have collectively kept fuel loads lower relative to the olive–pine intermix. Fuel treatments were also not allocated by the TOM process in areas with a high historical fire density. Overall, the results of the fuel treatment simulation showed that treatments can reduce burn probability and fire intensity on both land cover types. Most treatment units were between 200 and 900 ha, creating a network of adjacent units.

The network diagram of fire exchange among the land uses (Figure 4C) supports the need for a comprehensive fuel treatment program that extends beyond conifer forests to consider all land cover types and their respective contribution to large fires. Limited budgets need to be allocated to efficiently address fire risk, considering the spatial pattern of ignitions, fuel loading, weather patterns, values-at-risk, and suppression strategies on the different land cover types [39,68]. An effective fire risk management strategy should consider the role of direct fire suppression and indirect fuel management on fire size distributions, and understand how fire regimes will be naturally affected by climatic changes through changes in fire weather conditions or changes in dominant forest cover types [69].

In Lesvos, and Greece in general, fire-resilient landscapes have historically been created and maintained by land use practices associated with agroforestry and silvo-pastoralism. These practices were prevalent until the early 1970s and included abundant and frequent low-intensity fire. This is a useful reference condition similar to that used in western US conifer forests to describe resilient forests maintained by natural fires [70]. However, after thousands of years of human activities in Greece, natural and anthropogenic influences on fire regimes are inseparable, except for small enclaves in northern Greece where virgin forests are unaffected by humans with a high-severity stand-replacing fire regime (200–400 years). By contrast, the contemporary fire regime is characterized by <50 years of high-severity stand-replacing human-ignited fires burning in abandoned former agricultural areas with live fuel accumulation and spreading into unmanaged forested areas with dead fuel accumulation. This fire regime resulted from the rural exodus in the 1970s, and aggressive fire suppression policies that created positive feedbacks on the fire regime over time.

Increasing fuel loadings from land abandonment and afforestation need to be addressed with expanded use of agroforestry and silvo-pastoralism [71,72] in the areas surrounding conifer forests. Agroforestry reduces understory vegetation while also providing revenue from the sale of biomass as food or fuel [73]. Silvo-pastoralism can be used to target specific fuels, since grasses and herbaceous vegetation are preferred by cows, horses, and pigs, while goats have a preference for feeding on woody shrubs and young trees [71]. Grazing could also be intensified and reinforced with subsidies to peri-urban livestock farms in those areas we showed through simulated treatments can reduce fire spread rate [74]. One strategy to expand these practices is through implementation of the

European Union's Common Agricultural Policy (CAP), which can be leveraged to reduce fire hazard by: (1) promoting the reintroduction of livestock grazing in areas prone to abandonment [74], (2) creation of agricultural low-hazard belts around urban areas and values-at-risk, (3) the regulation of burning by shepherds and fire use, and (4) directing management to high fire risk areas, giving preference to agroforestry [75]. The result of these efforts could be heterogeneous agroforestry mosaics that allocate crops in an aggregated pattern (10 km yr^{-1} for Lesvos Island), thus providing more opportunities to suppress fires. CAP could also be leveraged to promote regional plans that sustain rural activities in remote areas to ensure the maintenance of croplands, orchards, or pastures over time [76].

In terms of community wildfire protection, it is useful to note that there are distinct land use patterns around developed areas and resulting fire exposure and mitigation strategies. For instance, the three major activities around the communities of Lesvos Island are olive cultivation, animal production, and tourism, where each has a typical fuel complex (Figure A6A,B) and optimal strategy for fuel management. Communities surrounded by conifer forests (Figure A6B) are a high priority for large landscape fuel management programs as demonstrated in this study. Communities in Figure A6C,D are surrounded by olive or other cultivations and orchards, in which case fire risk reduction is dependent on many small landowners managing fuels inside the plantations. The importance of olive plantations in the exchange of fire among land uses was a key finding in the study, where one third of all transmitted fire originated from these areas. Fuel management should be prioritized and spatially coordinated among landowners to create fuel break systems that can facilitate fire suppression as part of community protection programs.

The dense conifer forests were also a significant source of fire transmission to other land uses (one fifth of the total) and creating fire resilient forests will require significant expansion of traditional fuel management practices. The Greek Forest Service has the authority to license individuals from forested communities to extract forest biomass for household or commercial reasons, a cost-effective and socially accepted alternative to fuel treatments performed by contractors. Biomass extraction for bioenergy is one solution for Mediterranean policy makers to consider, but these programs need to be scaled over large areas to substantially reduce area burned during extreme weather events [77], and treatments need to include unmanaged or abandoned lands and private forests, and targeted to source areas that cause high exposure with high hazard. Currently, industrial timber production in high productivity timber stands ($>100 \text{ m}^3 \text{ ha}^{-1}$ and $\text{DBH} \geq 5 \text{ cm}$) is applied on 400,000 ha across all Greece, while in less productive stocks ($<100 \text{ m}^3 \text{ ha}^{-1}$), it is applied in more than one million ha [72]. The annual timber production is 1.1 million m^3 , 30% of which comes from private forests; one third is produced from conifer species, with most of the production ($\sim 65\%$) used as fuelwood. Collaborative actions between private contractors and the Greek Forest Service to perform silvicultural thinning could reduce wildfire activity and improve the ecology and health of future forests (e.g., stewardship contracting; see [78]). For the protection of private conifer forests, compulsory fuel removal on surrounding fire prone farmlands could help reduce the risk of transmitted wildfire from those lands.

The selection of fuel management projects presents a challenge to forest management agencies to reduce fuels at landscape scales while addressing, among others, the presence of human infrastructure and settlements, the smoke effects on human health and recreation, the protection of highly valued resources, such as wildland habitat and drinking water quality, and constraints such as timber targets set in forest management plans. Policies, constraints, and regulations that restrict treatment location, type, and total area treated can significantly degrade the performance of these strategies [56]. Using modeling approaches as described in this work can provide forest managers with a number of different potential treatment polygons that, in turn, using on-ground knowledge and spatial data, can be selected to design a strategy that will minimize negative effects while achieving fire risk reduction targets. Newer methods such as scenario planning and trade-off analyses can help predict optimal treatment locations to apply to each strategy [79,80].

All fuel management scenarios considered in this study assumed the use of mechanical means to reduce forest fuels and excluded the use of prescribed fire since it is currently illegal in Greece.

Legislative reforms to allow the careful application of prescribed fire could substantially accelerate policy to reduce fuel loadings by providing a low-cost method for fuel management. The effectiveness of fire in fuel management is widely supported by recent studies that found higher fuel treatment effectiveness under extreme conditions for treatments included broadcast burning, compared to thinning and/or pruning alone [32,81–83]. The latter treatments can contribute to surface fuel biomass accumulation and more severe wildfire effects. While it is still common and legal for farmers to use fire (pile and burn) in olive groves to remove fuels (Figure A7), frequent burning is required to maintain low fuels loads under Mediterranean conditions and prevent severe fires [1,32,84,85]. A recent study in Catalonia suggested that applying prescribed fire treatments (15,000 ha yr⁻¹ in an area of 32,000 km², i.e., 750 ha yr⁻¹ for Lesvos Island), can greatly contribute to a decrease in high intensity fire and extreme fire events [86]. In addition, allowing prescribed burning under a controlled forage burning program administered by an authorized agency would reduce the risk from frequent illegal fires set by livestock farmers to increase forage production.

We note several limitations and assumptions to this work. Fire behavior modeling of proposed fuel treatments can overestimate the effectiveness of potential fuels treatment to reduce fire behavior [87] if fuel models do not accurately reflect the post-treatment conditions. Fire managers are required to evaluate and justify the effectiveness of planned fuel treatments resulting from modeling processes in modifying fire growth, behavior and effects on resources and assets [88]. Validation of fire behavior modeling outputs was a crucial component of this analysis, and we performed local accuracy assessments to validate that the modeled fire behavior of each fuel model closely resembles the observed one (Appendix A). Accuracy and results validation for MTT simulations in Greece have been assessed during previous studies [47,89,90] (Appendix A). Surface fuel conditions and canopy cover have not experienced major disturbances within the study area since the time of field inventories (circa 2009), but a major source of potential simulation error comes from the accuracy of spatial inputs regarding fuel conditions in the canopy layer, especially regarding crown bulk density. This is a result from both mapping error (see [48]) and forest growth since the time of field inventories. Additionally, TOM assumes that reduction in large fire growth is obtainable through the collective effect of many units occurring on the landscape [38]. We also assumed that simulated wildfires were larger than the fuel treatment units to allow the analysis to focus on the directions in which fires move rather than their start locations [53]. We also did not account for the benefits of the proposed treatments on fire suppression, and thus we underestimated the reduction in area burned in the treated landscape. Another assumption is that we estimated the impact of large fires that can escape initial attack by burning under the most frequent, but also average–extreme weather conditions (average worst-case fire potential), thus simulating the proposed treatments to perform under these target conditions. A limitation of TOM is that it requires a single modeled weather scenario; thus, we restricted the modeling on a single fire front from one wind direction and speed. Less frequent weather scenarios and from different fire fronts could potentially highlight different treatment locations, but with lower probability of experiencing a wildfire. To address this, during stochastic MTT simulations, we used thousands of ignitions under different weather scenarios to account for both spatial and weather variability. Although we used three different weather scenarios, they describe only the current dominant weather conditions without considering the uncertainty related to climate warming scenarios and how climate change can exacerbate fire risk in Mediterranean Europe in the coming decades [91]. This makes even more critical the need for proactive fuel reduction treatments simultaneously combined with other management options (i.e., a more proactive and integrative management).

The spatial optimization of fuel treatments in this study assumes that all treatment units will be implemented at a given instance in time, but in reality, treatments are accomplished on an annual basis and treatment effects in reducing fire behavior diminish with time, approximately one decade after implementation [29]. Given the historical treatment rate that the Greek forest management agencies can implement annually, to effectively treat 7600 ha (16% of the landscape) as simulated here in the span of a decade, the annual treatment rate must be no lower than 760 ha yr⁻¹ (1.6% of the landscape), which

is actually twice as much as the percentage locally treated with best-case administrative conditions in Greece (e.g., the local Forest Service branch of Kassandra in Chalkidiki, northern Greece, with an area similar to our case study). Finally, we did not exclude high slope (20% of the proposed treatment is located on slopes $>20^\circ$), rugged and high elevation sites, which can substantially decrease the available land for fuel treatments.

5. Conclusions

This study explored the exchange of wildfire among diverse land uses on a typical Greek landscape and used an optimization approach to demonstrate the potential benefits of a fuel treatment program that targeted conifer forests. The optimized allocation of 7600 ha of fuel treatments inside conifer forests can substantially reduce wildfire intensity and burn probability, mostly on lands with high olive-conifer connectivity. By identifying major fire travel routes and attempting to block them through fire behavior modeling exercises, we gained an insight into the efficiency of current or proposed fuel treatments. The fuel treatment effectiveness presented here was achieved with an optimized allocation of treatment units with an area greater than 200 ha. While our study site does not directly address the full range of fuel conditions found in Mediterranean fire-prone ecosystems, our methodology can be applied at any geographical extent if the required spatial inputs for modeling exist. Future work will focus on cooperative landscape fuel management of olive groves and forested areas to create an *olea-pinus* landscape fuel management strategy that includes multiple adjacent treatments that cross vegetation type boundaries. The intensification and support of traditional land use practices provides an opportunity to reduce risk more efficiently with limited resources.

Author Contributions: Conceptualization, P.P. and K.K.; methodology, P.P., A.A.A. and K.K.; writing—original draft preparation, review, and editing, P.P., A.A.A., M.A.D. and K.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research has been supported by the USDA Forest Service International Programs (grant no. G-3-10895).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A.

Appendix A.1. Fire Simulations Validation

In a landscape, as there are numerous potential combinations of vegetation types, characteristics, and succession stages, and it is almost impossible to characterize all possible combinations, the most common approach used for fire-spread modeling is to generalize and characterize fuels into a finite number of fuel models [92]. Using fire simulation based on the Rothermel's model [93] requires the selection of standard fire behavior fuel models [51], or the calibration of custom fuel model parameters against observed fire rate of spread or flame length [93–95]. The selection of the standard fuel models for the simulations presented in this research effort was based on the similarity to actual fuels in terms of general fire-carrying fuel type, fuel properties (e.g., depth, live fuel load, compactness), photo-guides and expected fire behavior. For each land cover class, except for conifer forests, we assigned a standard fuel model from the set of 40 fuel models of Scott and Burgan [51]. For conifer forests, we used four previously created custom fuel models that describe the four types of conifer fuel conditions found in the study area. In this Appendix, we first provide a brief explanation of the characteristics of the custom conifer fuel models, and then we present the results of testing and comparison of simulated fire behavior for these four custom fuel models with standard fuel models [51] under three fuel moisture scenarios. Finally, we provide a comparison of the actual fire perimeters for five historical fires that occurred on Lesbos island with simulated fire perimeters using three indices: the Jacard coefficient, the areal association coefficient, and the Sørensen–Dice coefficient. Three of these fires occurred or burned in conifer forests, and we provide a comparison from two simulations, one with custom and

the other with standard fuel models for conifer-dominated areas. The other two fire events occurred and burned in olive groves or grass–shrub-dominated areas; thus, no custom fuel models were used. All simulations were conducted with FARSITE [96] to ensure that the wind variability simulated during all these events will be considered, since the minimum travel time (MTT) algorithm [54] uses only one set of wind speed and direction for each simulated fire event. The validation of stochastic fire simulations with MTT was achieved by comparing the average fire size of all simulated large fires (>50 ha) with historical fires, and by ensuring that the maximum simulated burned area matched the historical.

Appendix A.2. Methods

Appendix A.2.1. Characteristics of Custom Conifer Fuel Models

During our previous research efforts [47,48], we created four custom fuel models which describe the fuel conditions that can be found inside Calabrian pine (*Pinus brutia*) forests (Table A1). The first fuel model (FM01) describes the fuel conditions of conifer forests with maquis dominating understory (>20% understory cover) and an average height of over 1.5 m (*Pistacia lentiscus*, *Quercus coccifera*, *Arbutus unedo*, *Phillyrea media*), mixed with litter from Calabrian pine. The second fuel model (FM02) describes the fuel conditions of conifer forests with a mixture of brush and short shrub (phrygana) dominating understory (>20% understory cover) and an average height lower than 1.5 m (*Erica malipuliflora*, *Sarcopoterium spinosum*, *Cistus creticus*, *Cistus savofolius*, *Genista acanthoclada*, *Juniperus oxycedrus*), mixed with litter from Calabrian pine. Compared to FM01, shrubs are sparse and shorter, and fires are transmitted mostly from the combustion of conifer litter. The third fuel model (FM03) describes the fuel conditions of conifer forests with litter and other downed dead fuels dominating the understory (>70% cover), mixed with short sparse shrubs (<30% cover). Finally, the fourth fuel model (FM04) describes the fuel conditions of conifer forests that have been grazed, burned, or managed (timber or resin collection) with enclaves of regeneration, where the general fire carrier is low loading of canopy litter mixed with annuals, short brush, seedlings, and saplings.

Table A1. Parameters of the custom fuel models used in Lesvos simulations. Table adapted from [47].
Sa/V: fuel surface area-to-volume ratio; Lh: Live herbaceous; Lw: Live woody.

Fuel Model	1-hr Fuel Load	10-hr Fuel Load	100-hr Fuel Load	Live Herbaceous	Live Woody	Fuel Depth	Dead Fuel Moisture of Extinction	1-hr Sa/V	Sa/V Lh	Sa/V Lw	Live Moisture
units	tons/acre					feet	%	1/feet		type	
FM01	3.53	1.27	1.47	0.03	5.08	1.97	15	750	1800	1600	dynamic
FM02	3.43	1.45	0.73	0.04	1.32	0.82	25	1500	1800	750	dynamic
FM03	3.05	1.09	0.98	0.04	0.88	0.52	35	1800	1800	1600	dynamic
FM04	1.12	1.00	0.49	0.06	0.79	0.49	20	2000	1800	1600	dynamic

Appendix A.2.2. Fire Behavior Estimates of Custom Fuel Models

To test custom fuel model surface fire behavior and assess whether they are indicative of the actual fire behavior of conifer forests in Lesvos, we used the BehavePlus software [97] to first enter the necessary inputs to create each fuel model (Table A1) and then produce fire behavior estimates, keeping all other required variables constant (topography, fuel moisture, and wind speed). We used three fuel moisture scenarios (FMS) that correspond to the measured fuel moisture conditions of the fire period (May–September), as retrieved from a network of Remote Automatic Weather Stations in Lesvos island [57]. A fuel moisture scenario is a set of fuel moisture values representing moisture conditions of the surface fuel: 1-hr, 10-hr, 100-hr, live herbaceous, and live woody moisture (Table A2).

Table A2. The three fuel moisture scenarios used to test the simulated fire behavior of the four custom fuel models. See text for detailed descriptions of each fuel moisture scenario.

Fuel Moisture Class	Fuel Moisture Scenario		
	D1L1 ¹ (%)	M2 (%)	D2L2 ¹ (%)
1-hr	3	4	6
10-hr	4	5	7
100-hr	5	6	8
Live Herbaceous	30	50	60
Live Woody	60	80	90

¹ D1L1 and D2L2 are fuel moisture scenario codes from the BehavePlus fire modeling system [98].

The FMS D1L1 describes very low dead fuel moisture conditions with fully cured herbaceous vegetation, corresponding to weather conditions recorded during the heatwaves at the end of July and first half of August. The FMS M2 describes very low dead fuel moisture conditions, but with two-thirds cured herbaceous vegetation, corresponding to weather conditions recorded during June and the last days of August–early September. Finally, the FMS D2L2 describes low dead fuel moisture conditions with two-thirds cured herbaceous vegetation, corresponding to the typical weather conditions of May, early June, and late September. For all simulations, we set a constant wind speed of 24 km hr⁻¹ and a slope of 50%. Results were visualized with a set of fire characteristic chart diagrams that plots the relationship of rate of spread, heat per unit area, flame length, and fireline intensity. Each custom fuel model was compared with a set of three standard fuel models [51] that can potentially describe similar fuel conditions to each of the custom fuel models.

Appendix A.2.3. Accuracy Assessment Indices

We used three indices to estimate the accuracy of FARSITE simulations, namely the Jacard coefficient (JC), the areal association coefficient (AAC), and the Sørensen–Dice coefficient (SC). The JC index [99,100] estimates the similarity between burned and simulated area on a range of 0 (perfectly different) to 1 (perfect similarity) with Equation (A1):

$$JC = \frac{R1}{(R1 + R2 + R3)} \quad (A1)$$

where $R1$ is the number of cells with burn agreement, $R2$ is the number of cells with underestimation, and $R3$ is the number of cells with overestimation. This index does not account for cells that define non-burning agreement ($R4$). The AAC index [101,102] includes the estimation of similarity between both burned and unburned areas, with a range of 0 to 1, similar to the JC Index, estimated with Equation (A2):

$$AAC = \frac{R1 + R4}{(R1 + R2 + R3 + R4)} \quad (A2)$$

Finally, the SC is a non-symmetric index that can reveal the correlation between simulated and actual burned area [103,104] with a range of 0 to 1, similar to the JC Index, estimated with Equation (A3):

$$SC = \frac{2 \times R1}{2 \times (R1 + R2 + R3)} \quad (A3)$$

Appendix A.2.4. Spatial Validation of Historical Fires

Validation of fire simulations for Lesvos island was based on five large fire events that occurred on five different parts of the island: southeast, north, central-north, central and south. The southeastern fire burned 670 ha on 19th July 2006 and propagated through conifer fuels mixed with shrubs in a densely forested area. Fire burned mostly conifer forests, olive groves, and shrublands over an area with high slopes (~20°) under the influence of strong northern winds. The north fire occurred on 4th July 2011 and burned 62 ha in a landscape dominated by grass–shrub, partially covered by dense shrublands. Winds

were of moderate intensity blowing from northwestern directions. The central-north fire occurred on 7th July 2009 and burned 65 ha mostly inside sparse conifer forests. Fire propagated under the influence of moderate northern winds, mostly through conifer litter mixed with shrubs which shortly transmitted inside grasslands and neighboring olive groves through spotting. The central fire occurred on 31st July 2009 and burned 12 ha inside dense conifer forests. Fire propagated under the influence of moderate-low northeastern winds, mostly through conifer litter mixed with shrubs. Finally, the south fire occurred on 4th August 2011 and burned 850 ha. Fire ignited inside olive groves, initially under the influence of northern winds, which soon changed into northeastern of moderate intensity. The fire burned mostly olive groves and grass–shrub dominated areas.

Appendix A.3. Results

Appendix A.3.1. Simulated Fire Behavior from Custom Fuel Models

Table A3 shows the cumulative results of the four custom fuel models for the maximum rate of spread (ROS in m/min), flame length (FL in m), fireline intensity (FI in kW/m), and heat per unit area (HPUA in kJ m^{-2}). ROS is reduced on average across the three FMS scenarios by 50% when comparing FM01 to FM04 and by 25% from FM01 to FM03, but FM01 and FM02 have similar values. The average difference between FM01 and FM02 in terms of FL is 14%, from FM01 to FM03 is 40%, and from FM01 to FM04 is 63%. Differences appear between FM01 and FM02 when we compare them based on FI, with an average reduction of 33% from FM01 to FM02, and up to 89% reduction when comparing FM01 to FM04. The average reduction of FI from FM01 to FM03 is 53%, while from FM03 to FM04 to 67%. Similar results were found for HPUA. In the fire characteristics chart (Figure A1), we notice that FL values from FM01 and FM02 are above the 4.5 m threshold, requiring an indirect approach for firefighting. Fires burning in forests with FM03 require aerial means to aid suppression efforts, falling within the 3.3–4.5 m FL class, while for FM04, mechanical means are adequate to confront a potential fire event. A scaled increase and a clear separation of fire behavior characteristics is evident when comparing FM04 to FM03, FM03 to FM02, and FM02 to FM01. These results agree with observed fire behavior in those four distinct types of conifer forests on Lesvos island.

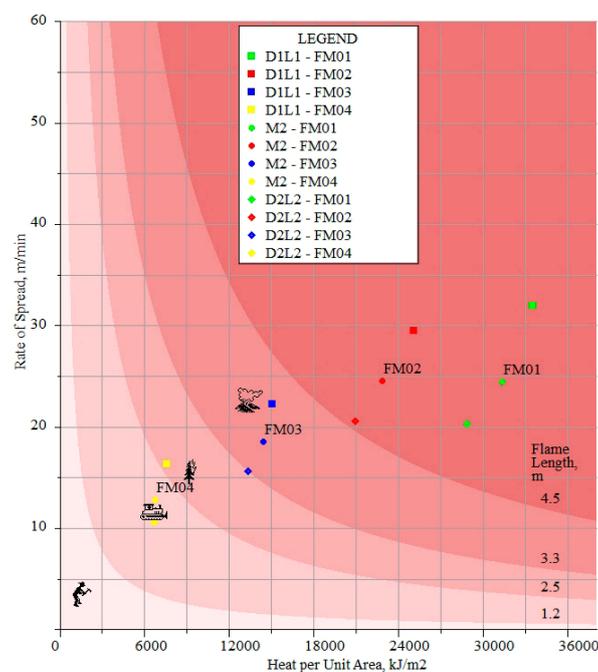


Figure A1. Fire characteristics chart of the simulated fire behavior of the four custom fuel models for conifer forests.

Table A3. Fire behavior simulation results using the BehavePlus software for the four custom fuel models for conifer forests. FMS: Fuel Moisture Scenario.

FMS	Maximum Rate of Spread (m/min)			Flame Length (m)			Fireline Intensity (kW/m)			Heat Per Unit Area (kJ/m ²)		
	D1L1	M2	D2L2	D1L1	M2	D2L2	D1L1	M2	D2L2	D1L1	M2	D2L2
FM01	32	24.5	20.3	7	6	5.3	18,099	12,979	9825	33,935	31,817	28,987
FM02	29.5	24.6	20.6	5.9	5.2	4.6	12,197	9473	7222	24,787	23,072	21,001
FM03	22.3	18.6	15.7	4.1	3.7	3.3	5717	4511	3486	15,362	14,526	13,321
FM04	16.4	12.8	10.6	2.6	2.2	2	2062	1480	1116	7543	6925	6289

When FM01 is compared with the standard fuel models, namely the TU5 (Very High Load, Dry Climate Timber–Shrub), the TL8 (Long-Needle Litter), and the SH7 (Very High Load, Dry Climate Shrub) we notice that HPUA and FL are substantially higher compared to TL8, the FL and ROS are higher compared to TU5, and the ROS are smaller compared to SH7 (Figure A2A). The simulated fire behavior for FM02 is between the TU5 and TU4 (Dwarf Conifer with Understory) standard fuel models, and substantially higher compared to TL8. FM03 is closer to the fire behavior of TL8 and TU4, but with evident differences in terms of ROS, while it is substantially lower compared to TU5 across all fire behavior metrics. Finally, FM04 showed moderate differences compared to the TU1 standard fuel model (Low Load Dry Climate Timber–Grass–Shrub), with similar ROS with TL8, and important differences across all fire behavior metrics with TU4. These results revealed a good separation of the four custom fuel models when compared to the standard fuel models and can bridge the gap of fire behavior modeling discrepancies when compared to the observed fire behavior.

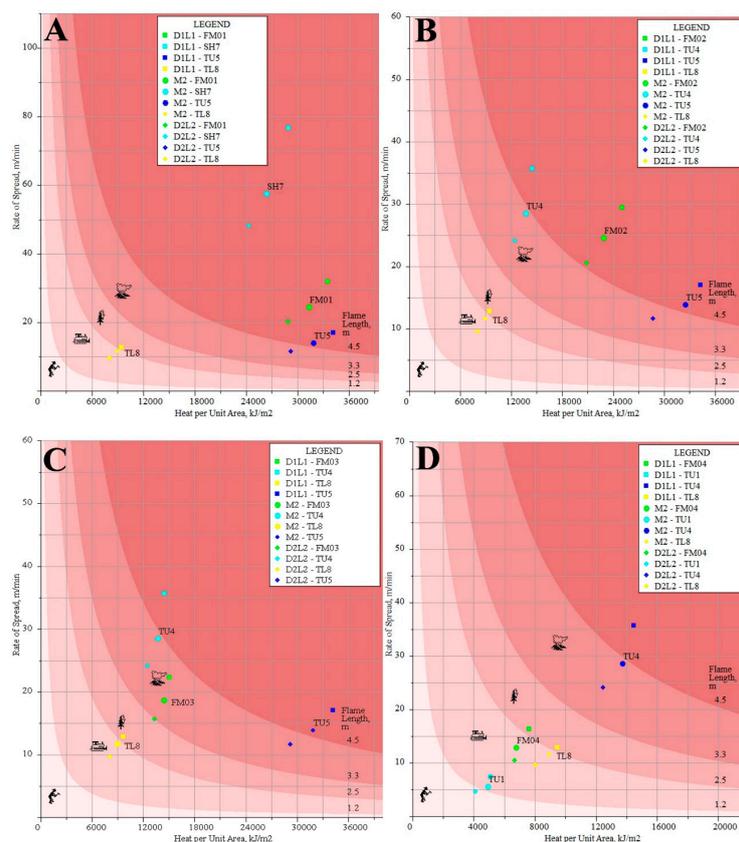


Figure A2. Fire characteristics chart of the simulated fire behavior of: (A) the custom fuel model FM01 with the standard fuel models TL8 (Long-Needle Litter), TU5 (Very High Load, Dry Climate Timber–Shrub), and SH7 (Very High Load, Dry Climate Shrub); (B) the custom fuel model FM02 with the standard fuel models TL8, TU5, and TU4 (Dwarf Conifer with Understory); (C) the custom fuel model FM03 with the standard fuel models TL8, TU5, and TU4; (D) the custom fuel model FM04 with the standard fuel models TL8, TU4, and TU1 (Low Load Dry Climate Timber–Grass–Shrub).

Appendix A.3.2. Spatial Accuracy and Validation of Historical Fires

In Table A4, we report the validation results of each fire from both custom and standard fuel model simulations using the three indices. The southeastern fire had better indices scores (closer to 1) for custom fuel models, with less burn agreement (R1) and higher underestimation (R2), but with substantial less overestimation (R3) and better non-burning agreement (R4) (Figure A3A,B). The custom fuel models FM01 and FM02 were used in most areas, with smaller parts characterized with FM03. We used the TU5 and TL3 for the standard fuel model simulations. The central-north fire had slightly higher scores for SC and JC, and slightly lower for the AAC. Across all metrics (R1-R4), values are similar, but custom fuel models had better burn agreement and higher overestimation (Figure A3C,D). The custom fuel models FM02 and FM03 were used in most area, while in standard fuel model simulations we used the TU5. The central fire has higher scores for SC and JC, but substantially lower AAC score. Standard fuel models underestimated the total burned area, while we noticed an overestimation across all directions for custom fuel models fire (Figure A3E,F). The custom fuel models FM02 and FM03 were used in most area, while in standard fuel model simulations, we used the TL8 and TL3. Since in all simulated fires we have not modeled fire suppression efforts, which were intense with rapid response for all fires, overestimation is an expected outcome and within our acceptable sources of error.

Table A4. Validation indices results from FARSITE simulations, comparing simulated with actual fire perimeter of five historical fires. R1: Burn agreement; R2: burn disagreement (underestimation); R3: burn disagreement (overestimation); R4: non-burning agreement. SC: Sørensen–Dice coefficient; JC: Jacard coefficient; AAC: areal association coefficient. Standard: Scott and Burgan [51] fuel models.

Fire Location	Fuel Model Type	SC	JC	AAC	R1	R2	R3	R4
Southeast	Standard	0.56653	0.395217	0.690489	6297	1159	8477	15,200
	Custom	0.61509	0.444136	0.813189	4647	2809	3007	20,670
Central-North	Standard	0.56253	0.391334	0.78539	578	164	735	2712
	Custom	0.57929	0.407743	0.766293	674	68	911	2536
Central	Standard	0.31214	0.184932	0.919377	27	109	10	1330
	Custom	0.40683	0.255361	0.741192	131	5	377	963
South	Standard	0.7736	0.630786	0.896039	8708	752	4345	35,223
North	Standard	0.47237	0.309217	0.812155	671	21	1478	5810

The north and south fires burned inside non-conifer fuels; thus, fire simulations were conducted only with the set of standard fuel models. The south fire has a very good burn agreement (Figure A4A), with overestimation over its northeastern boundaries and a small underestimation at the southeast. The SC, JC, and AAC indexes values were the highest (closest to 1) compared to all the other simulated fires. Fuel models GS1 and GR2 were used in the majority of the area, with a smaller area characterized with SH2 and TU5. Finally, the north fire had low values of SC and JC, but with high AAC (Figure A4B). The simulation had a perfect burn agreement, no underestimation, but important overestimation at the east and western directions. Fuel models GS2 and SH7 were used in most area, with smaller area characterized with GR2 and TU5.

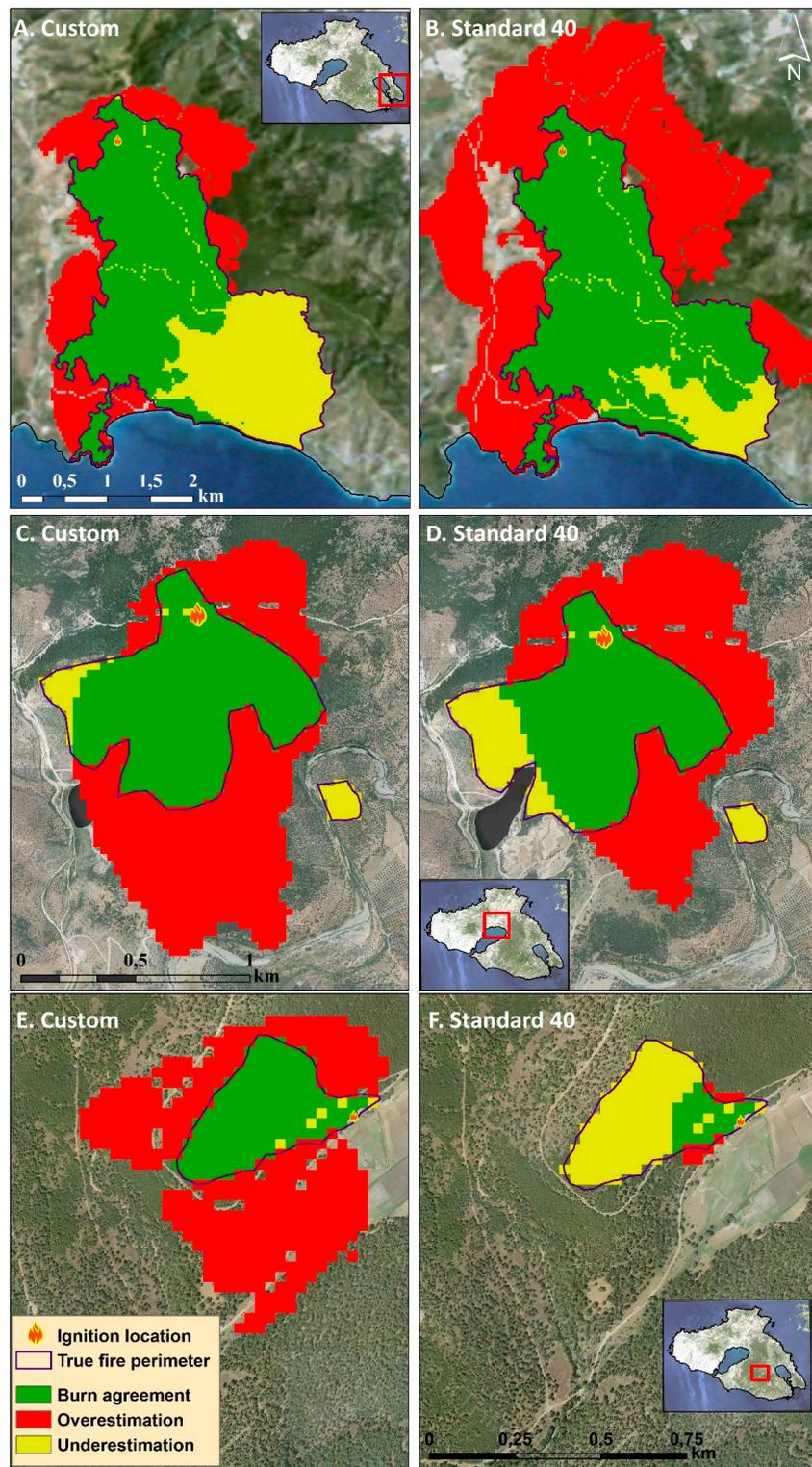


Figure A3. FARSITE simulation results comparing the four custom fuel models with the standard Scott and Burgan [51] fuel models for fires that burned mostly inside conifer fuel types. (A,B): southeast fire; (C,D): central-north fire; (E,F): central fire.

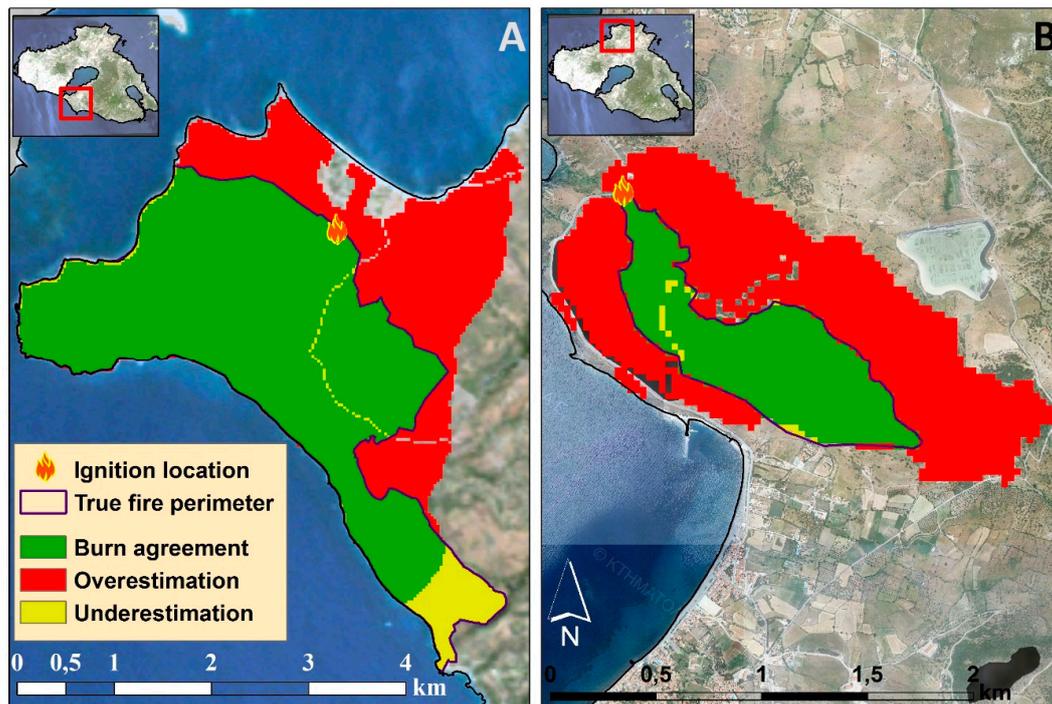


Figure A4. FARSITE simulation results using the standard Scott and Burgan [51] fuel models for fires that burned mostly on olive groves and grass–shrub fuel types. (A): South fire; (B): north fire.

As a final note, the stochastic fire simulation results of 10,000 ignitions on the base conditions revealed that the largest simulated fire matched the size of the largest historical fire in the study area (~2500 ha). The average fire size of all simulated large fires (8700 fires burning >50 ha; standard deviation 522 ha) with a 90% confidence level is 622 ± 9.2 ($\pm 1.5\%$) [612.8–631.2 ha]. The average historical fire size of the 11 fires in the study area > 50 ha is 626 ha (standard deviation 689 ha) and is within the confidence interval levels of the simulated large fires.

Appendix A.4. Conclusions

Validation of historical fires revealed a good simulation accuracy, with custom fuel models performing slightly better compared to the standard fuel models. We found a good separation among the four custom fuel models in terms of surface fire behavior characteristics, with each of them adequately representing the observed fire behavior of wildfires on Lesvos island. Overestimation and underestimation of the actual burned area possibly occurred from firefighting efforts which have not been modeled and are a great source of uncertainty in any fire simulation effort. Stochastic simulations with the MTT algorithm match the size of the largest wildfire recorded in the area (~2500 ha in 1994—a fire that burned mostly inside conifer forests), while the average simulated fire size of large fire events also matched the average fire size of the 11 historical fires within study area. Results enhance confidence in the outputs and conclusions of the main manuscript.

Appendix B.

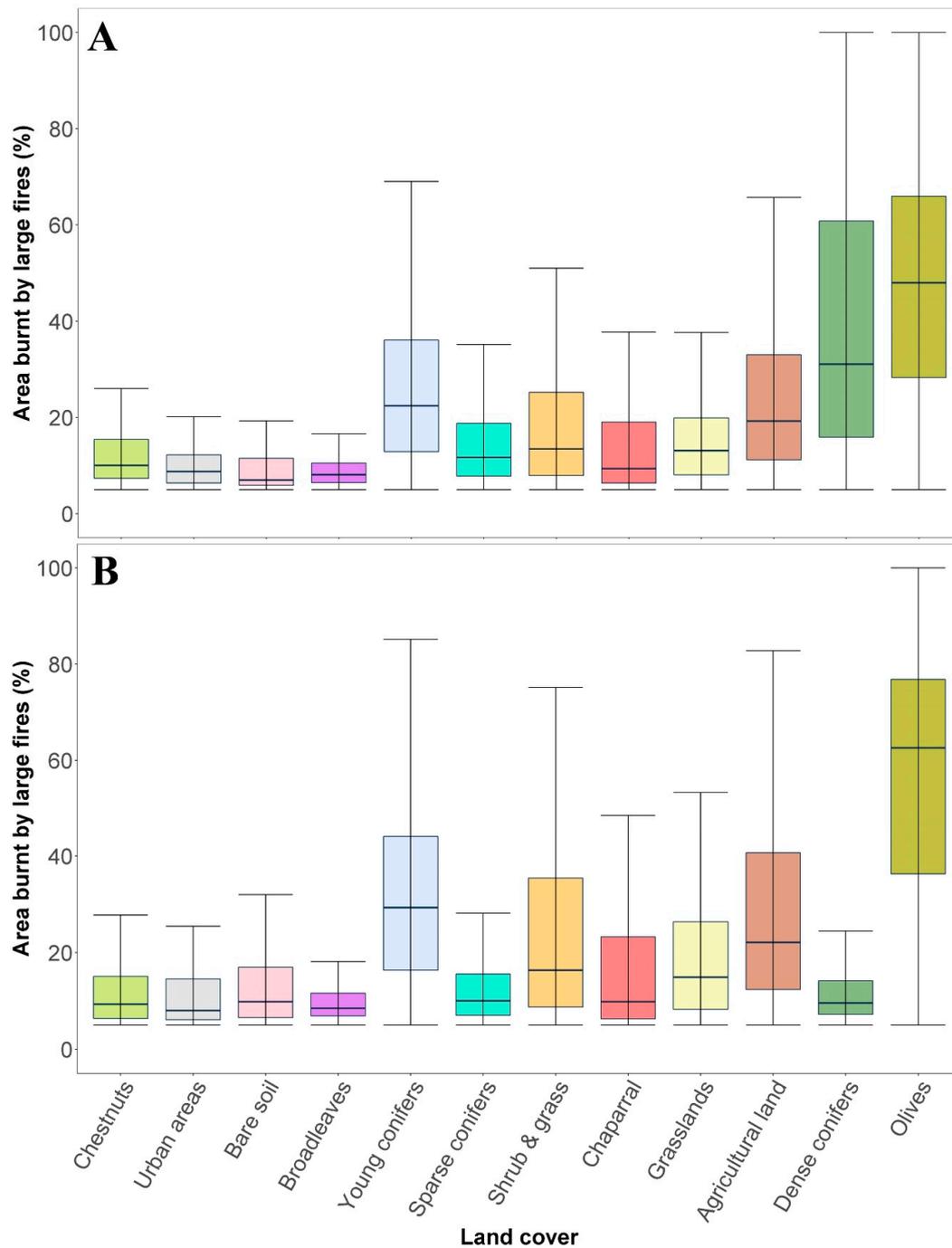


Figure A5. Statistical distributions for the percentage of burned area of each land cover type from the total area burned from each large simulated fire (>50 ha), obtained after 10,000 simulated fires with the minimum travel time algorithm for: (A) baseline conditions; (B) after the application of fuel treatments. The number of large simulated fires for (A) was 8470, while for (B) it was 5510. Values less than 5% from the total burned area of each land fire were not included in the statistical distributions (e.g., when a large fire of a total burnt area of 100 ha burned less than 5 ha in broadleaves).

Appendix C.



Figure A6. The typology of fuels around the communities of Lesvos Island: (A) agricultural encroachment and conifer deforestation; (B) high-amenity wildland–urban interface inside dense conifers and olive cultivations; (C) olive monoculture; (D) mixed broadleaves with conifers, shrubs, and orchards (source: Google Earth).



Figure A7. Pile burns of crown reduction residuals and shrubs, removed during the winter with mechanical means, in labor-intensive managed olive groves: (A,B) fuel conditions before the application of fuel removal and pile burning, with olive tree crowns in vertical continuity with tall shrubs, and understory where short dense shrubs mixed with tall grass prevail—fire behavior is represented with the fuel model GS1; (C) active combustion; (D) smoldering; (E) fuel conditions three months after the pile burns, where fuelbed consists of short grass and patchy short shrubs (photos by the authors).

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