`A geographical analysis of wildfire fuel characteristics by cover type in Greece

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Abstract. The main drivers of wildfire behavior are topography (e.g., slope), weather (e.g., wind and fuel moisture content) and fuel (e.g., quantity, arrangement, and continuity at both the surface and canopy levels). In this study, we examined how the fuel characteristics (fuelbed inputs grouped as fuel model, canopy cover and stand height) vary by cover type and across the different regions of Greece for the reference year of 2018. In addition, we investigated how the different fuel models vary in terms of canopy characteristics and topographic features. The analysis was conducted by combining vector and raster datasets. Canopy characteristics datasets were retrieved from open geospatial providers such as the Global Land Analysis and Discover team at the University of Maryland, USA, which used the Global Ecosystem Dynamics Investigation (GEDI) Lidar forest structure measurements to map forest height, and the Copernicus Tree Cover Density. The CORINE Land Cover vector dataset of 2018 served as the base mapping and analysis layer, supplemented by information from the National Forest Registry of Greece (circa 1992) to define vegetation species in each CORINE class. Results showed important regional variations of fuel model types that explain the regional differences in burned area. Also, the distribution of topographic features by fuel model is indicative of why certain fuel types burn more frequently and intensively than others. We provided a breakdown of canopy cover and height by species that can aid to the understanding of which are the forests that require management to reduce their density (high canopy cover) or can create more revenue (high stand height).

1 Introduction

The changes occurred on the Greek landscapes during the past three decades are phenomenal. It is not only the two seasons (2007 and 2021) of mega-fires that shook the societal and political *status quo* regarding the way we confront, manage and live with fires, but also the way that these mega-fires reshaped the biophysical and social realities. For example, the unpreceded 40,000 ha of 2021 in Evia destroyed the economic fabric of the region and huge funding were funneled there by the Greek government to maintain the social balance and change the established economic paradigm. In addition, the destruction of so many hectares of forested lands in an isolated islandic system, and the years required to regenerate, is paving the ground for more natural disasters such as increase flooding and soil erosion, rockfalls and soil loss. As we enter the era of mega-fires, we expect that similar wildfires will occur not only in regions prone to large fire propagation such as the Peloponnese, Attica and Evia, but also to high elevation ecosystems as those found in Central Greece and Epirus. By default, these ecosystems have reduced defenses from both the non-fire-resistant vegetation species that cover them and by the intense depopulation that led to land abandonment and in turn, fire deficiencies that enhance fuel accumulation. To put it simply, there is not a single region in Greece that can claim that will remain “fire-proof” during the era of mega-fires. From this standpoint, we ask where potential future fires will ignite and how they will propagate. Furthermore, how these future fires can affect populated places and other values-at-risk. One approach to examine this is through stochastic fire behavior modelling, producing thousands wildfire simulations. These simulations can in turn used to estimate community exposure and ecosystem risk and use the results to plan for potential preventive measures to reduce the estimated fire spread rate and intensity. To achieve this goal, it is important to create or find the necessary inputs for this fire behavior modelling software to run. In this study we created a combined dataset of basic fire simulation inputs (fuel models, elevation, slope, canopy cover and stand height) and critique their distribution across the Greek landscape.

2 Materials and Methods

Wildfire behavior models, such as those of Rothermel (1972) consider numerous empirical variables. While these inputs are important for equation outputs, they are often difficult and time-consuming, if not impossible, to measure for each fuel bed. A fuel model defines these input variables for a stylized set of quantitative vegetation characteristics that can be visually identified in the field. Depending on local conditions, one of several fuel models may be appropriate. As the base mapping layer, we used the CORINE Land Cover (CLC) (EEA 2022) inventory (2018 version) after intersecting its main forest related classes, i.e., Broad-leaved forest, Coniferous forest, Transitional woodland-shrub and Mixed forest with a detailed vegetation species layer produced by the First National Forest Inventory of Greece that captured the species distribution and cover for reference year 1992 (Palaiologou et al. 2022). Then, based on knowledge retrieved through extensive inventories across different Greek ecoregions (Kalabokidis et al. 2016) and expert knowledge regarding the potential fire behavior of each vegetation class, we assigned one or more fuel models at each class depending on topographic and other conditions. For example, olive groves received three different fuel models depending on the slope of each pixel considering that smaller slopes are easier to treat and maintain in a low fuel state by their owners (≤5°; Fuel Model: GR1, Short, sparse dry climate grass), compared to those pixels with slopes between 5-15° (FM: GS1, Low load, dry climate grass-shrub) and >15° (FM: GS2, Moderate load, dry climate grass-shrub), where fuel is usually comprised of tall grass mixed with short shrubs and other vegetation. Similarly, grasslands burn differently across the elevation gradient, with higher altitudes be moister and with different plant properties, i.e., density, height, mixture with shrubs, dead fuel moisture of extinction and curing period. We assigned five different fuel models to grasslands and pastures based on the elevation gradient where the pixel was located, i.e., 0-600 m: GS2, >600-800 m: GS1, >800-1200 m: GR4, >1200-1700 m: GR2, and >1700 m: GR1 (see Table 1 for fuel model definitions). All pixels from the European Settlement Map Built-up areas, after resampling, were assigned with a non-burnable fuel model since those areas are mostly residential buildings or roads. For stand height, we used the ETH Global Canopy Height 2020 (Lang 2022), which is a product that fused the GEDI with Sentinel-2 though probabilistic deep learning model to retrieve stand height at 10 m ground sampling distance for the year 2020. Tree canopy cover was retrieved from the Copernicus portal, showing the level of tree cover ranging from 0 (all non-tree covered areas) to 100% for the reference year 2018 in 10 m spatial resolution. Lastly, using the University of Maryland Forest Loss per Year (Hansen et al. 2013), we retrieved the locations of pixels that faced forest loss during 2019 and assigned the fuel model GS1 to describe the conditions that prevail after a disturbance, mostly wildfires in our case, that is characterized by a mixture of tall, cured grasses during the summer mixed with short shrubs. For canopy layer, for disturbances occurred after the reference years of 2020 for tree height and 2018 for canopy cover, we assigned a pixel value of zero. All raster datasets, both the inputs and the final layers, were resampled at 30 m spatial resolution.

3 Results

The most widespread fuel model for forested areas is the TL6, assigned mostly to mixed broad-leaved forests (5.4%), *Quercus* spp. (4.24%) and *Fagus* spp. (1.5%) (Table 1). Next, TU1 was assigned to transitional woodland-shrub dominated by *Quercus* spp. (3.9%), sparse vegetation dominated by *Quercus* spp. (1.3%) and agricultural lands mixed with sparce *Quercus* spp. and other natural vegetation (1.4%) and broadleaf shrubs (0.5%). The TU5 was primarily assigned to *Pinus* spp.(2.5%), mixed broadleaf-coniferous forest (1.2%), *Pinus halepensis* (1.5%) and transitional woodland-shrub dominated by *Abies* spp. (0.7%). The TL9 was assigned mostly to high elevation conifers, such as *Abies* spp. (1.7%), and mixed broadleaf-*Abies* spp. (0.4%). Last, the TU4 fuel model was assigned mostly to sparse *Pinus halepensis* (1.10%). Regarding the non-forest fuel models, GS1 was assigned to natural grasslands with sparse wooden vegetation (8.2%), land principally occupied by agriculture, with significant areas of natural vegetation (5.4%), complex cultivation patterns (5.2%) and olive groves (5%). The SH5 was assigned to sclerophyllous vegetation (11.9%), natural grasslands with significant area covered with shrub (1.3%) and mixed forest with shrub understory (1%). The GR1 was assigned to non-irrigated arable land (8.9%), pastures (0.85%) and vineyards (0.6%). The GS2 was assigned to discontinuous urban fabric (1.6%), agricultural areas with natural vegetation and significant area covered with shrub (1.3%) and sparse vegetation with shrubs (0.55%). The GR4 was mainly assigned to natural grasslands (1.6%). Finally, the SH1 was assigned to fruit trees and berry plantations (1%) and pastures with sparse and short shrub (0.15%).

Table 1. Fuel models distribution over the Greek landscape

Fuel Model Type	Description	Area (ha)	Percent
GS1	Shrubs are about 1-foot high, low grass load. Spread rate moderate; flame length low.	3,648,959	24.68
SH5	Heavy shrub load, depth 4 to 6 feet. Spread rate very high; Flame length very high.	2,110,436	14.28
TL6	Moderate load, less compact. Spread rate moderate; Flame length low.	1,683,304	11.39
GR1	Grass is short, patchy, and possibly heavily grazed. Spread rate moderate; flame length low.	1,596,590	10.80
TU1	Fuelbed is low load of grass and/or shrub with litter. Spread rate low; flame length low.	1,075,986	7.28

TU5	Fuelbed is high load conifer litter with shrub understory. Spread rate moderate; flame length moderate.	950,141	6.43
NB3	Agricultural field, maintained in non-burnable condition.	932,250	6.31
GS2	Shrubs are 1 to 3 feet high, moderate grass load. Spread rate high; flame length moderate.	583,043	3.94
SH7	Very heavy shrub load, depth 4 to 6 feet. Spread rate lower than SH5, but flame length similar. Spread rate high; flame length very high.	437,221	2.96
TL9	Very high load broadleaf litter; heavy needle-drape in otherwise, sparse shrub layer. Spread rate moderate; flame length moderate.	309,797	2.10
GR4	Moderately coarse continuous grass, average depth about 2 feet. Spread rate very high; flame length high.	299414	2.03
NB8	Open water	253029	1.71
TU4	Fuelbed is short conifer trees with grass or moss understory. Spread rate moderate; flame length moderate.	194115	1.31
SH1	Low shrub fuel load, fuelbed depth about 1 foot; some grass may be present. Spread rate very low; flame length very low.	180016	1.22

In Figure 1, the fuel model map is presented, covering the entire Greece and a 20-km buffer zone expanding into Albania, North Macedonia, and Bulgaria. This zone has not been expanded to Turkey, since the river Evros that defines the border between the two countries was considered as a barrier to fire transmission, eliminating the need to further expand the study area.

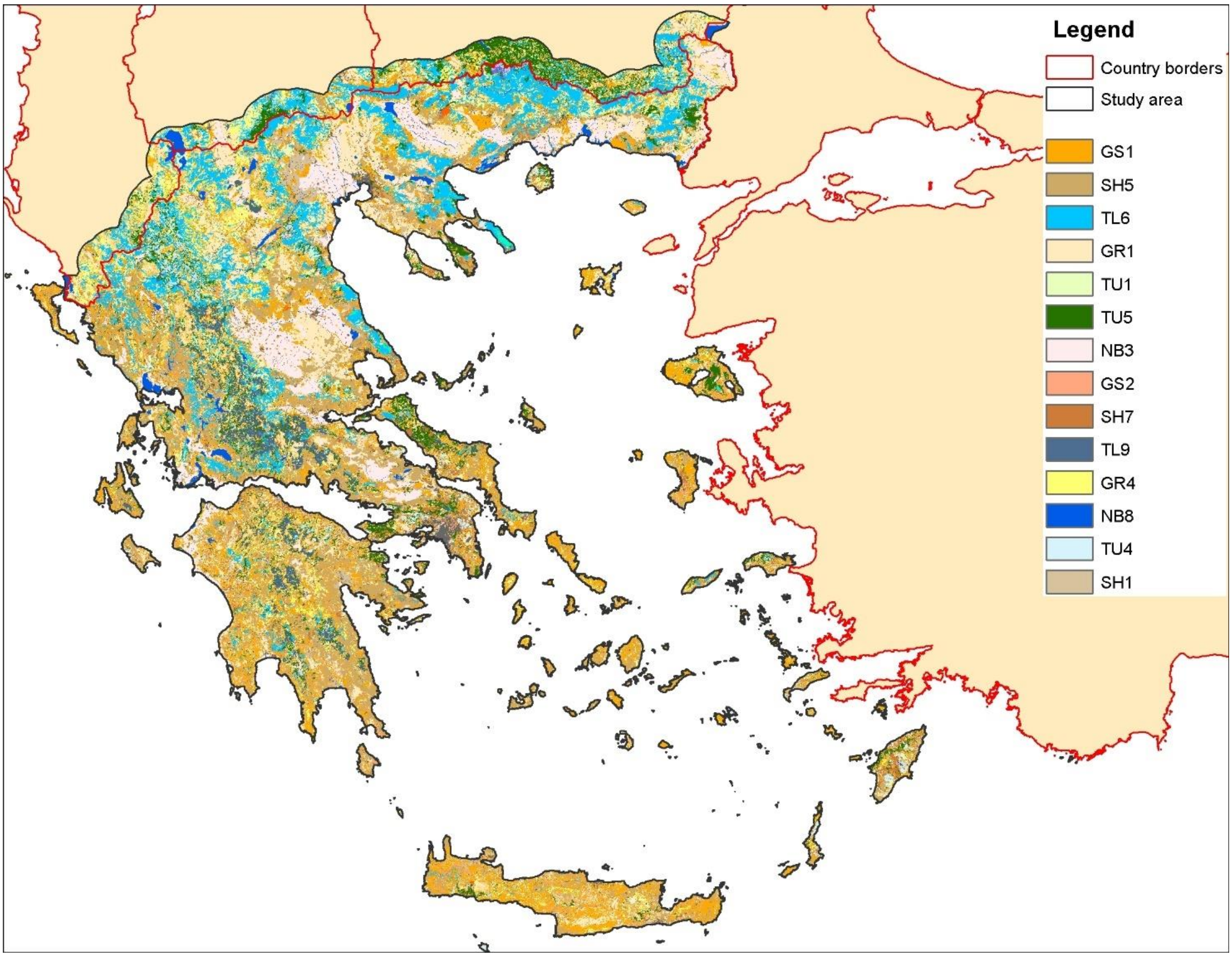

Figure 1. Fuel models of study area, including a buffer zone of 20-km at the northern borders of Greece.

Below, we examine the four main fuel models used for forested areas (TL6:186; TU1: 161; TU5: 165 and TL9: 189) based on their elevation, slope, stand height and canopy cover properties. In Figure 2, the TL6 fuel model that describes conditions of moderate load broadleaf litter is dominant mostly on elevations < 1300 m and on moderate to high slopes (between 12 and 30 degrees). The majority of pixels of stand height are in the range of 17.5-37.5 m (77%), followed by a 14% with a height > 37.5 m. For the TU1 fuel model where the primary carrier of fire is low load of grass and/or shrub with litter that produces low spread rates and flame length (Figure 3), 30% of all pixels are in elevations < 600 m and 45% between 600 and 1000 m. Above 1000 and below 1450 m we find the 21% of all pixels with this fuel model. Regarding slope, 10% of all values are <5°, 33% between 12 and 21° and another 33 between 21 and 30 °. Almost 20% of all values are in slopes > 30°. This fuel model has an important percentage with low canopy cover (32% of pixels with <15% canopy cover), but on the other hand, 42% of all pixels have cover between 55-85%. For stand height, almost 60% of all pixels are in the range of 17.5-37.5 m, suggesting that mature old-growth forests exist there, while 33% have heights <2.5 m, an indicator that these are mostly shrublands.

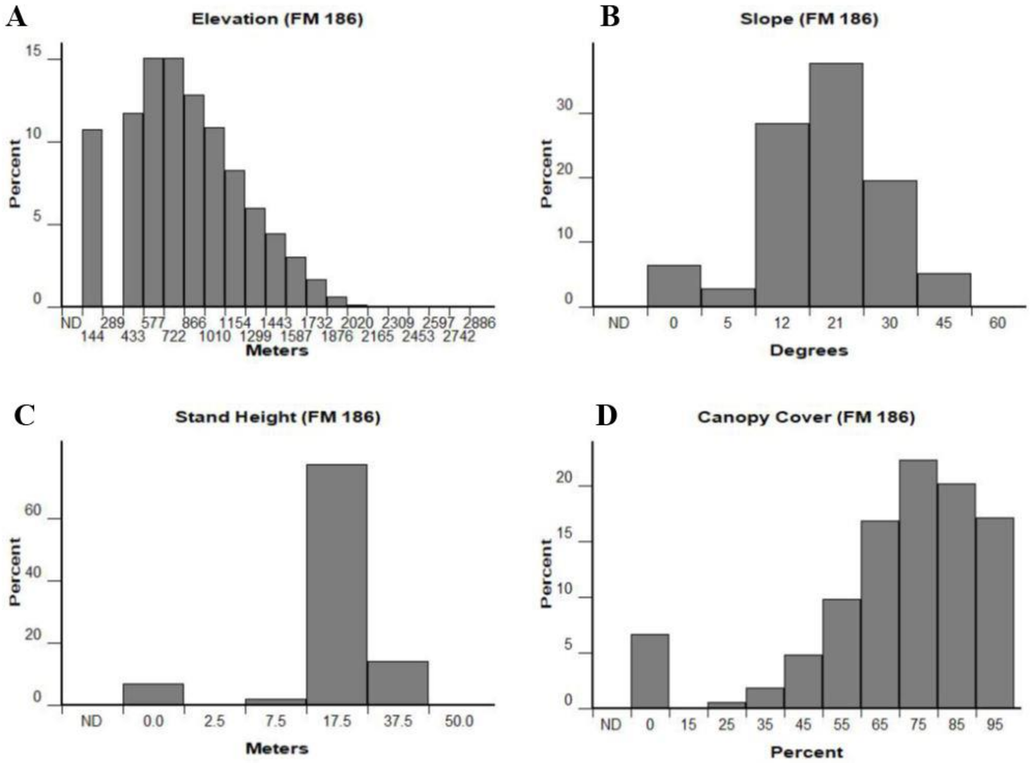

Figure 2. Characteristics and properties of the locations assigned with the fuel model TL6 - Moderate Load Broadleaf Litter. **(A)** Elevation. **(B)** Slope. **(C)** Stand height. **(D)** Canopy cover.

In Figure 4, the distributions of the TU5 fuel model are presented. For this fuel model, the primary carrier of fire is heavy forest litter with a shrub or small tree understory producing moderate spread rate and flame length. We found that 28% of all pixels with TU5 fuel model are located below 600 m elevation, and 25% between 600-1000 m. A very high percentage (46%) is located on very high elevations >1000 m above sea level. The most frequent slope category is the 21-30 degrees with 35% of all pixels, followed by the 12-21 degrees (27%) and 30-45 degrees (20%). Almost 80% of all pixels have canopy cover >55%, with a substantial percentage of 30% with cover >85%.

Last, in the stand height class of 175.-37.5 m falls the 58% of all pixels with this fuel model, with another 26% falling in the class of 37.5-50 m. An important finding is that 13% of all pixels have a height < 2.5, suggesting potential errors in the input datasets for that fuel model. Finally, for the fuel model TL9 (Figure 5) that describes conditions of very high load, fluffy broadleaf litter with moderate spread rate and flame length, we found that 80% of all pixels with that fuel model are in elevations between 1000-1600 m. In addition, a 16% of all pixels are in slopes steeper than 45°, with 65% falling in slopes between 21-45°. An impressive 44% of all pixels have closed canopies with >95% cover, with another 37% of pixels having canopy cover between 75-95%. Finally, these forests are very tall, with almost 40% of all pixels falling in the stand height class of 37.5-50 m, and 55% in the class of 17.5-37.5 m.

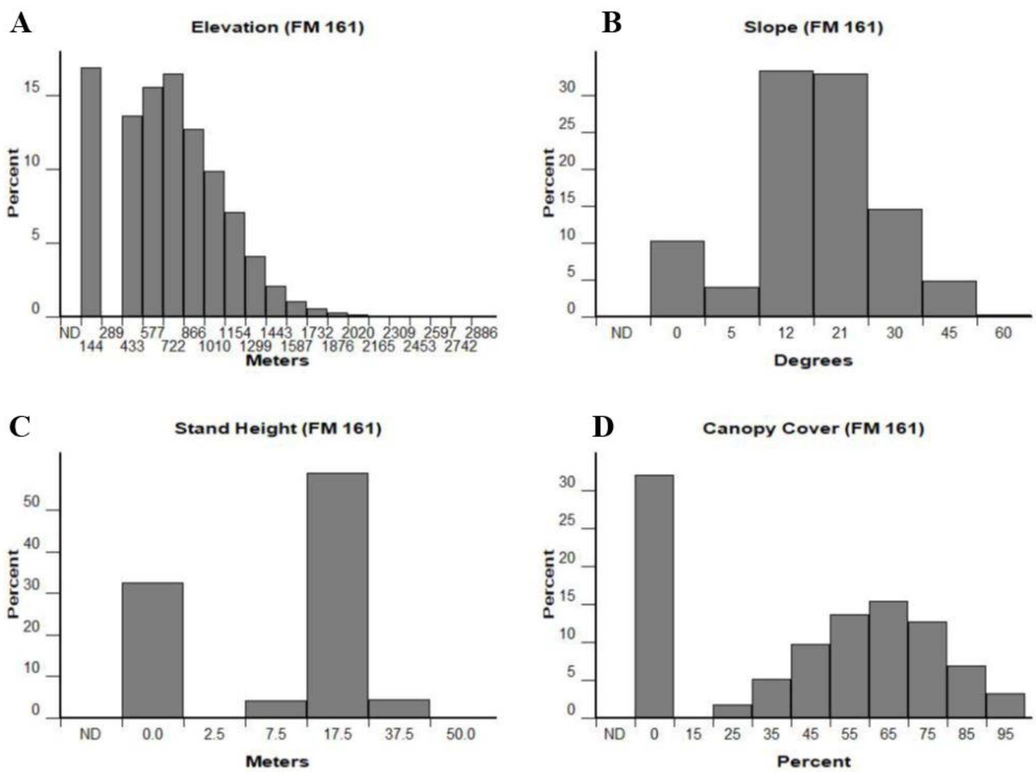

Figure 3. Characteristics and properties of the locations assigned with the fuel model TU1 - Low Load Dry Climate Timber-Grass-Shrub. **(A)** Elevation. **(B)** Slope. **(C)** Stand height. **(D)** Canopy cover.

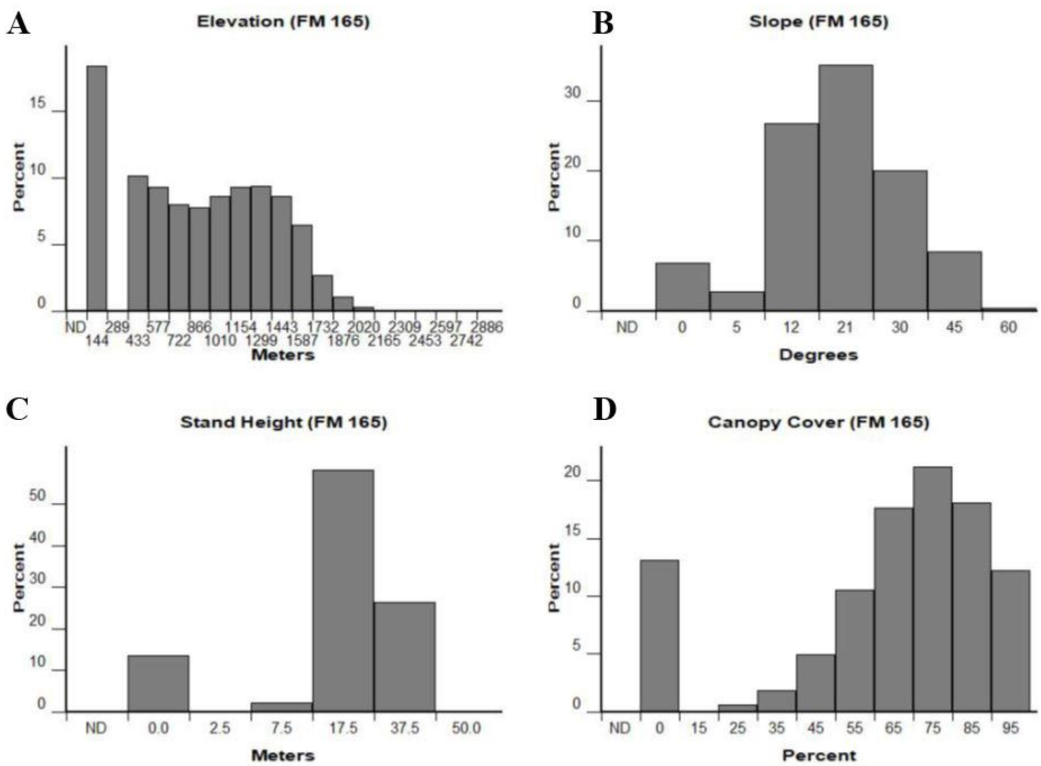

Figure 4. Characteristics and properties of the locations assigned with the fuel model TU5 - Very High Load, Dry Climate Timber-Shrub. **(A)** Elevation. **(B)** Slope. **(C)** Stand height. **(D)** Canopy cover.

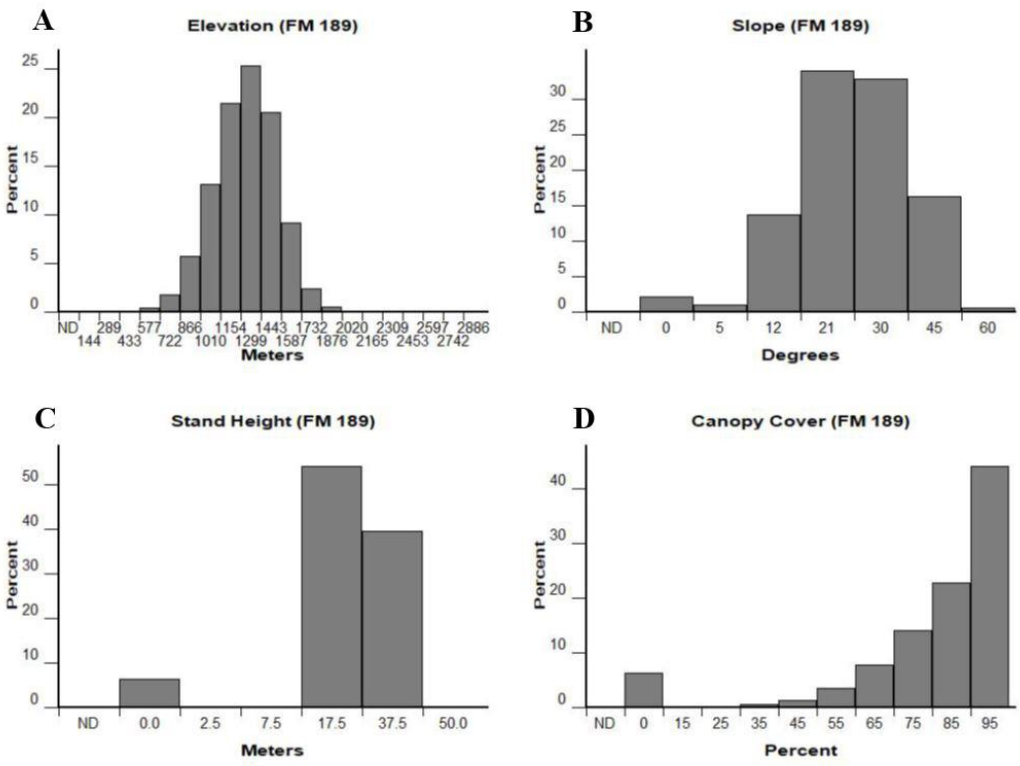

Figure 5. Characteristics and properties of the locations assigned with the fuel model TL9 - Very High Load Broadleaf Litter. **(A)** Elevation. **(B)** Slope. **(C)** Stand height. **(D)** Canopy cover.

3 Concluding remarks

Creating model-ready datasets and applying them to analyze wildfire risk and exposure for Greece is a tractable problem if Copernicus data and other datasets from trusted publishers/creators are used in conjunction with local knowledge and auxiliary datasets that describe the forest conditions and the fire history of each area. We found that large parts of Greece are covered by non-tree species, and little can be done there to reduce fire risk, except for suppression. Fuel models that exclusively describe forest stand conditions cover a much smaller portion of the landscape and there, it is possible to reduce the potential fire spread and intensity through fuel management. We also found that certain ecosystems can become more resilient if low intensity fuel treatments are applied there, for example, in tall forests covered with the TL9 fuel model or in very dense canopy cover areas, where thinning can promote both natural regeneration and reduce fuel load and canopy compactness.

Acknowledgements

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