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Article

Canopy Fuel Load Mapping of Mediterranean Pine Sites Based on Individual Tree-Crown Delineation

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Abstract: This study presents an individual tree-crown-based approach for canopy fuel load estimation and mapping in two Mediterranean pine stands. Based on destructive sampling, an allometric equation was developed for the estimation of crown fuel weight considering only pine crown width, a tree characteristic that can be estimated from passive imagery. Two high resolution images were used originally for discriminating Aleppo and Calabrian pines crown regions through a geographic object based image analysis approach. Subsequently, the crown region images were segmented using a watershed segmentation algorithm and crown width was extracted. The overall accuracy of the tree crown isolation expressed through a perfect match between the reference and the delineated crowns was 34.00% for the Kassandra site and 48.11% for the Thessaloniki site, while the coefficient of determination between the ground measured and the satellite extracted crown width was 0.5. Canopy fuel load values estimated in the current study presented mean values from 1.29 ± 0.6 to 1.65 ± 0.7 kg/m^2 similar to other conifers worldwide. Despite the modest accuracies attained in this first study of individual tree crown fuel load mapping, the combination of the allometric equations with satellite-based extracted crown width information, can contribute to the spatially explicit mapping of canopy fuel load in Mediterranean areas. These maps can be used among others in fire behavior prediction, in fuel reduction treatments prioritization and during active fire suppression.

Keywords: tree crown extraction; GEOBIA; object based; canopy fuel load; forest parameters

1. Introduction

Mediterranean landscapes have long been subjected to wildfires, and therefore, burning has become part of their dynamic natural equilibrium [1]. While wildfire risk has been mitigated historically by extensive grazing and harvest activities, reduction and abandonment of these practices has led to an increase in the amount of fuel available for burning [2,3]. Mediterranean fuels are distinctly different from other fuel complexes worldwide in terms of fuel load (fuel weight per unit area), thus creating conditions of extreme fuel hazard [4]. Low-elevation Mediterranean Aleppo pine (*Pinus halepensis* Mill.) and Calabrian pine (*Pinus brutia* Ten.) forests in southern Europe are extremely prone to crown fires and represent about one-third of the total burned area in the Mediterranean Basin [5]. In addition, the broadleaved evergreen shrub understory (known as "maquis") below the live canopy fuel complex creates ladder fuels that facilitate fire transition from the forest floor to the canopy layer. In Greece alone, the Aleppo and Calabrian pine forests represent 23% of the total burned area [6].

Effective fire management decision support systems, incorporating fire behavior models for analysing spatial variation in wildfire exposure and mitigating risk [7], require accurate descriptions of fuel complex characteristics [8]. Until recently, fuel complex quantification was limited to surface fuel beds, due to the restricted applicability of fire behavior models, such as the BEHAVE system [9], to this fuel layer [9]. The development of fire behavior models and systems (NEXUS, FARSITE, FlamMap, *etc*.) designed to predict crown fire behaviorhas pointed out the need for accurate aerial fuel descriptions [10]. When describing aerial fuels, the term"crown" is applied to describe aerial fuels at the tree level and "canopy" at the stand level. Because canopy fuels are the main fuel layer supporting crown fire spread, canopy fuel load has become essential for fire management planning, especially in coniferous forests [11,12].

Spatially explicitly maps of canopy fuel loading can be used to predict fire behavior and guide operational responses during active fire suppression, to prioritize areas for hazardous fuel reduction treatments, and to evaluate the effects of past fires and other disturbances [13]. Furthermore, estimates of canopy fuel loads are essential inputs in determining crown flame length, fuel consumption during crown fires, crown fire severity and crown fire effects on ecosystems and carbon emission from crown fires. Several studies have estimated the canopy fuel load in the Mediterranean Basin; however, most were conducted by applying allometric equations derived from extensive field sampling and common stand parameters [14–16]. Field sampling is costly, complex, and time consuming. In addition, fuel quantities are dynamic, and consequently, they require periodic updating; however, this is difficult to achieve, due to the nature of data collection methods.

Remote sensing technologies can provide improved estimates of canopy fuels for wildfire behavior modeling, accurately representing the spatial heterogeneity of forest ecosystems [17]. So far, several studies have examined the contribution of remote sensing to fuel properties, such as fuel type, fuel load and structure, and fuel condition mapping on global, regional, and local scales [8,11]. Yet, most studies have focused on forest fuel classification [18–21], whereas relatively few studies have been conducted to estimate fuel load [22,23]. At the regional level, medium to high optical spatial resolution sensors have been used for the development of empirical regression equations between fuel load parameters and recorded reflectance values [24,25]. Furthermore, few studies have explored the use of microwave data for fuel load estimation, as in the work of Saatchi *et al.* [26], who developed algorithms for estimating canopy fuel load, canopy bulk density, and foliage moisture content using AIRSAR data. At the local level, airborne LIDAR efficiency in estimating canopy fuels has been well proven [17,26–29]; however, there are limitations associated with using airborne laser (as well as microwave) products and their platforms, including the high costs associated with data acquisition and limited availability for wildfire management agencies across the world [30]. Regarding the use of passive, high to very high spatial resolution imagery, Jin and Chen [22] recently used Quickbird satellite images to develop linear regression equations to estimate surface fuel loads at the plot level over central China. The authors stated that although their approach gave good results for fine fuels, there is still room for improvement, particularly for the relationship between coarse fuels and stand characteristics.

Thus, fuel load estimation and mapping from commercially available passive high and very high spatial resolution remote sensing data remains a great challenge. To fulfill such a task, tree crown delineation and extraction are important in order to obtain information at the individual tree level. In this regard, several algorithms have been presented for automatic individual tree recognition and crown extraction for satellite imagery, such as valley following algorithms, crown-modeling and template-matching-based methods, and marker controlled watershed segmentation [31,32]. However, so far, the main body of the research on individual tree detection and delineation has mainly focused on coniferous species in areas of North America and Northern Europe, which are characterized by an abundance of even-aged, evenly spaced pure stands with trees and species, presenting uniform height, crown size, and crown shape, and thus, similar reflectance patterns in the same image [33]. In contrast to those forest ecosystems, Mediterranean forest areas are known for the high spatiotemporal heterogeneity of their vegetation patterns with respect to species composition and stand structure resulting from strong human pressures, the diversity of tree species, topographical variability, and climate conditions [34–36]. While this heterogeneity makes them aesthetically attractive, accurate mapping of forest-related parameters has been the weak point of applied remote sensing technology, especially for local scale mapping tasks [37], as in the case of fuel type and fuel load mapping.

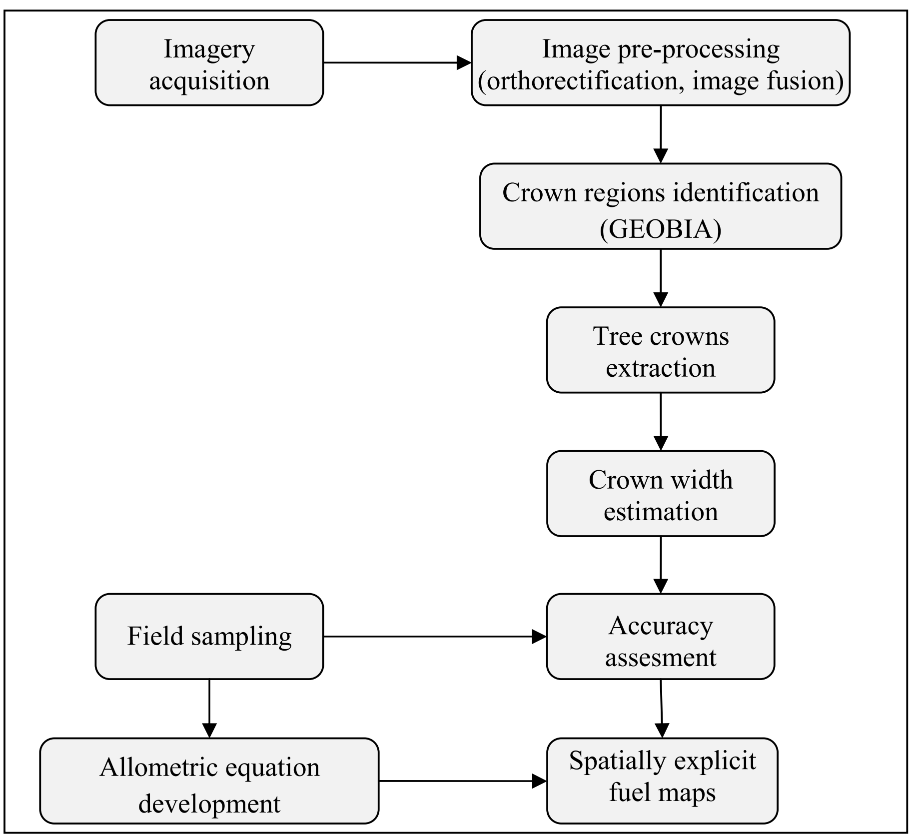
The overall aim of this study was the assessment and mapping of canopy fuel loads of Mediterranean heterogeneous pine forests on a local scale using high spatial resolution satellite imagery and an individual tree crown recognition approach. Within this context, we evaluated the application and performance of individual tree crown delineation in the Mediterranean environment using high spatial resolution satellite imagery. In addition, an allometric equation was developed by using destructive sampling for Aleppo pine canopy fuel load estimation based on crown width, a tree characteristic that can be estimated from passive fine spatial resolution data.

2. Materials and Methods

2.1. Outline of the Methodology

Our approach for local scale fuel load mapping in the Mediterranean is demonstrated and evaluated in two different coniferous sites in Northern Greece that consist of pure Aleppo pine and Calabrian pine stands, respectively (Figure 1). A GEographic-Object-Based Image Analysis (GEOBIA) segmententation and classification approach was adopted in order to isolate and delineate the tree crown regions from the understory and other land cover classes, using pansharpened high resolution imagery. Different classification schemes were followed for each site, based on scene properties and spectral similarities of tree crown areas with other image objects. The classification relied on manually defined fuzzy-rules based on trapezoidal functions using spectral-related features. Individual tree crowns were subsequently extracted using a watershed segmentation algorithm. Through field destructive sampling of representative trees, we developed an allometric equation for crown fuel load estimation of Aleppo pine based on crown width, while an existing empirical model was used for the Calabrian pine trees. Based on the satellite-extracted tree crown widths and the allometric equations, spatially explicit maps of canopy fuel load were produced for both sites at landscape level.

Figure 1. Flowchart of the overall methodological approach.



2.1. Study Sites

2.1.1. Kassandra Forest

The Kassandra forest site is located in the north-central part of Greece (Figure 2), where the bioclimate is characterized as semi-arid, with severe summer drought and relatively low humidity. This area was chosen because it is representative of coastal Aleppo pine forests in Greece. The mean annual rainfall is about 602 mm, and the mean temperature is about 16°C. Elevation ranges from sea level to 360 m.

Figure 2. Location of the two study sites.

The main topographical characteristic of the landscape is the abrupt relief, especially in the northwest-facing slopes. Sandy and sandy-clay type soils prevail in the study area, which is rather degraded due to high erosion. The forested land consists mainly of old mature Aleppo pine (*Pinus halepensis* Mill.) (over 80 years old) and shrubs (*Quercus conferta*, *Quercus ilex*, and *Pistacia lentiscus*), which sometimes dominate the overstory within the stands [38].

2.1.2. Thessaloniki suburban forest

The "Seih-sou" suburban forest of Thessaloniki in Northern Greece (Figure 2), extends over 2,979 ha at the northeastern part of the city and because of its amenity and ecological value it is under a special protection regime, used only for recreation purposes. The dominant tree species is mature Calabrian pine (*Pinus brutia* Ten.), which originated from extensive reforestation undertaken in the 1930s and 1940s. The altitude of the study area ranges from 50 m to 450 m. The mean annual precipitation is 445.6 mm, and the mean annual temperature is 15.9 °C. The soils are shallow, infertile, of low productivity, and heavily degraded. They are slightly acid up to neutral, shallow, infertile, of low productivity, and heavily degraded and are characterized by weak structure, low porosity, and a high percentage of stones and pebbles [39].

2.2. Crown Fuel Load Estimation

Crown fuel load was measured by destructive sampling 40 Aleppo pine trees (Table 1) during the summer of 2003 in the Kassandra peninsula, Chalkidiki. Sample trees were selected from representative stands found in both poor and good sites in terms of site quality. Every effort was made to ensure that the selected trees were representative of the wide range of growing conditions in the forest. In addition, the sampled trees were selected to represent the full range of tree sizes in the forest [40].

Trees extremely lopsided in the crown, heavily defoliated, and broken topped were excluded [41]. For each sampled tree, the crown width was measured on each tree as the average of two perpendicular measurements taken on the ground. Crown fuels were separated into the following diameter classes: needle foliage and twigs 0.0–0.63 cm in diameter. These fuel classes represent the available fuel load which is totally consumed during a crown fire [42]. After weighing all fuel components in the field, samples of each fuel size were taken in the laboratory for moisture content determination. Moisture contents of all fuel classes were determined after the samples were dried at 105 °C for 48 hours and then weighed. Oven-dry weights for crown fuels (needles and twigs 0.0–0.63 cm in diameter) were plotted against crown width in order to provide a visual assessment of the relation between crown fuel load and the independent variable. Table 1 presents the descriptive statistics of the variables used in the analysis. Least-square regression models were developed for individual variables testing several curvilinear models.

Table 1. Descriptive statistics of Aleppo pine sampled trees.

	Canopy Fuel Load (kg) (Needles + twigs 0.0 – 0.63 cm)	**Crown Width (m)**
Number of sampled trees	40	40
Minimum	1.2	1.4
Maximum	50.6	10.8
Mean	21.2	4.8
Stdev.	15.8	3.3

The Calabrian pine crown fuel load was estimated by obtaining and using an empirical regression model from Küçük *et al.* [16]. The linear model was developed based on measurements in the north and northwestern regions of Turkey, in similar environmental conditions as northern Greece:

$$Ln(y) = a\ CW^{b} \tag{1}$$

where y is the oven-dry weight of crown fuel in kilograms, CW is the crown width in meters, and a, b are the estimated coefficients ($R^2 = 0.931$ and standard error of estimate-$SEE = 0.467$).

2.3. Satellite Data and Preprocessing

An 11-bit depth IKONOS satellite image acquired in June 2000 in multispectral and panchromatic mode (4m and 1m ground resolution respectively) was used for the Kassandra study site (Figure 2). Also, a pansharpened 11-bit depth Quickbird image with 0.6 m resolution, acquired in July 2003, was used for the Thessaloniki case study. Both images were orthorectified using ground control points extracted from orthophotos, at 1:5,000 scale, and a digital elevation model (DEM) generated from 20m interval contour lines. The Gram–Schmidt method of image fusion was adopted in order to fuse the multispectral and panchromatic IKONOS imagery and enhance the dataset spatially. In addition, the normalized difference vegetation index (NDVI) (infrared-red/infrared+red) and the ratio vegetation index (RVI) (infrared/red) indices, which contribute well to the discrimination of shrubs and tree vegetation [43], were calculated in order to diminish problems in the discrimination of the classification categories, resulting from the limited spectral resolution of the original imagery [44].

2.4. Identification of Crown Regions

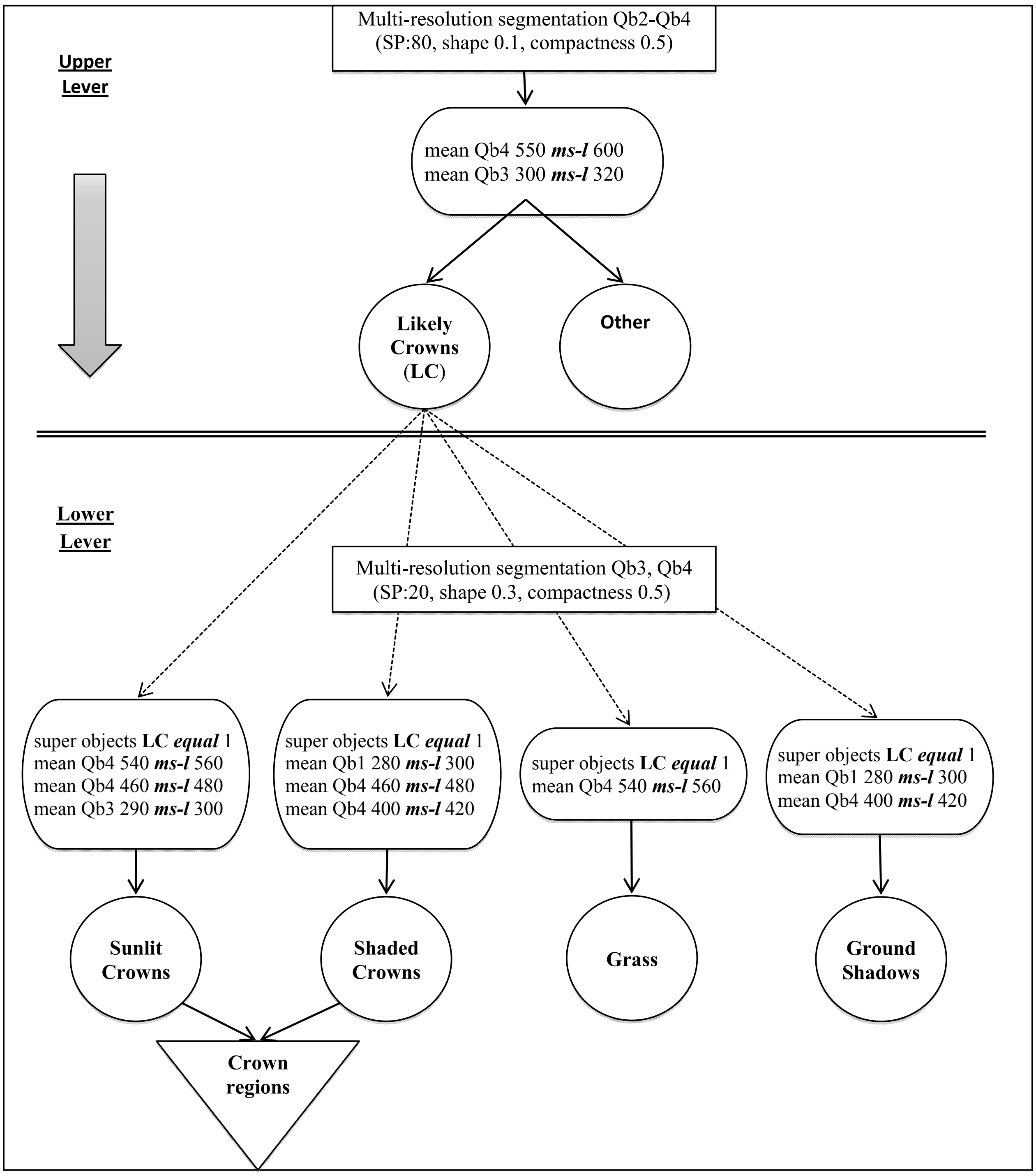
The GEOBIA approach adopted in our study included the generation of a multiscale object hierarchy through image segmentation, followed by fuzzy-rule-based classification. The segmentation algorithm applied in our work is a component of the multiscale object-oriented fractal net evolution approach (FNEA) concept [45]. FNEA utilizes fuzzy set theory to extract the objects of interest, at the scale of interest, segmenting images simultaneously at both fine and coarse scales. The analyst determines the processes of interest within the scene and generates the corresponding levels of segmentation forming a network of horizontally (neighbour) and vertically (upper and lower) connected objects [37]. By establishing semantic links between networked image objects, local contextual information, spectral information, image-object form and texture features can be used to improve classifications [46].

In this bottom-up segmentation technique, embedded within the commercial software Trimble eCognition Developer 8.7, individual pixels are perceived as the initial regions, which are sequentially merged pairwise into larger ones, with the intent of minimizing the heterogeneity of the resulting objects. The sequence of the merging objects, as well as the size and shape of the resulting objects, are empirically determined by the analyst [37]. The analyst specifies the layers of the image, as well as their importance, to be used for estimating spectral homogeneity/heterogeneity. The analyst, also, defines whether changes in the form of the objects resulting after the merge, will be considered in the heterogeneity estimate. A crucial unitless threshold, named scale parameter, is determined to specify the maximum allowed increase in the heterogeneity after a pairwise merge of the objects [45].

In both sites, two levels of segments were generated for tree crown area extraction (Figure 3). The upper level in Kassandra and Thessaloniki was developed using the NIR and red and green bands (scale parameter 80 and 100 respectively, shape 0.1) while the lower layer in both areas was derived with NIR and red bands giving more weight to objects shape (scale parameter 20, shape 0.3)

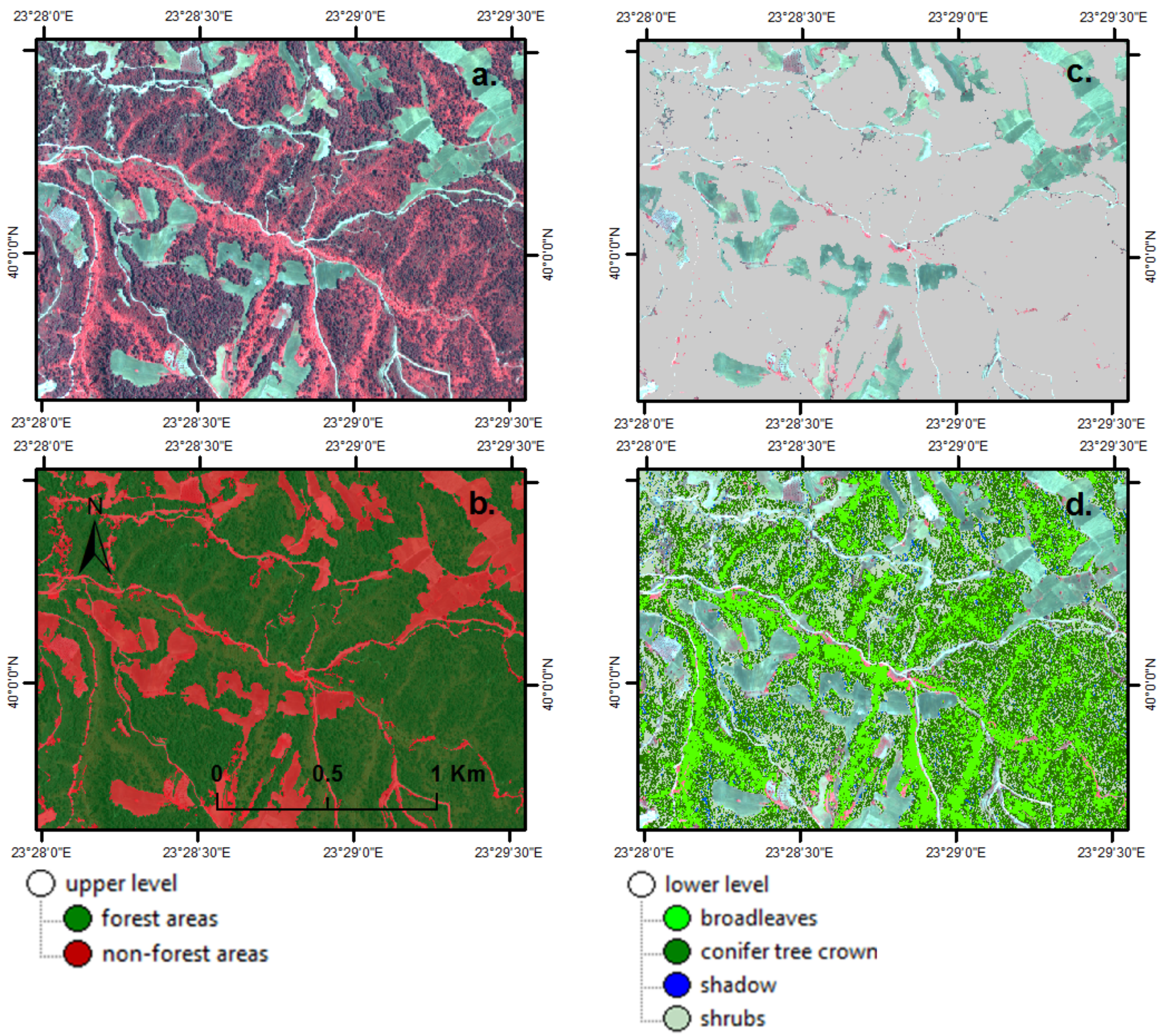
In the Kassandra site (Figure 4), the upper level developed, was used for forest/non-forest area classification based on spectral information from the red band. The lower, finer scale level of segments, was generated to discriminate conifer tree crown segments from broadleaf crown segments, understory (shrubs) in open stands, and shadows. Class discrimination was based on fuzzy rules, based on the mean NDVI and the maximum difference in all spectral bands. In the Thessaloniki forest, in the coarser upper level, likely conifer tree-crown segments were discriminated based on their red and near-infrared mean values.

Figure 3. GEographic Object-Based Image Analysis (GEOBIA) flowchart for the Thessaloniki site. (rectangle = segmentation; oval = rule; circle = class; triangle = merge process; dashed line = hierarchy linkage; ***ms-l*** = sigmoid-left membership functions).



A finer segmentation below these overestimated tree-crown segments was the basis for classifying sunlit and shaded portions of canopy tree crowns, ground shadows, and small grass-covered gaps among the trees, using mean near-infrared, red, and blue values.

Figure 4. Segmentation (upper panel) and classification (lower panel) results in a subset of the Kassandra study site for upper (**a**,**b**) and lower (**c**,**d**) levels of the hierarchy.



Differences in the classification scheme adopted for the two sites, especially at the lower finer level, was motivated by the absence of shrub understory and the large off-nadir acquisition angle (*i.e.*, more intense presence of shadows) of the Quickbird image in Thessaloniki site. While shadows in high spatial resolution images can provide geometric and semantic information such as indications about the shape, surface characteristics and the relative position of objects, they may also influence negatively tasks such as image segmentation, automated object recognition, change detection and scene matching through the loss of feature information, false color tone and objects shape distortions [47].

2.5. Identification of Individual Tree Crowns and Crown Width Estimation

Based upon the similarity between geographic reliefs and tree crown surfaces, the watershed segmentation approach is widely used to segment imagery for tree crown delineation [48]. The approach was initially used to segment digital elevation models of terrains into catchment basins. In the case of tree crown delineation, tree crowns correspond to catchment basins. Adjacent trees whose crowns are attached have a common crown boundary which corresponds to a watershed line. A watershed line is, as known, a ridge of land that separates two adjacent catchment basins. In our study, binary images containing object primitives (crown regions), were produced from the GEOBIA classification phase and processed so that individual tree crowns were identified as catchment basins using a binary morphological watershed segmentation of a distance transform. Tree crown area isolated from the background with object-based classification was converted in a binary image, with tree crown area coded as 1 and the rest of the image as zero. To identify the individual tree crowns, the distance transformation (*i.e.*, the distance from every pixel to the nearest pixel with non-zero value) was applied to the opposite of image's complement. In the complement of a binary image, zeros become ones and ones become zeros. After this transformation, adjacent tree crowns were identified as different catchment basins. In this way, the transformed binary image included also information about the common crown edges, existing between connected crowns, identified as ridge lines, or in other words as watershed lines. The watershed function was then implemented producing a label matrix, identifying the tree crowns as catchment basins, even in the case of attached crowns and labeling each cathment basin (*i.e.*, tree crown) with a different positive value. In this way, pixels belonging to unique watershed regions (*i.e.*, crown regions), had positive integer values, e.g., pixels with value 1 formed the first watershed region corresponding to the first tree crown, pixels with value 2 formed the second watershed region corresponding to the second tree crown *etc*. In the label matrix, pixels belonging to watershed lines, the common boundary between connected tree crowns, had value 0. These pixels were used to segment the adjacent tree crowns. A function was applied, giving the instruction pixels with value 0 in the label matrix to become 0 in the initial binary image.· So, the output was a binary image, where the connected crowns were separated. In this binary image tree crown area was again coded as 1 and the rest of the image as zero. The watershed segmentation method was implemented using MATLAB software [48].

Tree crown widths were then calculated based on extracted tree crowns area and assuming an ellipictal shape and the smallest enclosing method. The mean crown was then estimated through averaging of the major and minor axis of the ellipse.

2.6. Accuracy Assessment of Tree Crown Identification and Crown Width Estimation

In order to validate the tree crown extraction process, we compared the extracted tree crown objects to manually delineated reference tree crowns created within a GIS environment. For the Kassandra and the Thessaloniki study sites, a total of 250 and 1976 reference crowns, respectively, were digitized, based on the visual interpretation of the pansharpened IKONOS and Quickbird images, half-meter natural color orthophotographs available on a Web Mapping Service (WMS) (http://gis.ktimanet.gr/wms/wmsopen/wmsserver.aspx) and air photo stereo pairs. The relative area of overlap within the reference and extracted objects was used as a measure of accuracy [49,50]. We defined a perfect match in the case where the area of overlap between a crown object and reference object is >50% of the area of either the crown object or reference object. In addition, the coefficient of determination (R^2) and the root-mean-square error (RMSE) measure [51,52] were estimated for evaluating crown width extraction accuracy, following the methodology of Ke and Quackenbush [51].

$$RMSE\% = \sqrt{\frac{\sum(RS_i - F_i)/N}{\bar{R}}} \quad (2)$$

where RS_i is the image-based diameter, F_i is the field measured diameter, N is the mumber of the sampled trees and $\bar{R}$ is the mean field measured diameter.

For 41 perfectly matched trees in the Thessaloniki site, crown size (width) was measured in the field and compared to the automatically delineated tree crowns during autumn 2011. While the time elapsed between image acquisition and field crown measurements could be likely be perceived as a limitation of our approach, the maturity of the pine stands in the site (60–70 years) and the lack of silvicultural treatments (*i.e.*, thinnings and pruning) in the study site due its protection regime, raise little or no concerns regarding any differences due to crown growth within the eight year period.

The ground-based tree crown width was measured in two directions. One measurement was made along the maximum axis of the tree crown, while the second measurement was made along the perpendicular direction to the maximum axis. The individual reference crown width was the average of these two measurements.

3. Results and Discussion

Based on the allometric equations for the Aleppo pine trees, crown fuel load was expressed as a simple power function of crown width (CW):

$$y = a\, CW^b \quad (3)$$

A good fit of the data was found when plotting the values of dry crown fuel load against crown width with the simple power function.The relationship among the available crown fuel load and crown width were able to explain 90% of the observed variation (R^2 = 0.901, RMSE = 5.106 and estimated coefficients a = 4.805 and b = 0.932).

The overall accuracy of tree crown isolation (Figure 5) expressed as the proportion of perfect matches between the reference and GEOBIA-delineated tree crowns was 34.00% for the Kassandra site and 48.41% for the Thessaloniki site (Table 2).

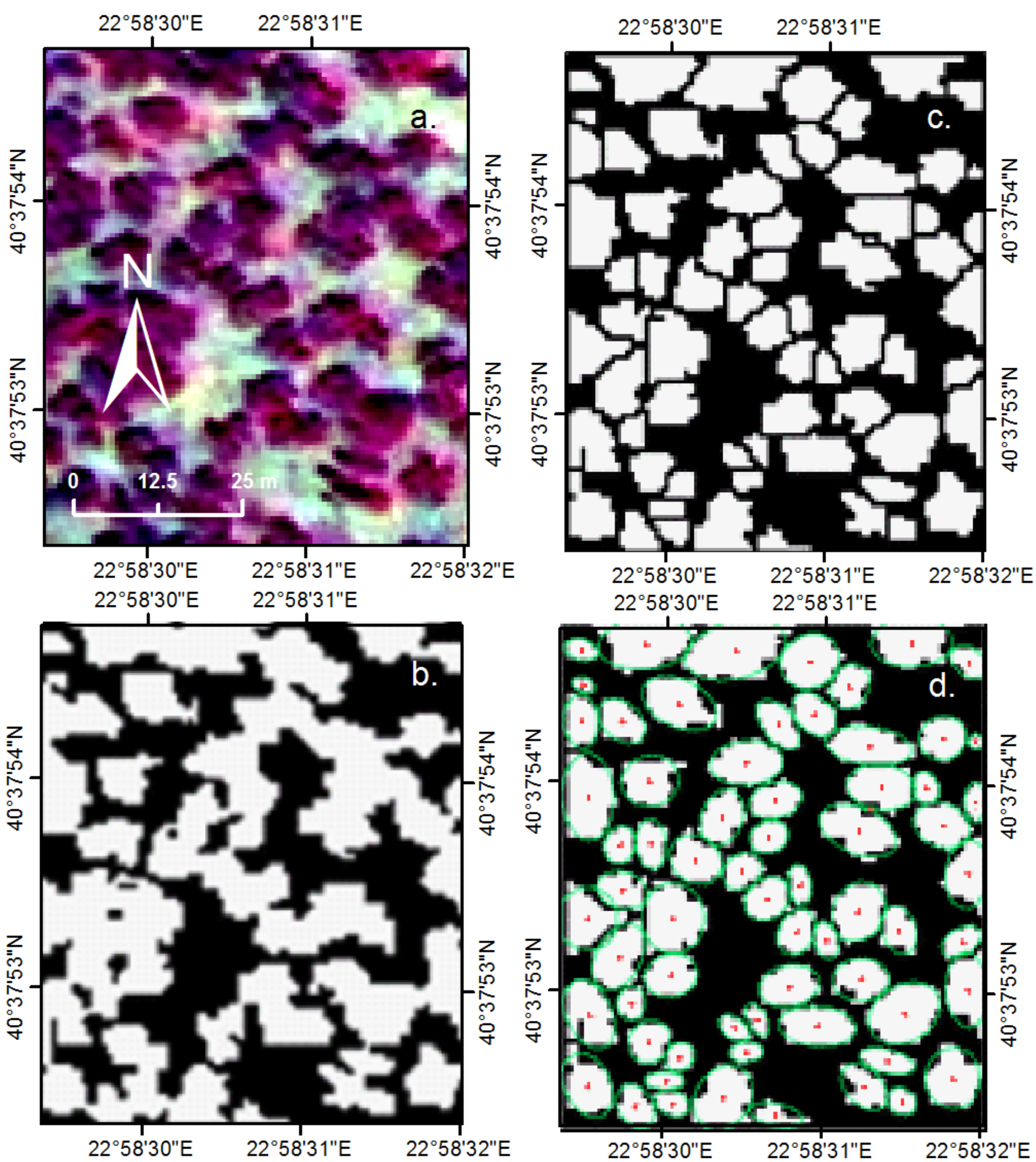
Table 2. Accuracy assessment results of the extracted tree crowns for the Kassandra and Thessaloniki sites.

	Number of Tree Crowns	**%**
	Kassandra forest	
Reference crowns	250	
Perfectly matched	85	34.00
Delineated crowns with > 50% overlap with reference	178	71.20
Reference crowns with > 50% overlap with delineated	107	42.80

Table 2. *Cont.*

	Number of Tree Crowns	%
Thessaloniki suburban forest		
Reference crowns	1,796	
Perfectly matched	870	48.41
Delineated crowns with > 50% overlap with reference	989	55.07
Reference crowns with > 50% overlap with delineated	1,353	75.33

Figure 5. (**a**) Subset of the QUICKBIRD fused image, (**b**) results from the GEOBIA-based identification of pine tree crown regions, (**c**) preliminary results from watershed segmentation and (**d**) Matlab visualization of watershed segmentation with centroids (red) and ellipses (green) of detected crowns.

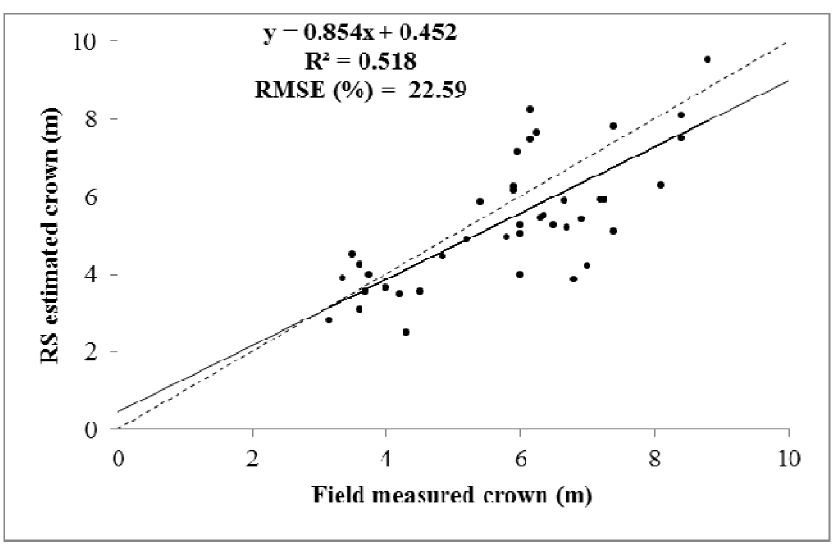


Previous studies suggest that the accuracy of crown isolation can be influenced by factors such as illumination conditions, irregularity of crown shape, reflectance pattern of the crown, the algorithm and the spatial resolution of the images used [53].

The overall modest performance of the approach in this study over Meditteranean landscapes, as well as the differences observed between these two sites, can be attributed to both site characteristics and image properties. In the natural forest areas of Kassandra, the multiple canopy layers and the existence of tall understory shrubs complicates individual tree crown recognition and delineation. In addition, the one-meter resolution of the pansharpened IKONOS image is a constraining factor for high delineation accuracy. In the Thessaloniki site, where Calabrian pine tree crowns are more sparse and distinguishable from the background, along with the better resolution (0.6 m) of the satellite image, higher accuracies were obtained. A limiting factor in this case is the large acquisition angle (approximately 25°) of the Quickbird image. Furthermore, the irregular geometrical crown shape (irregular hemispherical) of these two closely related Mediterranean lowland species, deviates from the ideal uniform conical shape, which would have increased the classification accuracy. However, the accuracies attained in our study are comparable to the results obtained from other studies. Ke and Quackenbush [33], in a study of a hardwood test site in central New York using Quickbird imagery, achieved accuracies of 10–59%, depending on the crown extraction method and plot variability. On the other hand, Whiteside *et al*. [50] who adopted an object-based tree crown delineation approach using Quickbird data for estimating canopy cover of *Eucalyptus* in tropical savannas, observed a perfect match between extracted and reference crowns over 75% of the reference crown sample.They noted however, that this is related, among others, to the openness of the savanna landscape, where trees are wellspaced and well identified from each other and the surrounding understory and ground cover.

According to the crown delineation results in the Thessaloniki site, the delineated crown width, was modestly associated (Figure 6) with the field measured dimension (R^2 = 0.5 and RMSE% = 0.23), adversely affected by the large off-nadir view angle during image acquisition.

Figure 6. Correlation between field-measured and image-extracted crown widths for the Thessaloniki site. The solid line represents the line of best fit by linear regression analysis, and the hatched line depicts the line of identity.

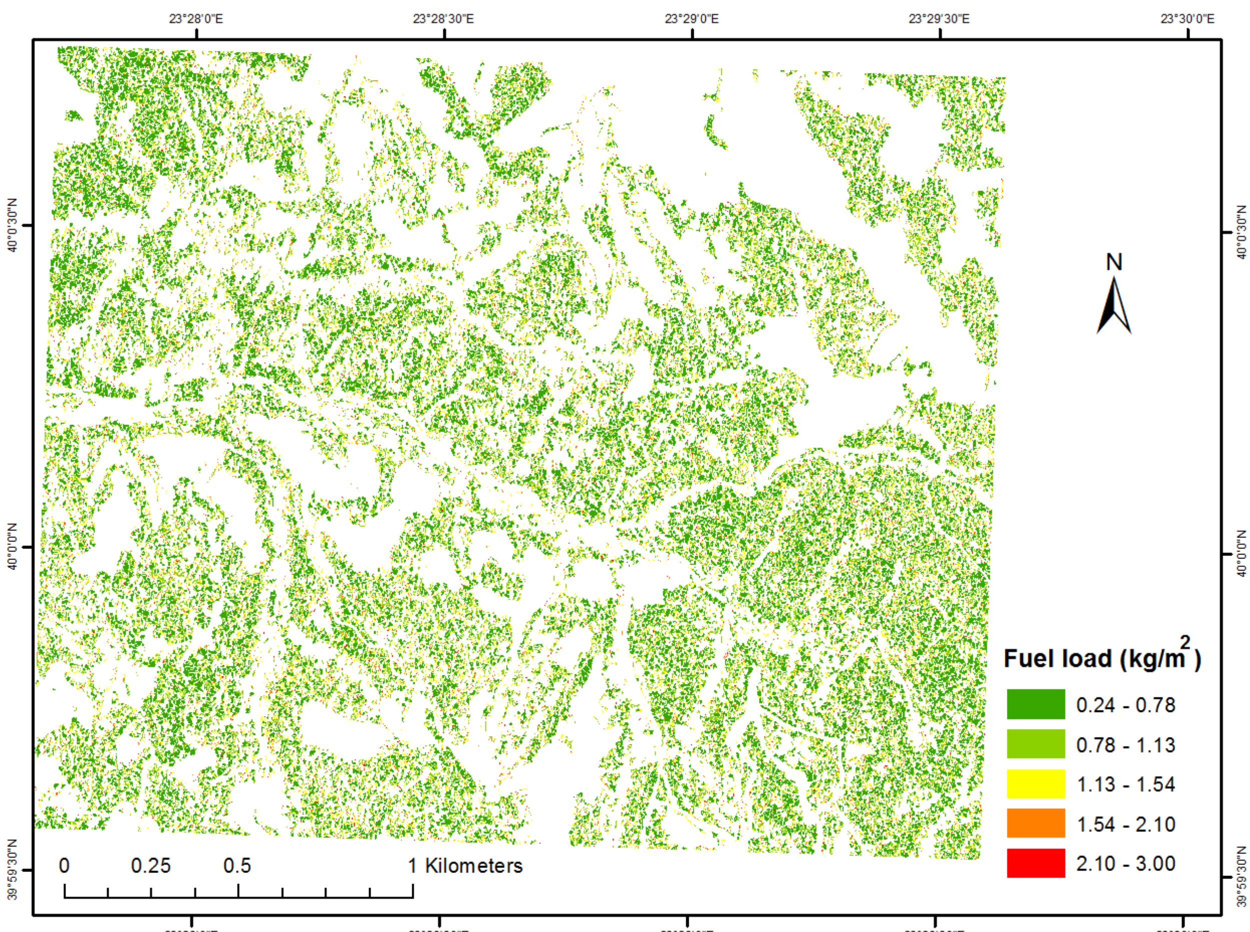


Another reason for the modest correspondence is that the field-based diameters are usually measured at the crown base while the delineated diameters are estimated from above view. When crown overlap occurs, the delineated crown edge in the area of overlap is at higher positions in thecrown and not at the base, leading to mismatch [52]. Furthermore, an irregular crown shape as in the Allepo and Calabrian pines makes it problematic to estimate average crown width, both on remotely sensed images and on the ground in the forest stand [53,54].

Based on the extracted tree crowns, and by applying the allometric equations to them, crown fuel loads were estimated, and the spatially explicit maps of canopy fuel loads for the Kassandra (Figure 7) and Thessaloniki (Figure 8) sites were produced by spatially integrating the crown fuel load values in a 10 m spatial grid.

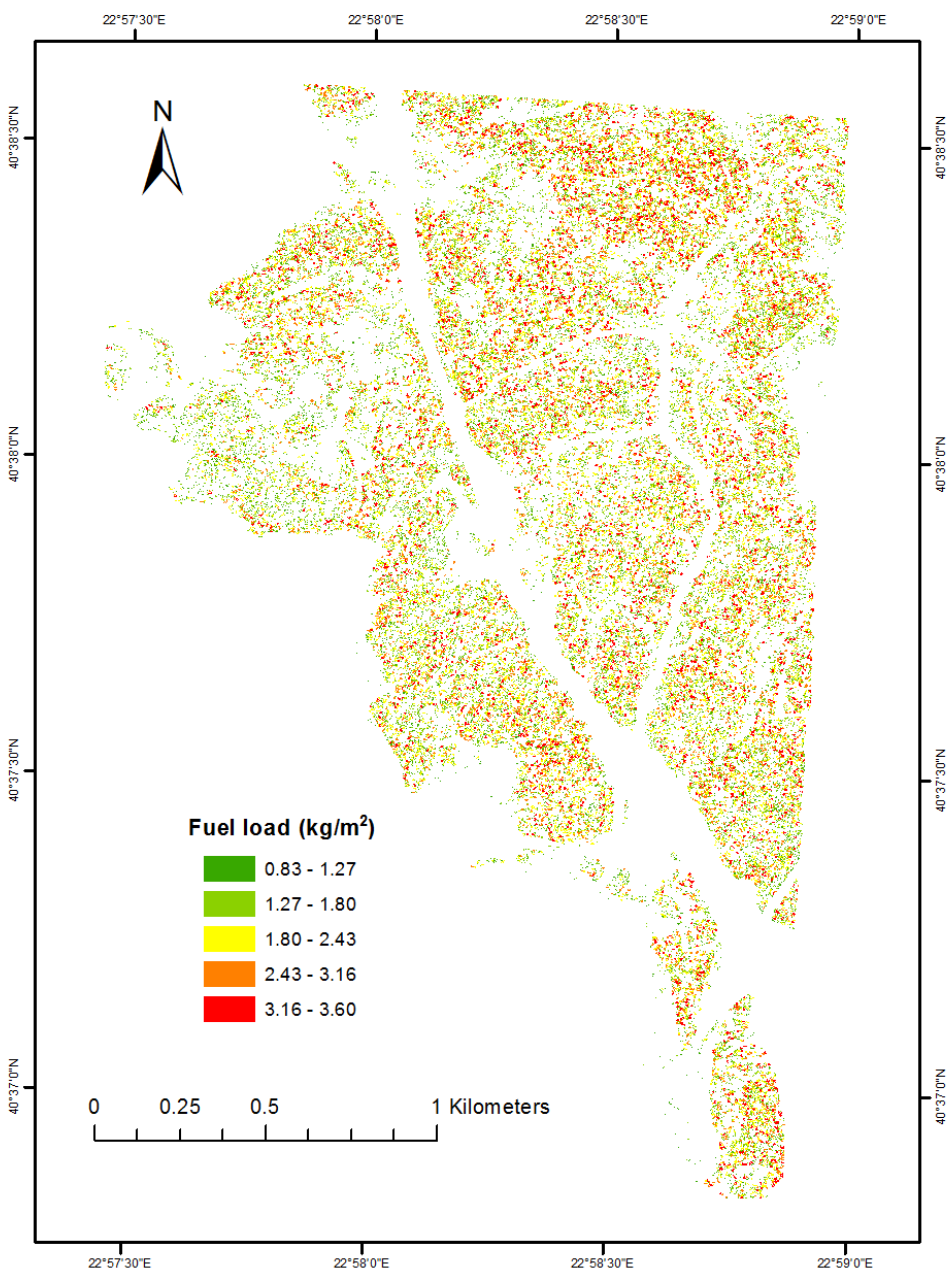
Canopy fuel load presented mean values of 1.65 ± 0.7 for Thessaloniki and 1.29 ± 0.6 kg/m^2 for Kassandra similar in comparison with other studies worldwide. Visual observation of the fuel load maps, indicates high degree of spatial variability. This heterogeneity in terms of fuel loads, implies a wide range of crown size values that differ across landscape within the two sites.

Figure 7. Canopy fuel load map for the Kassandra site.



Alexander *et al.* [55] mention that the canopy fuel load of the International Crown Fire Modeling Experiment plots ranged from 0.6 to 1.5 kg/m^2. Cruz *et al.* [9] reported canopy fuel load distributions for various fuel types. The mixed conifer fuel type had the highest mean value (1.4 kg/m^2), followed by *Pinus contorta* (1.0 kg/m^2), *Pseudotsuga menziesii* (1.0 kg/m^2), and *Pinus ponderosa* (0.61 kg/m^2). The above-mentioned results of the published studies must be interpreted with care, as the crown fuel allometric equations that were used to estimate canopy fuel load were not developed from the same stands as the study sites. Furthermore, for some species with no published allometric equations, surrogate species were used based on similarities in tree crown structure. The stem densities of the stands used in the present study are characterized by low values, thus affecting the final low canopy fuel load values. It is expected that the canopy fuel load values will be higher in denser stands. Minor deviation of the canopy fuel load values could be expected across landscape, since they are predicted from crown width estimates and not from field measured crown widths. This deviation is attributed to the calculated RMSE of the allometric equations and remote sening estimates errors.

Figure 8. Canopy fuel load map for the Thessaloniki site.



Measurements and mapping of canopy fuel load are a prerequisite of reliable crown fire behavior prediction. Information on the amount and distribution of canopy fuels are crucial components for identifying areas with high crown fire potential. The spread of a flame front and the mass transport of firebrands (spotting) occur when adequate canopy fuel load is available [56]. Traditionally, the most accurate way to estimate canopy bulk density and canopy base height has been the use of canopy fuel load equations applied to stand inventory data [57].

Quantitative and spatially explicit canopy fuel load estimates are required to test fuel treatment options to reduce canopy bulk density, to increase canopy base height, to remove ladder fuels, and ultimately, to modify fire behavior in conifer stands and landscapes [58,59]. Recent studies showed that remote sensing data such as that acquired from LiDAR sensors has been successfully used to extract information relevant to canopy fuel attributes [13,27]. Within the heteregoneous Meditteranean forest areas, the use of satellite sensed optical data, with high spatial resolution, for canopy fuel load extraction, requires further research considering the importance of fuel-related information as well as the widespread availability of such imagery compared to the data acquired from airborne, active sensors.

4. Conclusions

In the present study, canopy fuel load was estimated and mapped in two Mediterranean lowland conifer species, based on a synergy of individual tree crown extraction analysis using high spatial resolution satellite data and an allometric equation which estimate crown fuel load from crown width. The trees sampled in the present study are representative of the sizes and conditions of Aleppo and Calabrian pine most commonly found in the eastern Mediterranean Basin.The allometric equation developed enables the estimation of crown fuel load at tree level for Aleppo pine, based on crown width. The model presented a good fit for crown fuel load ($R^2 = 0.90$) at tree level. The extrapolation of the model at stand level through remote sensing may enable fire managers to assess canopy fuel hazard, evaluate fuel treatments, and predict crown fire behavior and effects at the stand and landscape levels. As biomass relationships for crown fuel size load based on crown width have not been reported for other Mediterranean regions, these equations could be applied elsewhere on an interim basis. However, for future research, further destructive sampling on the crown fuel load–crown width relationship of Aleppo and Calabrian pine should be investigated and validated, in order to render these equations more globally applicable.

The overall accuracy of the tree crown isolation expressed through a perfect match between the reference and the delineated crowns ranged between 34.00% and 48.11% for the two sites, while the coefficient of determination between the ground measured and the satellite extracted crown width was 0.5. The relatively modest accuracies obtained from the automatic crown extraction approach are a stimulus for further research, implying that possible improvements might be achieved.

In order to improve the accuracy of the results, and to investigate further the feasibility of such an approach in fire and fuel management, other types of imagery with better image characteristics (higher spatial and spectral resolution) could be used in the near future, as well as over other forest parameters and fire prone species. The developed approach, apart from fire and fuel management could potentially used for the Kyoto protocal requirements of carbon changes in Mediterranean lowland pine forests.

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Conflict of Interest

The authors declare no conflict of interest.

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