Mapping Treeline Ecotone Dynamics along a Latitudinal Gradient using Fine Scale Resolution Imagery

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February 2019

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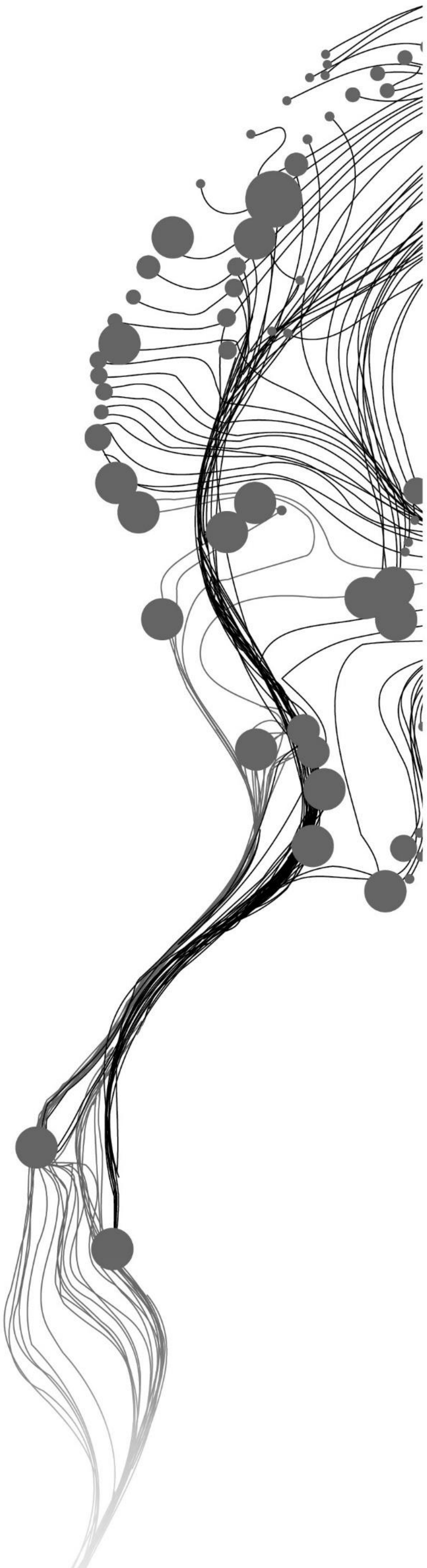

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Enschede, The Netherlands, February 2019

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Natural Resources Management

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DISCLAIMER

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ABSTRACT

Treeline ecotone metamorphosis over time has been a commonplace observation globally. This ecosystem has significant ecological values and acts as a vital signal for climate change. It is thus necessary to understand its dynamics. Applications of fine-scale resolution imagery covering the historical and the contemporary eons are imperative for the mapping and quantification of treeline ecotone changes. These products were used for treeline ecotones studies in Lefka Ori, Olympus, Rodnei and Tatra mountains located along the European sub-continent latitudinal gradient. The investigation suggests that the treeline positions are determined by the latitudes, continentality and the mass elevation effect. The images were classified using object-based image analysis and the results showed satisfactory accuracies (above 80 %). The analysis revealed non-significant changes in the treeline ecotones.

The treeline ecotones are densely covered at lower altitudes than the higher parts across the study sites. Linear mixed models were used to analyze the significance of various explanatory variables on treelines, canopy cover and their changes. The LMMs showed that TPI is significantly correlated with the formation of treelines while treelines at lower altitudes shifted more than those in higher elevations. Furthermore, profile curvature was negatively and significantly correlated with canopy cover changes. The marginal explanatory power of the putative variables on treeline ecotones establishment and their changes suggests possible effects of other factors not used in the study. In conclusion, the observed canopy cover increase in treeline ecotones is more due to the crown diameter increase and foliation rather than tree population increase.

Keywords: **Treeline, ecotone, historical, contemporary, latitudinal, altitudinal, shifts.**

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

GLORIA: Global Observation Research Initiative in Alpine Environments

IPCC: The Intergovernmental Panel on Climate Change

FAO: Food and Agriculture Organization

GE: Google Earth

DEM: Digital elevation model

ASL: Above sea level

LMM: Linear mixed model

ML: Maximum likelihood

REML: Restricted maximum likelihood

TPI: Topographic Position Index

OBIA: Object-based image analysis

RMSE: Root mean square error

1. INTRODUCTION

1.1. Background

The high-altitude life zones are distributed globally from tropical to polar zones and occur in continental and oceanic climates (Singh et al. 2012). Mountains cover 20 % of the Earth's land surface and are a source of 50% of water consumed by humans (Fagre 2008). In the last 50 years, high latitudes, as well as high mountainous areas, are experiencing a greater rise in temperature (Walther et al. 2005). Some researchers predict high rates of animals and plants extinctions especially in mountains areas being the most vital hotspots of endemic species (Myers et al. 2000).

Movement of tree limits towards the alpine zones and poleward have been observed across the globe (Greenwood & Jump 2014) as a result of fast increasing temperatures, and many other factors which are crucial either alone or in conjunction with climate (Holtmeier & Broll 2005). These factors include, but are not restricted to, rising mortality at the treeline, vertebrate herbivory, insect's infestation (Tenow 1996), soil moisture, seedlings constraint (Malanson 1997), forest clearings and natural disturbances (Holtmeier & Broll 2007). Bader et al. (2008) also claim that with more trees recruited at the upper zones further forest expansion is observed due to positive feedback. Globally, average altitudinal treeline migration range per decade has been estimated to lie between 6.1 m (Payette & Filion 1985; Parmesan & Yohe 2003) to 12.2 m (Chen et al. 2011). The speed of treeline movement is also species-specific (Zhang et al. 2009).

Although south-facing slopes have favorable temperatures, in the northern hemisphere, the treelines may occur at relatively lower altitudes due to moisture deficiency, as demonstrated in many Mediterranean mountains with dry summers (de Andrés et al. 2015). This is exemplified by the Sudetes in Central Europe, where moisture deficiency influences the treelines on the southern slopes (Treml & Chuman 2015). Generally, scholars have established that temperature is the primary control of tree-line position, maintenance, and development (e.g., Kullman 2007; Barbeito et al. 2012), just as it is the primary factor controlling the vegetation distribution globally (Tukhanen 1984). This argument is underpinned by researchers who have found out forests recruitment above the historical limits of tree growth in tandem with the observed rise in global temperatures (e.g., Gamache & Payette 2005; Truong et al. 2007).

It is generally known that treeline positions decrease typically towards the north but there exist considerable variations (Odland 2015). Körner (1998) documented that, the relationship between latitude and treeline position is not uniform. The positions decline abruptly between temperate and boreal zones but are constant between ~32°N and 20°S. It suggests that treeline elevations are determined by other parameters not related to latitude. This is exemplified by the treeline decreasing trend from the Alps to North Scandinavia previously approximated to be 75.6 m per latitudinal increase of one degree however with major regional deviations from this trend (Odland 2010).

Treelines respond to climate warming through boundary expansion towards higher altitudes and more northerly latitudes as well as improved productivity and increased canopy coverage (Zhang et al. 2009). According to the study conducted by Harsch et al. (2009) in 166 open treeline areas, 52.4 % depicted upward shift, 46.4 % showed no changes in treeline positions, and 1.2 % exhibited downward movements. Lloyd & Fastie (2002) also observed an increase in treeline position from 1900-1950 and a decrease after 1950 in some of the Alaska Range sites.

Treeline ecotones are habitats to a vast variety of species with population densities higher than the communities in areas below and above them (Körner 2003; Greenwood & Jump 2014). It is thus likely that migration of vegetation zones will finally result in loss of species and lowering of biodiversity richness through the elimination of specialized species with small niche tolerance and growth by more common species from lower elevations (Jump et al. 2012). This is due to the trees outcompeting the alpine species regarding substrate and space (Grabherr et al. 1994). An example of this case is the 10-30 % reduction of alpine grassland and heath area coverage due to forest increase in the Urals (Hagedorn et al. 2004). Additionally, treeline shifting will result in a decline in food resources and medicinal plants (Cresswell & Hellen 2016).

Treeline advance also has positive impacts on the mountain ecosystem. Increased forest area and density results into increase carbon storage and sequestration (Peng et al. 2009; White et al. 2000). Moreover, it provides ecosystem services such as slope stabilization and prevention of erosion (Stoffel et al. 2006). Treeline modification will influence climate, regionally and locally (Holtmeier & Broll 2007).

The upper edge of tree form existence, commonly referred to as treeline, timberline, treeline limit, tree species line or treeline ecotone as used in different studies are the most visible forest boundaries (Kullman 1998; Körner & Paulsen 2004; Kullman 2001). In this study, the uppermost limit of tree existence is referred to as the treeline whereas treeline ecotone is the transition zone from the highest altitude of closed forest to the lower boundary of the alpine zone. Treeline ecotone dynamics denotes the changes in the treeline positions and the treeline ecotones canopy cover between historical and contemporary periods. FAO (2000) defines a forest as land with more than 10% of tree crown cover and an area of more than 0.5 ha with trees able to attain a minimum height of 5 m. Young natural stands and all plantations set up for forestry purposes, but less than 10% crown cover or tree height of 5 m are also included under forests (FAO 2000).

Figure 1 below illustrates a treeline ecotone and its concepts.

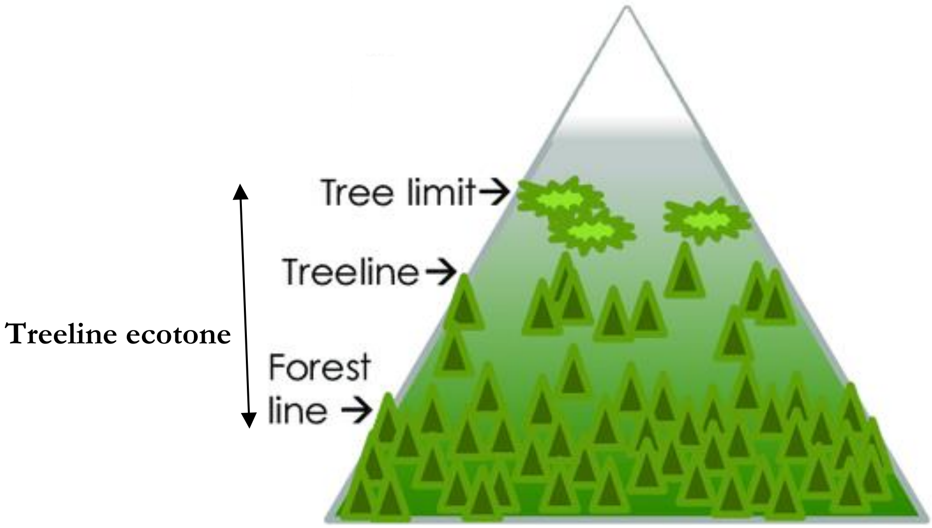


Figure 1: A diagrammatic representation of a treeline and a treeline ecotone (Modified from Cansler et al. 2018)

The rate of tree growth declines close to the treeline. A treeline is not always a clearly defined line, but it is a zone of reduced tree population or heights amalgamated with shrubs. In principle, the sharper environmental gradients signify higher sensitivity of species and thus a narrower treeline ecotone and more does the tree border approaches a line (Körner 2003).

1.2. Reasons for treeline ecotone changes

Alpine zones are susceptible to invasion by the trees from the treeline ecotone leading into the colonization of the alpine species by those from the sub-alpine areas. Knowledge of a multitude of factors affecting treeline growth and regeneration is paramount to the understanding of the treeline dynamics. Advances and retreat of trees have been observed in many mountainous areas and thus treeline changes have been regarded as indicators of global warming (Haeberli et al. 2007; Caccianiga et al. 2008). However, Fallis (2013) asserted that the relationship between temperature and treeline ecotone shifting is too weak due to the effects of other factors and thus cannot be used as an indicator of climate change. Treelines sensitivity to climate warming depends on the regional and local topographical conditions and therefore differs in its intensity, extent and change process (Holtmeier & Broll 2005).

Topographical characteristics resulting from Digital Elevation Models(DEMs) have been utilized commonly for mountain vegetation modeling as alternatives for field-derived environmental data (Hoersch et al. 2002) since they highly correlate with temperature, wind flow, nutrients, disturbances, soil moisture, snow depth-duration and soil types distribution (Holtmeier & Broll 2009). The terrain factors include but are not limited to topographic position index (TPI), slope, aspect and terrain curvature.

1.2.1. Topographic Position Index (TPI)

TPI, also known as the topographical roughness compares the altitudinal position of each cell in a DEM to the average elevation of a defined local neighborhood (Mokarram et al. 2015), and thus it is a relative position. The index is crucial in the identification of landscape boundaries and patterns that may correlate with soil traits, dominant geomorphic processes, rock type and vegetation (Cooley 2016). The TPI values close to zero represent areas of constant slope, high positive values represent ridges and peaks while negative values signify canyon bottoms and valleys. Lower topographical positions are more suitable for woodland than the higher topographical position. At lower slope positions are more substantial water amounts and accumulation of organic matter (Clark et al. 1999). Furthermore, firewood extraction, livestock grazing and other anthropogenic activities tend to be more on the lower positions of the slopes, especially those with the steepness of less than 7% (Martorell & Peters 2005).

1.2.2. Eastness and Northness

In the northern hemisphere, the south-facing slope receives more solar radiation than the north-facing slope (Holland & Steyn 1975). South and west facing slopes are drier compared to the north and east-facing slopes respectively (Mowbray & Oosting 1968). Hence, tree species occur higher in East-facing slope than in the West-facing slopes due to higher maximum temperatures and lower minimum temperatures on the East-facing slopes resulting from clear mornings followed commonly by cloudy afternoons (Smith 1977). Permafrost presence limit treeline movement in the north-facing slopes (Danby & Hik 2007).

Aspect is a directional vector, but in ecology, it is transformed into Eastness and Northness. Large aspect values can be quite close to small values and hence necessary to be changed into a linear data. Eastness affects wind intensity, morning and afternoon solar radiation and moisture while Northness influences solar radiation in summer and winter (Bader & Ruijten 2008).

1.2.3. Slope angle

A steep slope has a high vulnerability to soil erosion due to a rapid surface run-off leading to soil degradation (Bareja 2011). Slope angle effects can be active on plant diversity, dispersal, growth and richness mainly because of its impacts on soil drainage and depth (Boll et al. 2005). Steep slopes are less stable thus inhibiting soil formation. Flat areas or gentle slopes amasses weathered material which when mixed with water and mineral nutrients, such areas became amenable for animals, plants and microbe colonization (Nagy & Grabherr 2009).

1.2.4. Plan and profile curvature

Curvature shows the shape of the slope. It is the quantification of slope curvedness. It is subdivided into plan and profile curvature. The straight line has a value of 0. A negative value shows concave shape, and positive values represent the convex shape. However, in other publications, the interpretation of curvatures is reversed; that is, the positive values represent concave surfaces while the negative values represent convex surfaces (Blaga 2012). Plan curvature is the curvedness perpendicular to maximum slope direction. It influences wind, erosion, deposition, moisture, and solar radiation (Bader & Ruijten 2008). On the other hand, profile curvature is the curve in the vertical plane parallel to the maximum slope direction (Abuckley 2010). It regulates water drainage, surface flow rate, deposition and erosion (Tchoukanski n.d.). Concave shape encourages deposition of soils while convex surfaces promote soil erosion (Amatulli et al. 2017).

1.2.5. Altitude

Precipitation increases with elevation, and the rate of evapotranspiration decreases with height (Goulden et al. 2012). Soil depth also decreases with altitudes. With increasing altitude, there is a decline in temperature, which leads to the disparity in the length of growing seasons in different mountain elevations. The moist air cools and its moisture holding potential reduces as the warm moist air ascends the windward side of the massif. The rising air becomes cold and too dry beyond certain elevations thus depressing tree growth (Nagy & Grabherr 2009). Growth rates may dwindle with an increase in altitude because of the adiabatic effect (reduced soil and air temperatures), increase exposure to wind, shorter growing seasons and reduced nutrient supply (Coomes & Allen 2007). Altitudinal variations lead to different vegetation types and forms (Heydari & Mahdavi 2009).

1.2.6. Tree canopy cover

Trees alter their surroundings and create more favorable environmental settings able to shelter seedlings and saplings from extreme temperature fluctuations and strong winds (Presas et al. 2009), particularly near the upper tree border where abiotic disturbances are strong (Callaway 1998). Small-scale feedbacks can generate stable conditions for vegetation thriving. The abundance of trees favors seed dispersal leading to more tree establishment. Proximity to trees promotes positive feedback leading to outward expansion of trees. Trees are also crucial in landslide and avalanche prevention as well as slope stabilization (Bebi et al. 2001)

1.3. Problem statement

According to Stocker et al. (2013), each of the previous three decades has been consecutively warmer than the other decades from 1850. Climate change scenarios expect a mean global temperature rise ranging from 0.3 to 4.8 °C by 2100 as compared to 1985-2005 average (Ciais et al. 2013). Consequently, mountains, especially at higher elevations have experienced more rapid temperature increase as compared to other land areas (Diaz et al. 2003).

Treeline migration is a gradual process and may occur in the order of meters per decade. Methods such as geo-statistics, field observations, dendroecology, and remote sensing have been applied for treeline studies. Nonetheless, remote sensing is the current widely recognized method for biophysical features assessment for historical and contemporary eras (Weiss & Walsh 2009). It is acknowledged as a vital tool for viewing, characterizing, and making decisions related to oceans, land, atmospheric components as well as alpine treelines (Danby 2011). Aerial photos are the most relevant treeline information remote sensing sources due to their ability to detect the characteristics of the inaccessible areas, higher resolution and long history which is suitable for improved change detection (Okeke & Karnieli 2006).

Many treeline studies have focused on the factors predicting treeline ecotone dynamics on individual mountains. A recent study compared treelines along a latitudinal gradient (Cudlín et al. 2017). Moreover; there are a few published studies on treelines which used high-resolution Corona imagery, for instance, Groen et al. (2012) used the recently declassified corona imagery in synergy with the freely available modern Google Earth images in Osogovo Mountain (Bulgaria) and concluded that these products are suitable for treeline mapping. This research, thus, advances these studies by adopting these products and using them to find out the factors affecting treeline ecotone formations and changes along a part European latitudinal gradient. The study was conducted in four GLORIA sites namely Lefka Ori, Olympus, Rodnei and Tatra Mountain.

This study will boost the understanding of the future vegetation patterns through evaluation of the species-habitat interactions enhanced by the GLORIA monitoring initiative and findings.

1.4. Objectives

The primary objective of this study is to map treeline ecotones and find out the best explanatory factors explaining their establishment and variations along the European sub-continental gradient. This objective was divided into three specific aims namely:

1. To detect the current treeline positions and their vertical shifts.
2. To map and quantify canopy cover changes.
3. To explain the treeline ecotones and their changes.

1.5. Research Questions

From the objectives, several research questions were developed as presented below.

1. What are the current treeline positions in all the study sites?
2. Are there shifts in treeline positions?
3. What are the decennial magnitudes of the possible treeline movements?
4. Are there changes in canopy cover in the treeline ecotones?
5. What are the decennial canopy cover change rates?
6. Which putative predictors best explain the treeline ecotones and their changes?
7. Are the treelines and treeline movements negatively or positively correlated with the independent variables?
8. Are the correlations between the canopy cover and their changes with the explanatory variables positive or negative?

1.6. Research Hypotheses

Several hypotheses were constructed in order to answer the research questions and meet the objectives of the study as shown below.

1. Treelines have shifted upwards across all the study sites.
2. Treeline ecotones canopy cover have increased in all the study sites.
3. Northness, slope altitude, profile curvature, plan curvature, and TPI values correlate negatively and linearly with treeline ecotones and their changes.
4. Eastness and historical canopy cover relate positively and linearly with treeline ecotones and their changes.

2. STUDY AREA, MATERIALS AND METHODS

2.1. Description of methods

A number of analyses were conducted to meet the research objectives. The first step involved the orthorectification of the corona images in correcting for geometric distortions. Historical and contemporary treeline positions were detected and spatiotemporal changes in their positions were quantified. Historical and recent images were then classified, and decadal canopy cover change per plot detection performed. The final stage involved the statistical evaluation of the presumed factors structuring treeline ecotones and their changes. The steps followed are illustrated in *Figure 2* below.

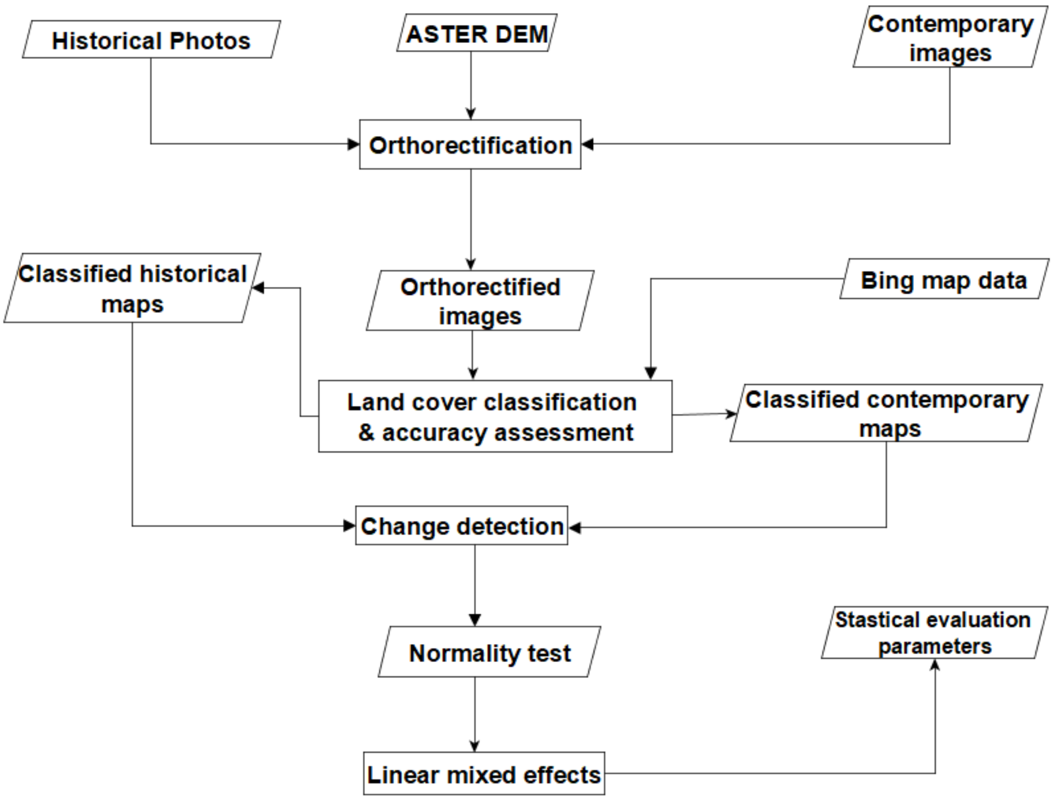


Figure 2: The research workflow

2.2. Study Areas

The study sites span across four mountains along the latitudinal gradient, between 35.28 N and 49.62 N, namely, Lefka Ori (The White Mountains) and Olympus in Greece, Rodnei in Romania and Tatra in Slovakia as shown in *Figure 3* below.

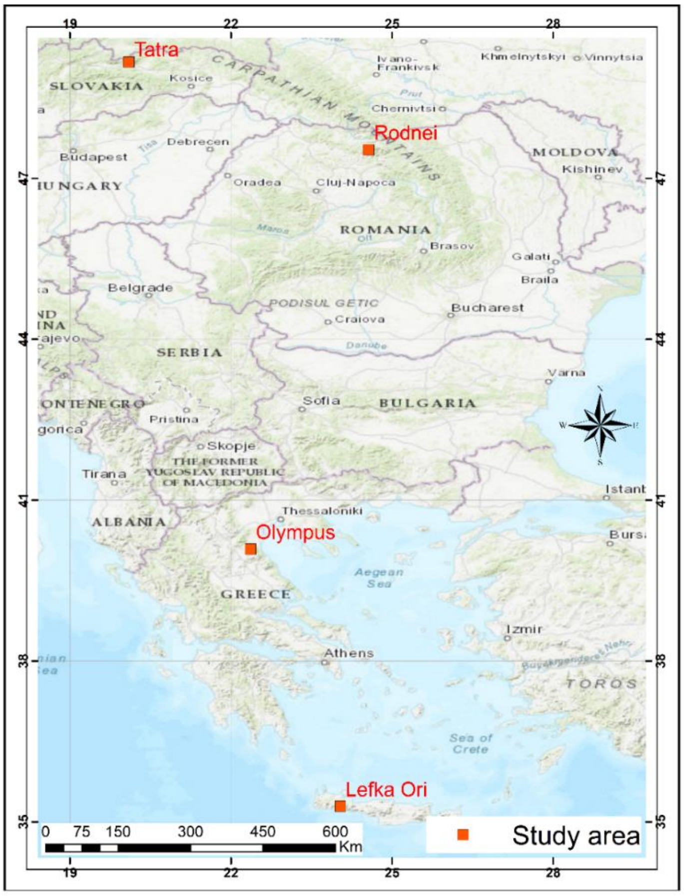


Figure 3: Spatial distribution of study sites as indicated by the red squares.

Lefka Ori (The White Mountains) occupies West of the Crete Island in the Mediterranean climatic zone and has an orthographic area cover of 42 km² above 2000 m above sea level (asl) (Nyktas 2012). It is composed of over 15 summits with elevations of over 2200 m, the highest being Pachness rising to 2453 m (Vogiatzakis et al. 2003). The most upper limit of forest growth on the northern side is 1700 m and 1600 -1650 m on the southern side with aridity increasing from north to south and from west to east (Pungetti et al. 2008). The treelines ecotone is dominated by *Cupressus sempervirens, Quercus coccifera* and *Pinus brutia*. The White Mountains is a dolomite massif and rugged marble-rich in karstic structures and rock debris (Pungetti et al. 2008). Grazing is by far the main human impact in the White Mountains and has been intensified due to the changes in the land use in the lower zones and also the European Union subsidies provided to ameliorate the rangeland infrastructure such as cisterns and road network (Kazakis et al. 2007).

Olympus Mountain, the highest mountain in Greece, is in the form of a massive limestone covering approximately 500 km ² and has 52 peaks with altitudes ranging from 760 m to 2918 m asl(Geoffrey et al. 1997). The climate in the mountain is influenced by its volume, geographical position, display of slope and rocks (Filippidis & Mitsopoulos 2004). The average winter temperature ranges from -20º C to 10º C while the summer temperatures are 0° C to 20º C, but there exist exceptions outside these ranges (Filippidis & Mitsopoulos 2004). The mean annual precipitation is approximately 2000 mm (Styllas 2017). The tree limit is found at 2500 m and dominated by the *Pinus heldreichii* appearing in a crawling form (Organization of the National Forest Management of Olympus 2018).

Rodna (Rodnei) Mountain is in the Northern part of Romania and is amongst the most extended continuous ridges in the country. The highest summits are Ineu and Pietrosul Rodnei measuring 2279 m and 2303 m respectively. The substrate in the area is made of the shallow, organic crystalline shale. It experiences mean annual precipitation of 1200-1400 mm at high altitudes and a temperature range between 0-2 º C (Kucsicsa 2015). Traditional activities like forest work, grazing and mining are practiced in the region. The transition area between the forest and the sub-alpine belt is often lowered by human pressure (Kucsicsa 2011) and thus the treeline is not at its natural limit. The mountain is dominated by *Pinus mugo* on the treeline ecotone with an upper edge at 1600 m asl (Kucsicsa 2011).

Tatra mountain is a mountain range forming a border between Poland and Slovakia. It is the tallest range and one of the most protected regions of the Carpathians mountain (Grodzki et al. 2003) rising to 2655 m asl. Human activities in Tatra are much restricted.70 % of the area is forested while 30 % comprises of meadows, alpine zones and rocks (Švajda et al. 2011). The mean annual temperature increase between 1950 to 2016 in Tatra was 1.30 º C (Czortek 2018). The mountain experiences yearly average precipitation of 1200 mm and a mean annual temperature of 4º C. The continuous interactions between human impacts and natural forces have greatly impacted on the Tatra mountain treeline ecotone. As a general rule, the Slovakian Mountains treelines are not located at their natural limits (Dinca et al. 2017). *Pinus mugo* covers the treeline ecotone from 1550 to 1800 m asl (Wiersum 1995).

2.3. Data requirements

The study leveraged the Corona satellite imagery and aerial images to retrieve the past treeline positions and tree canopy cover. Google Earth (GE) images were used to extract the current treeline positions and canopy cover of the treeline ecotones. Besides, GE images were used in orthorectification of the corona images with the help of ASTER DEM. Additionally, the DEM was deployed in the generation of the topo-climatic factors likely to influence the establishment and the spatiotemporal variation in treeline ecotones. Image classification quality was assessed using Bing maps data. *Table 1* shows a summary of the data used to meet the research objectives.

Table 1: Sources and specifications of the data used in the study.

Data	Source	Spatial Resolution
Corona images	USGS	2 m and 3.2 m
Contemporary images	Google Earth Pro/Bing Maps	3.2 m
ASTER DEM	Alaska Satellite Facility	12.5 m
Aerial Photos	Scanned Photos	1 m

2.4. Preprocessing

Corona images were orthorectified using ASTER DEM and high spatial resolution google earth images by applying the third rational polynomial model to remove image distortions and thus enhance direct and accurate measurements of positions, distances, and areas. The procedure involved the identification of more than fifty evenly distributed tie points between Google Earth and Corona imagery. Unprocessed Corona satellite images contain extreme spatial distortions resulting from the absence of camera information, satellite orientation and position, making their correction extremely challenging (Casana & Jackson Cothren 2013). Sohn et al. (2004) and Schenk et al. (2003) developed two rigorous methods for Corona images correction and related them with polynomial models of the higher order. Both research teams concluded that with many control points, the accuracies for the 2nd or 3rd order polynomial models are comparable to those of rigorous models.

The images were then draped over the ASTER DEM. Although STRM DEM is a widely used elevation model, ASTER DEM was preferred for this study since it proves to be a potential tool for mapping mountainous areas while STRM is more suitable for relatively flat areas as per the comparison carried out by Isioye & Yang (2013). All the images were then brought to a similar spatial resolution of 3.2 m and the study extents of 4 km long. Images covering the same study site were projected into the same reference system. The historical imageries were auto-synced to the modern imagery using Automatic Point Measurement (APM) generator in Erdas Imagine to correct for minor misalignments. RMSE values were used to evaluate the quality of orthorectification and co-registration.

The images were successfully orthorectified and their RMSE were 0.03m, 0.01m, 0.02 m and 0.05 m for Lefka Ori, Tatra, Rodnei and Olympus respectively. These values show that the data were fit for analysis. Specifications of the images used are shown in *Table 2*.

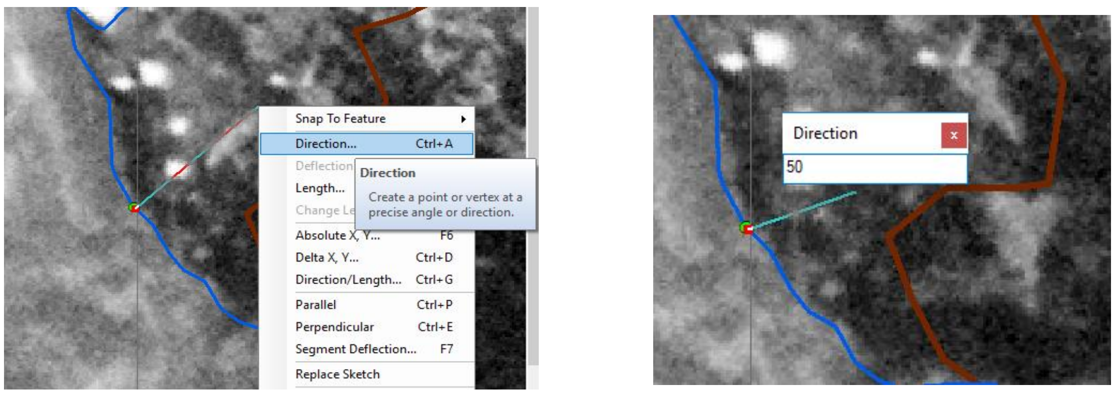
Table 2: Details of the imagery used.

Study site	Projection	Historical image		Contemporary image	
		Acquisition date	**Source**	**Acquisition date**	**Source**
Lefka Ori	WGS_1984_UTM_Zone_34N	1945	Aerial photo	2007	Aerial photo
Olympus	WGS_1984_UTM_Zone_34N	1968	Corona	2012	Google Earth
Rodnei	WGS_1984_UTM_Zone_34N	1962	Corona	2011	Google Earth
Tatra	WGS_1984_UTM_Zone_33N	1968	Corona	2006	Google Earth

2.5. Treeline movement

Treelines were identified and digitized along the uppermost limit of their existence in both the historical and the current imagery using the tonal and textural characteristics. Twenty random points were generated along the historical treelines at a minimum interval of 200 m between two subsequent points.

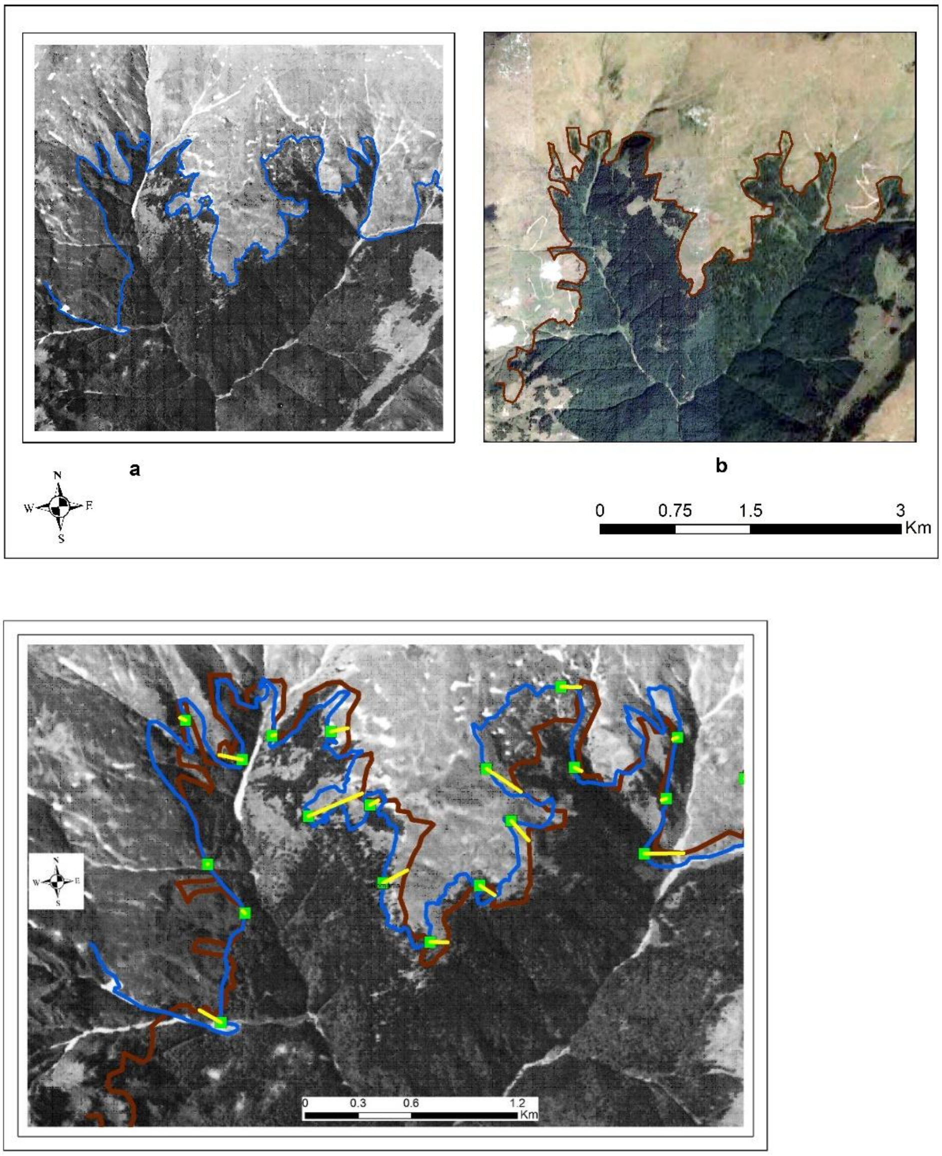
Using the ASTER DEM, the elevation values of the random points were extracted. To get the treeline migration direction and distance, aspect map was created from the DEM and their values extracted to the points to find the current, corresponding aspect value at each of the 20 random points. Lines were then drawn perpendicularly to the slope, opposite of the slope aspect at every random point to where it intersects the current treeline. To do this, 180° was added to the aspect-value at that specific random point. For example, to draw a line in an exactly opposite direction of a position at an aspect of 230 °, we add 180 ° which is equal to 410° (equivalent to 50 °). With the direction digitization toolbar in ArcMap, lines were created with a set direction attached to it as illustrated by *Figure 4* below.



(a) (b)

Figure 4: Quantification of treeline migration. (a) The icon for determining the direction of shift (b) Setting the direction of movement

The elevation value at the point where the shift lines (lines perpendicular to the slope) intersect the current treeline denotes the contemporary treeline position. The difference between the elevational value at the points where the shift line intersect the historical and the current treeline indicates the quantity of vertical change between the two study periods. An example of the resultant treeline shifting map is presented in *Figure 5* below:



c

Figure 5: A delineated treeline (a) historical period (b) contemporary period (c) random points (green) and the shift lines (yellow)

The mean shift of the random points was derived. They were then converted to a decadal scale by using the formula below.

$$Rate\ of\ shift\ (m/decade) = \frac{Mean\ shift}{Contemporary\ date - Historical\ date} X\ 10$$

2.6. Object-based image analysis (OBIA)

Two methods available for extraction of information from the remote sensing data are the object and pixel-based classification. Although pixel-based classification is a commonly utilized approach for land classification, it often produces poor classification with high spatial resolution images (Lu et al. 2010). On the other hand, OBIA has been proven to generate better classification results than the per-pixel classification with high spatial resolution images (Blaschke, 2010; Lu et al., 2010). Multiresolution segmentation technique was used to slice historical and contemporary imagery into image objects using the eCognition Developer software. This method was preferred due to its powerful performance in comparison with other image segmentation processes (Belgiu & Drăguţ 2014). Support Vector Machines (SVM) classifier within eCognition Developer was implemented to group the image objects into a binary map containing the treed and non-treed land cover types using brightness value and texture. The SVM was chosen due to its superiority to the commonly used maximum likelihood approach according to Mondal et al. (2012). However, other classifiers were not tested to see how they compare with the SVM.

2.7. Accuracy assessment

Random points were created on the Bing images and classes assigned to them based on visual interpretation. The images were used to provide an alternative to fieldwork data, which is enormously challenging to collect owing to the limited accessibility of alpine areas (Morley et al. 2018). A total of 90 randomly generated points were used to assess the accuracy of each classified modern image. For the historical images, a land cover class was assigned to the randomly generated points by checking their radii of 10m; if it is relatively dark, then it is tree canopy cover, else non-treed (Platt & Schoennagel 2009). Ninety points were also used for accuracy evaluation of the historical images. Kappa statistics and overall accuracy within the confusion matrix were the two parameters used to evaluate the quality of the image classification.

2.8. Treeline ecotone canopy cover change

Twenty sample plots of 100 m by 100 m surrounding the random points were created along the treelines. The evaluation of canopy cover change per plot was executed by calculating the area covered by tree canopy in each sample plot. To do this, image segments generated from eCognition Developer were exported to the ArcMap. Areas with tree canopy cover were selected from the attribute table and exported to create a new layer. The layer was then clipped to extract areas covered by tree canopy only within the plots. They were intersected with the plots to get the area of forest within each plot. This was done for both the historical and recent images and was assigned a common field. The differences in tree canopy cover within the plots were obtained. The changes per plot were converted to a decennial scale since the images were acquired at different dates.

2.9. Statistical analyses

2.9.1. Generation of factors affecting treeline ecotone dynamics

The relationships between the treeline ecotone and their changes with the terrain factors were analyzed to evaluate the possible drivers of treeline variations over time in the study areas. The putative predictors were adopted based on their presumed importance at high altitudes. Explanatory indices used included Eastness, Northness, slope angle, plan curvature, profile curvature, TPI and the historical canopy cover.

TPI values were derived from creating minimum elevation, maximum elevation and a smoothed DEM raster using the focal statistics under the Spatial analyst tool in ArcMap. After that, the Raster calculator was used to retrieve the TPI by following the method used by Ebert (2015) as shown below:

(Smoothed DEM –Minimum DEM)/ (Maximum DEM –Minimum DEM).

The higher the TPI value, the higher the disparity between the cell elevation and the mean elevation giving the mensuration of the terrain ruggedness.

Eastness and Northness were derived by converting the aspect degrees into radians.

(rad=pi*degrees)/180

pi=3.143

Using the trigonometric functions in ArcMap, the cosine of the aspects in radians were computed to generate the Northness while Eastness was calculated by finding the sine of aspect values in radians (Roberts 1986). Northness values range between 1(due North) and -1(due South). Similarly, Eastness ranges from 1(directly East) to -1(due West).

The plan and profile curvature raster data were created from the curvature tool in ArcMap, 3D Analyst toolbox. Two different rasters were produced, that is, plan curvature, profile curvature.

2.9.2. Normality test

Shapiro-Wilkinson (SW) analysis was used to examine the normality of all the variables using the R program developed by the R Core Team (2018). The alpha level for this study was 0.05. A paired t-test was used to check the significant differences in normally distributed data while the Wilcoxon signed rank test was applied for the hypothesis testing when data were not normally distributed.

2.9.3. Linear mixed models

Linear mixed models (LMMs) were constructed using the *lmer* function of the *lme4* package in R to identify the significant predictors of the treelines, canopy cover and their changes. The linear mixed effects were utilized because they extend the functionality of the simple linear regression by modeling a mixture of fixed and random effects, particularly when the data is non-independent, low-sample sized and there are many covariates to be fitted.

Four LMMs were built to identify the critical factors for treeline positions, canopy cover distribution and the treeline ecotone changes. In the models, slope, TPI, plan curvature, profile curvature, historical tree canopy cover, Eastness and Northness were used as fixed components while the study sites were considered as the random effects of the models. Fixed effects are factors expected to have an impact on the response variable (Hajduk 2017). On the other hand, random effects are commonly grouping factors whose influence on the dependent variable are frequently not of interest and refer to a diverse hierarchical level of the data. Historical treeline position, historical canopy cover and the decadal treeline ecotone changes were used as the response variables. The models were fitted with the use of restricted maximum likelihood (REML) because their estimates of variance are less biased as compared to the maximum likelihood (Hajduk 2017). Colinearity was also checked before the interpretation of LMMs results and one of the correlated variables with a correlation index bigger than 0.5 or smaller than 0.5 was eliminated from the model. The significance of the independent variables was evaluated by a Wald test using the *Anova* function of the *car* package in R at 95% confidence level.

The assumptions of the LMMs were also diagnosed before interpreting the results. These included linearity of variables, the normality of residuals and the homogeneity of variance.

3. RESULTS

3.1. Exploratory data analysis

The initial investigation performed on the data to reveal the characteristics of different aspects inherent in the study areas revealed variations along the latitudinal gradient. The results are as presented in *Figure 6* below.

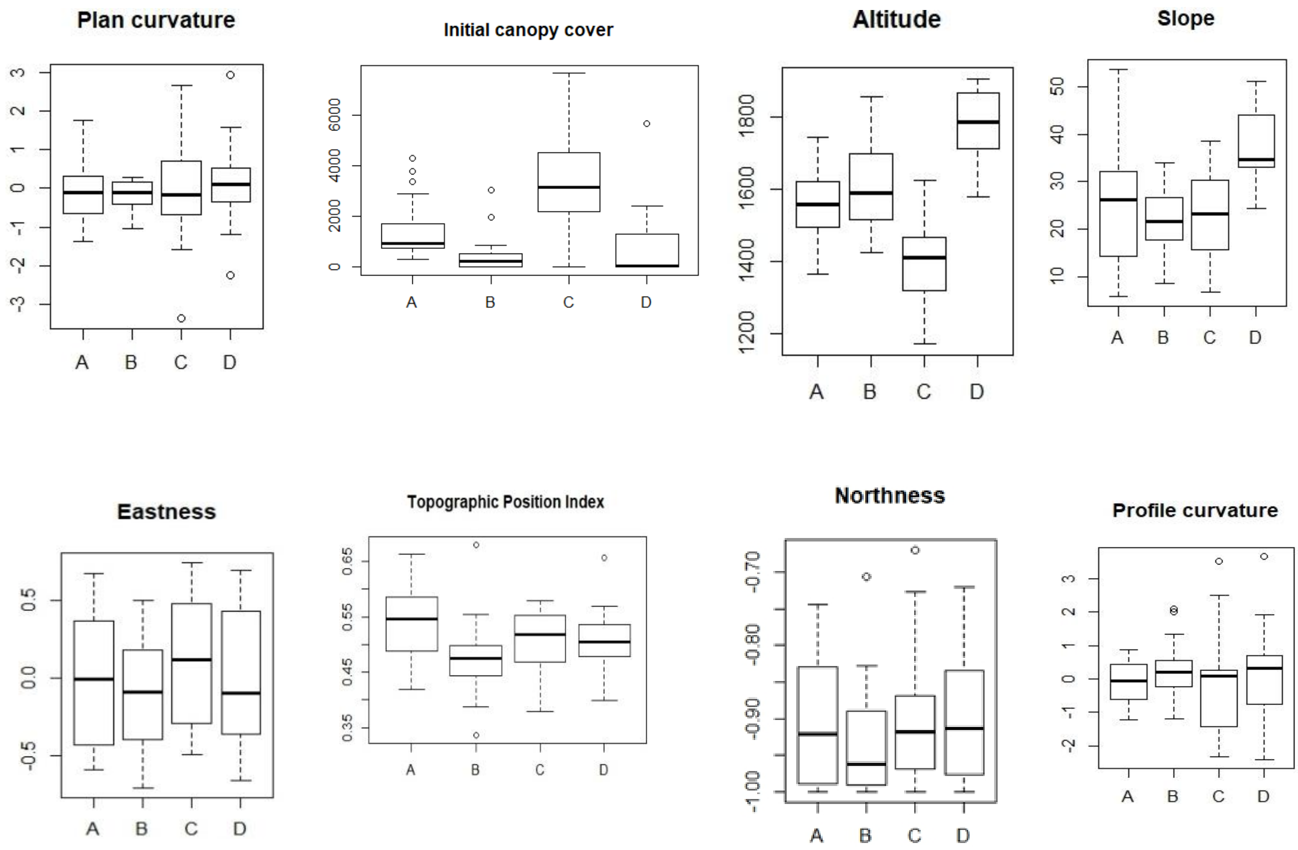


Figure 6: Distribution and nature of variables across the study sites: (A) Lefka Ori, (B) Olympus, (C) Rodnei (D) Tatra

The boxplot graphing tools above depicts the centers and spread of variables within and among sites in the study areas used in statistical analysis. Some of the variables had outliers denoting the existence of extreme characteristics inherent in the study sites. However, the outliers were not eliminated during the analysis albeit significantly influencing the outcome of the analyses. The reason for including them is because they possibly emanated from the variability of distribution rather than systematic or random errors.

Normality tests conducted for the tree line positions are presented in *Table 3* below.

Table 3: Shapiro-Wilk tests values for treeline positions.

Site	Altitude (Historical)		Altitude Current	
	W statistic	P value	W statistic	p-value
Lefka Ori	0.96	**0.49**	0.96	**0.48**
Olympus	0.96	**0.64**	0.96	**0.52**
Rodnei	0.96	**0.55**	0.97	**0.81**
Tatra	0.95	**0.42**	0.96	**0.47**

Altitudinal positions for the two study periods were normally distributed (*Table 3*) based on the Shapiro-Wilk test p-values. Further, the normality test outcomes of the tree canopy cover in the plots are shown in *Table 4* below.

Table 4: Shapiro-Wilk tests values for canopy cover

	Canopy cover (historical)		Canopy cover (modern)	
	W statistic	P-Value	W-Statistic	P-Value
Lefka Ori	0.79	0.0005	0.71	<0.0001
Olympus	0.63	<0.0001	0.78	0.0004
Rodnei	0.98	**0.92**	0.05	**0.05**
Tatra	0.63	<0.0001	0.67	<0.0001

Unlike the tree line positions, canopy cover was not normally distributed except in Rodnei mountain.

3.2. Treeline positions and shifts

3.2.1. Treeline positions

The treeline positions varied from one geographical location to the other. The current mean elevations of the treelines along a latitudinal gradient were shown using a graph below (*Figure 7*).

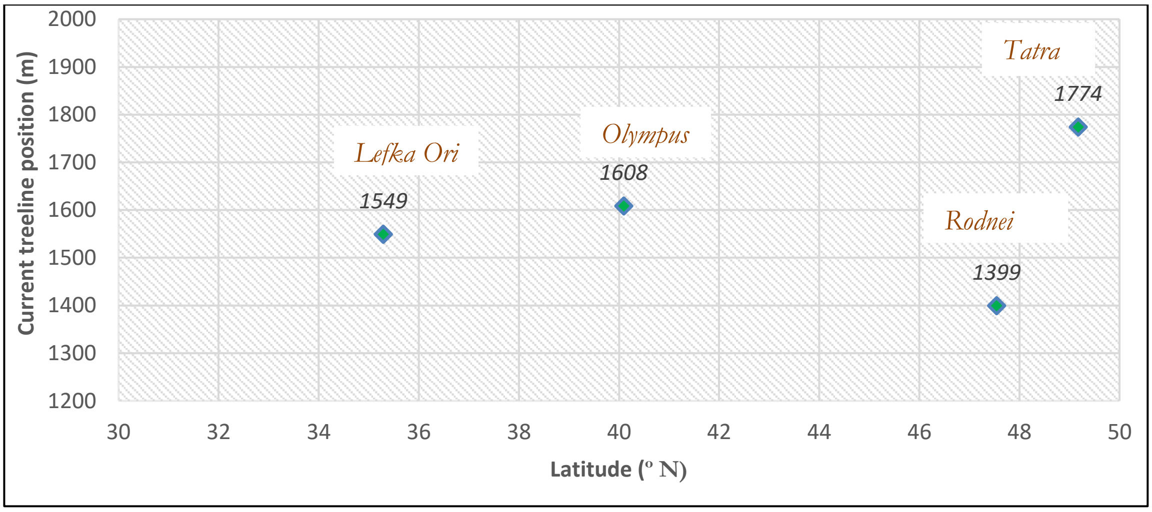


Figure 7: Variation of the treeline positions along a latitudinal gradient

Treeline positions are not decreasing with the increase in latitudinal locations but haphazardly distributed with Tatra Mountain, being further north reaching the highest mean elevation. Rodnei registered the lowest treeline position despite being close to Tatra Mountain. Olympus Mountain treeline is located at a higher elevation than Lefka Ori despite being at a higher latitudinal position.

3.2.2. Treeline movement

Analysis of treeline movement revealed negligible shifts between the historical and the contemporary periods (*Table 5*).

Table 5: Mean treeline elevation, shift and latitudinal location of each study site

Site Name	Mean decadal shift (m)	Latitude	Mean treeline position (m)	
			Historical	Current
Lefka Ori	-0.81	35.29 N	1554	1549
Olympus	-0.45	40.09 N	1610	1608
Rodnei	0.61	47.54 N	1396	1399
Tatra	-1.84	49.17 N	1781	1774

Moreover, the variation in treeline positions was visualized using box and whisker plots. Despite the mean shifts being insignificant, there was a high disparity in the treeline changes within the study sites. The disparities in the shifts also differed from one mountain to the other with Tatra being the most variable and Lefka Ori having the least variation (*Figure 8*).

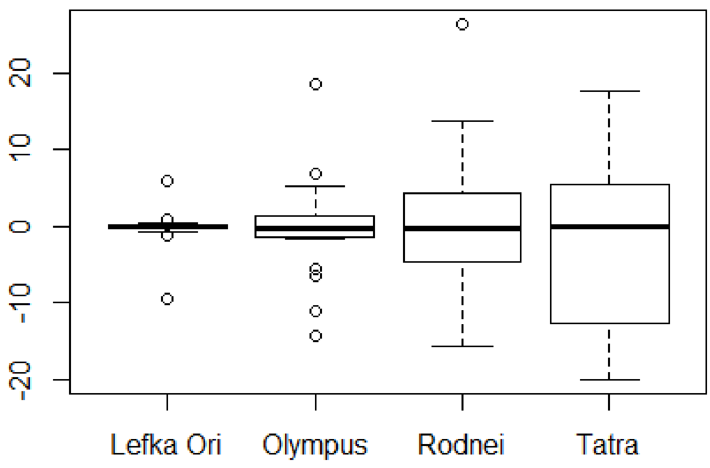


Figure 8: Quantities and variations of treeline movements within and across the study sites

Treeline position receded by 0.81 m/decade in Lefka Ori. The highest tree limit in 1945 was at 1744 m and 1736 m in 2007. The maximum decadal upslope shift was 5.97 m although the treeline had a highest downward migration of -9.52 m. The lowest treeline position was at 1365 m in 1945 but changed to 1387 m in 2007.

In Olympus, the highest limit of tree growth was at 1857 m as compared to the current position at an elevation of 1862 m. While the overall migration was a downward movement of 0.45 m decadally, there was recorded a maximum upward shift of 18.64 m and a downward shift of 14.32 m. The lowest point of the treeline was at 1425 m in 1968 but dropped to 1416 m in 2012.

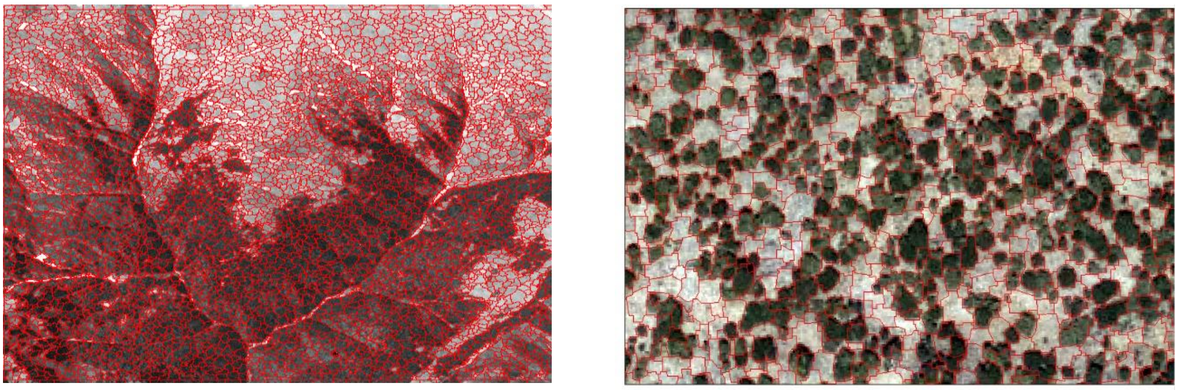
Rodna experienced an average shift of 0.61 m/decade. The highest point of tree existence was at 1625 m in 1962 but descended to 1615 m in 2011. The maximum changes in treeline positions were 26 m and 15 m per decade for upward and downward shifts respectively. The lowest tree limit was at 1171 m in 1962 while at 1232 m in 2011.

In Tatra Mountain, the overall decadal variation was 0.84 m ascent. The maximum upward migration was a shift of 17.63 m, and the maximum descent was 20 m per decade. The maximum treeline position did not change in Tatra between 1968 and 2006. The lowest treeline position was at 1581 m as compared to 1582 m in 2006.

The paired t-test conducted showed a p-value of 0.66, 0.79, 0.76 and 0.45 for Lefka Ori, Olympus, Rodna and the Tatra Mountains respectively. The values signify insignificant treeline movements.

3.3. Segmentation, classification and accuracy assessment

The image objects resulting from the multiresolution segmentation of the images were generated as shown in *Figure 9* below



(a) (b)

Figure 9: Segmented image samples (a) historical (b) current

The object-based classification of the eight images yielded two classes, that is, tree and non-treed area *(Figure 10)* with accuracies ≥80% in all the study areas as shown in *Table 6*.

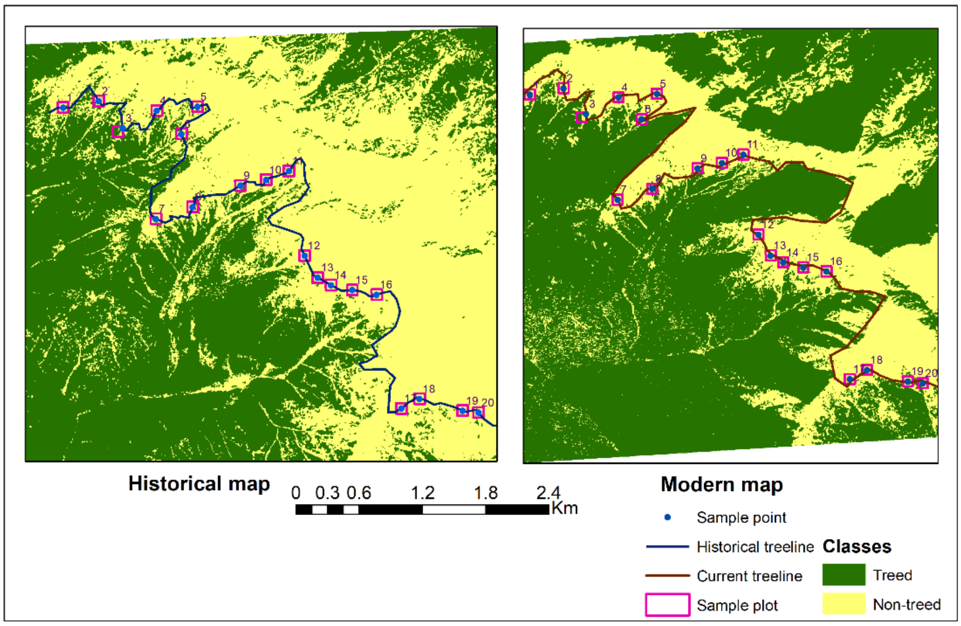


Figure 10: Sample classification maps of historical and contemporary images.

The Kappa Index of Agreement (KIA) and overall accuracy derived from each classified map is provided in *Table 6* below:

Table 6: Overall accuracies and Kappa coefficients from the classified images

Site	Historical image		Contemporary image	
	Overall accuracy	**KIA**	**Overall accuracy**	**KIA**
Lefka Ori	88%	77%	92%	84%
Olympus	80%	60%	95%	91%
Rodnei	88%	76%	86%	71%
Tatra	82%	64%	80%	60%

Using the overall accuracy and the Kappa coefficient scheme according to Landis & Koch (1977), the classification accuracies obtained were satisfactory.

3.4. Temporal changes in canopy cover

The ecotonal canopy cover analysis reveals an increase in all the study sites. The canopy cover per plot changes trends are, however, intricate since some areas portray canopy cover decrease, others increase, and others remained constant. The canopy cover distributions across the study areas were not normally distributed, except for the Rodnei Mountain. Even after subjecting to different types of data transformation, they could still not assume a normal distribution. Wilcoxon test was used to evaluate the significance of changes between the two analyzed periods in all the study areas.

In Lefka Ori, five plots increased in canopy cover; ten plots did not change while five plots experienced canopy cover decrease. The overall mean decadal canopy cover increase is 20.81 m². In Olympus, there was no change in five plots. These plots had negligible canopy cover in 1968 as well as in 2012. Five plots reduced in tree canopy cover and ten plots indicated an increase in canopy cover. The overall change experienced was 51.64 m² per decade. In Rodnei Mountain, there was a decrease in 10 plots and a rise in 10 plots. The total difference was 33.30 m² per decade. Tatra mountain had a decadal tree canopy cover increase of 241.41 m² per plot. Four plots maintained their tree canopy cover, nine reduced and seven increased.
The Wilcoxon p-values were 0.96, 0.18, 0.21 and 0.94 for Lefka Ori, Olympus Rodnei and Tatra respectively. These values denote insignificant canopy cover changes.
The graph below (*Figure 11*) summarizes the decadal increase in canopy cover in all the study sites.

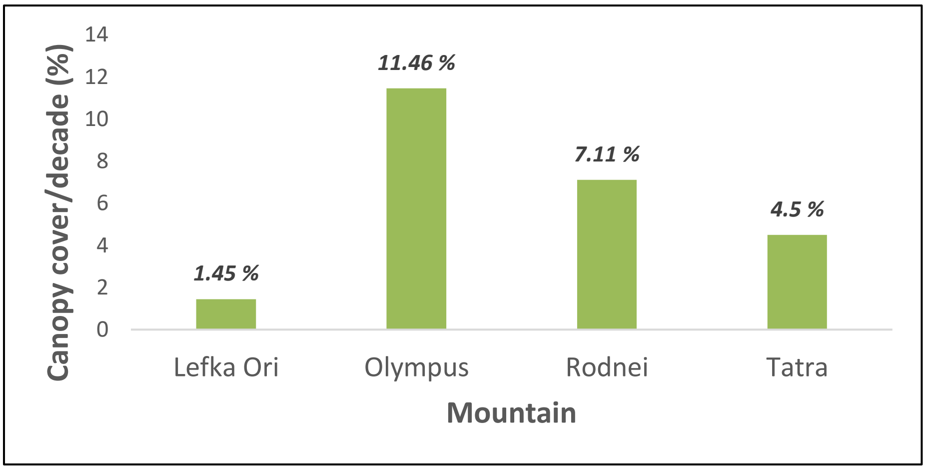


Figure 11: Average decadal canopy cover changes per plot within each site.

It can be noted from the graph that the highest canopy cover increase occurred in the Olympus mountain and the smallest being at the Lefka Ori. The changes are thus randomly distributed regarding the latitudinal positions. Besides, the analysis at the local scales showed variation in tree canopy cover change at every study site as illustrated by *Figure 12* below.

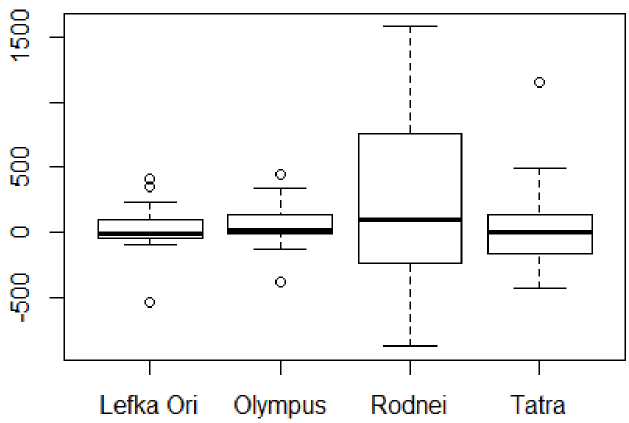


Figure 12: Variation in canopy cover changes within each site

The Rodnei mountain changes displayed more variation than all the other sites and had no outliers like other sites.

3.5. Linear mixed effects

The predictors of treeline ecotone variation showed concern of collinearity between altitude and historical canopy cover with a collinearity index of -0.5 as well as between plan curvature and the profile curvature with a value of 0.6. Thus, the plan curvature and the historical canopy cover were not used as independent variables in the models.

The analysis of predictors of historical treeline position revealed a significant positive relationship with the TPI with a p-value of 0.0002 and an R^2 of 5% while the elevation was the significant variable negatively correlated with historical canopy cover ($p= 0.001$, $R^2=17.3$ %).

The model revealed a significant influence of altitude as the primary variable governing treeline movement ($p= 0.003$, $R^2=11$ %). Trees at higher elevations experienced less shifting as compared to those at a lower altitudinal position.

Table 7 below summarizes the results of the LMM of treeline movement and the predicting variables.

Table 7: Results of the correlation between the treeline migration and the topographical variables

Fixed effect	Estimate	Standard error	Pr (>|t|)
Altitude	-0.02	0.005	**0.004**
Northness	-19.0	10.5	0.8
Eastness	-1.2	2.1	0.6
Slope	0.1	0.1	0.3
TPI	17.8	13.5	0.2
Profile curvature	0.4	0.8	0.6

The results of the model showing the variation of tree canopy cover as a function of the terrain variables are also summarized in *Table 8* below:

Table 8: Results of the correlation between the tree canopy cover changes and the topographical variables

Fixed effect	Estimate	Standard error	Pr (>|t|)
Altitude	-0.6	0.3	**0. 04**
Northness	106.6	552.8	0.9
Eastness	-173.8	112.6	0.1
Slope	3.1	4.4	0.5
TPI	913.9	723.3	0.2
Profile curvature	-91.7	40.6	**0.02**

The assessment of canopy covers temporal variation depicted altitude ($p=0.05$, $R^2=10$ %) and the profile curvature ($p= 0.02$, $R^2=5$ %) as the significant predictors of canopy cover changes. When plan curvature and altitude were used together as independent variables in a model, their synergetic effect showed a contribution rate of 40 %.

Model diagnostic results are as presented in *Figure 13* below:

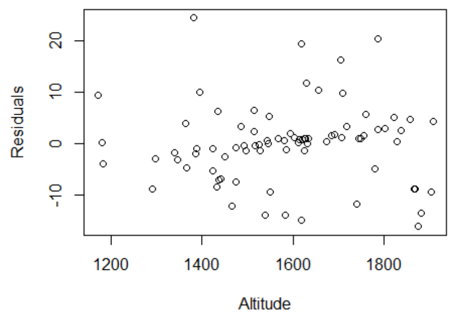
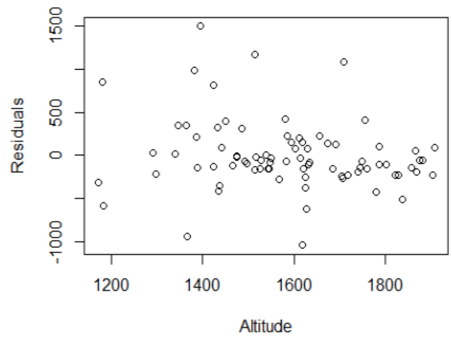
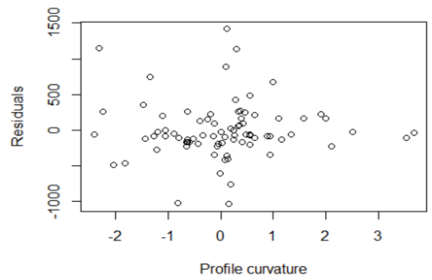
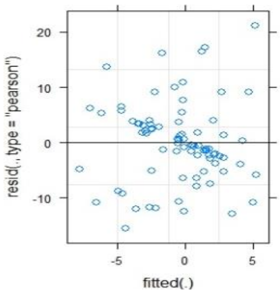
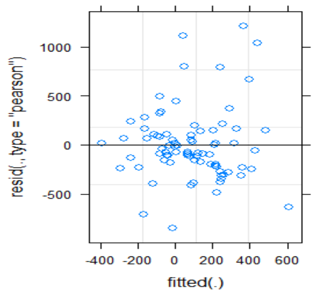
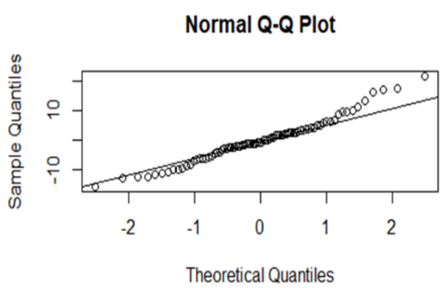
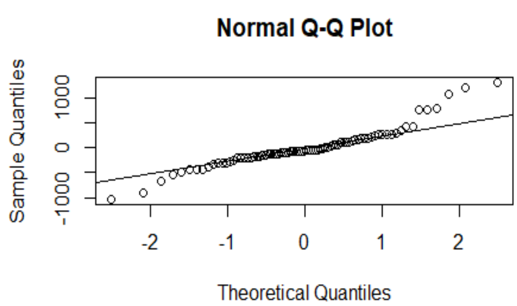
Assumption	**Treeline shifting**	**Tree canopy cover per plot change**
Linearity of variables	 (a)	 (b)
		 (c)
Homogeneity of variance	 (d)	 (e)
Normal distribution of the residuals	 (f)	 (g)

Figure 13: LMMs diagnostics.

Plots *a*, *b* and *c* show that the residual variance does not seem to be a function of the explanatory variable. Secondly, plots *d* and *e* do not show any visible trend. The correlation test between the residuals versus fitted values shows a p-value of 1 for both changes. This shows that the variance is homogenous. The normal Q-Q plots *f* and *g* show that the residuals are normally distributed as indicated by the negligible deviations of residual points from linearity. These diagnostics showcase that the models fulfilled the necessary assumptions of the linear mixed models.

4. DISCUSSION

4.1. Image classification and accuracy assessment

In this study, the overall accuracies for all the classified images obtained from the OBIA method in this study are higher than 80 %. According to the accuracy values grouping developed by Congalton & Green (1999), these findings indicate a strong link between reference data and image classifications. These accuracies are in line with those obtained by previous researchers on OBIA such as Blaschke (2010), Maggi et al. (2007), Hsieh et al. (2017) and Yu et al. (2006). Secondly, the differences in the accuracies of the panchromatic and Google Earth images are roughly the same. Such high accuracies show that OBIA can be used to overshadow the shortcomings of pixel-based classification on low spectral resolution images.

The accuracies obtained validates the use of high-resolution imagery for accuracy assessment of classification images as suggested and used previously by other treeline researchers (Tilahun 2015). The high accuracies might have also resulted from the consolidation of different land cover types into only two classes.

4.2. Treeline positions

The establishment of tree limits in this study is not occurring in a monotonic pattern along a latitudinal gradient. Temperature decreases gradually with increasing latitude and altitude. As a general rule, a latitudinal increase of one degree is equivalent to approximately 122 m of altitudinal decrease and 0.55º c of temperature fall (Lee 1969; Montgomery 2006).

Treelines are expected to decrease with a latitudinal increase; however, on a global scale, there is no strict correlation between latitude and the treeline distribution (Körner 1998). Anatolian Valley and Tibetan Plateau in Eastern Asia are at the same latitude but have treeline positional differences of more than 2000 m (Schickhoff 2005). This observation suggests that the treeline positions are regulated by other climatic factors unrelated to latitude (Berdanier 2010). Zhao et al. (2014) put forward that mass elevation effect (MEE) is a primary determinant of treeline positions without which trees could only develop to an elevation of about 3500 m and the global ecological pattern would be less complex. MEE is defined as the heating effect of a large mass of a plateau (Shi & Wu 2013). The moving air masses towards a raised terrain cool forming clouds at the mountain periphery, but the interior parts of the mountain become drier. Isotherms in the interior of the mountains thus shift to higher elevations (Körner 2012) creating a more conducive environment for tree growth and development. Some of the factors responsible for MEE include mountain area and mountain height. Furthermore, Zhao et al. (2014) also stated that continentality plays a vital role in the global and hemispherical altitudinal distribution of treelines. Generally, treeline positions have been found to descend from the continental inland to the island, central parts of huge mountains to the periphery and from tropical areas to polar regions (Fallis 2013).

Rodna mountain shows the lowest treeline position and is the lowest of all the study sites although it is at a lower latitudinal position than the Tatra mountain. Thus, the MEE likely explains the disparity. It is also possible that latitudinal positions explain the difference. Olympus mountain is taller than the Lefka Ori and has treelines at higher elevations. Thus, MEE is also the possible decisive factor of the difference in treeline elevations in these study sites. Tatra mountain is at a higher latitudinal position and shorter compared to Olympus mountain. Treeline in Tatra is found at a higher altitude. This is due to Olympus being near the Aegean Sea. This indicates that the continentality could be the main factor distinguishing the treeline heights in the Tatra and Olympus mountains. Thus, it is likely that treeline positions are explained by the MEE, latitudes and continentality in these study sites.

4.3. Treeline ecotones and their changes

In this study, treeline ecotones displayed insignificant canopy cover changes as well as upslope expansions. This is contrary to the observation by other researches that, treeline ecotone infilling and treeline movement are two common patterns for the mountains in the Northern Hemisphere (Harsch et al. 2009; Bolli et al. 2007). Altitude negatively correlates with historical canopy cover with an index of 0.5 denoting a gradual transition of canopy cover from a dense to a sparse cover towards the upper edges of the treeline ecotones.

Besides, treeline ecotones distribution and changes do not occur randomly but in a manner that can be predicted by the topographical variables. Based on the statistical analysis, altitude plays a significant role in the canopy cover in the treeline ecotones while TPI significantly and positively correlates with treeline positions. The correlation of TPI with treeline positions points to the restraint of treelines by frost and waterlogging in depressions and valleys (Dobrowski 2011; Fletcher et al. 2014; Bader & Ruijten 2008) in contrast with the mid-lower slope positions having higher levels of soil surface wetness than the uplands (Lookingbill & Urban 2004).

Terrain factors also explain the treeline ecotone changes in the study sites. Altitude was the only significant factor in the treeline migration predicting 11% of the shifts. The correlation between the upslope movement and elevation is negative as hypothesized. On the other hand, altitude and profile curvature are the significant putative predictors of canopy cover changes. They both correlate negatively with the changes. Concave terrains have a higher tree canopy cover increase than the convex terrains. Individually, altitude and profile curvature predict 5 % and 10 % respectively. The interactive power of both variables produces a predictive potential of 40% of the canopy cover variation. The significance of profile curvature and altitude denotes that there is possibly higher suitability of concave areas at the lower parts of the treeline ecotone than the ones at the upper edges.

The importance of concave curvature shows that concave-shaped surfaces are more conducive for canopy cover increase than the convex terrains. The significance of concavity at high elevations on hill slopes mirrors terrain shape providing sufficient soil moisture but allowing for drainage, thus inhibiting the negative impacts of frost or waterlogging on tree growth (Das et al. 2015). Concave areas also shelter trees from higher air temperature and windy conditions during the growing season (Hiemstra et al.; Kjallgren & Kullman 1998), which consequently result in dense canopy growth (Hammer & Walsh 2008). Concave surfaces also have longer snow cover duration than convex sites (Broll & Keplin 2005) which will be the source of water during spring (Cermak et al. 2005). Snow cover duration determines the length of the growing season and the release of nutrients and water which are vital for plant growth (Inouye 2000).

Altitude has an ecological meaning on the temperature and moisture while profile curvature is a significant determinant of water and erosion or deposition. TPI influences cold-air ponding, water logging and moisture. In general, it is likely that temperature positively controls tree establishment and changes while the precipitation is negatively correlated with treeline ecotones in these study sites and their changes as stated by Körner (2012).

Global warming is expected to lead to treeline movement to higher elevations and latitudes (Schwab et al. 2018) as well as an increase in canopy coverage. However, there is no significant treeline movement detected in all the study sites. This may be due to the time lag. Körner (2012) states that treeline movement cannot be assessed at a scale of less than half-century due to the time delays related to reproductive, maturity age and mortality. The time scale between the historical and modern eras in this study are less than 50 years except for Lefka Ori mountain. Moreover, if the trees in the treeline ecotones are in krummholz form, like in Lefka Ori, then insignificant changes are foreseeable since they are quite insensitive to climate change (Dai et al. 2017).

Despite treeline ecotone limit, canopy cover and their changes being predictable by the topological variables, there remains a large amount of variation which is not explained. The remaining variation might be because of other topographical factors not used in the model or factors not related to topography. It is also reasonable that anthropogenic activities shape the treelines in the study areas due to the claim in several studies that grazing in European mountains depresses treeline ecotones (Dirnböck et al. 2003; Kuemmerle et al. 2009). This assertion is furthermore bolstered by the observed uneven distribution of treeline shifting within the sites. The trees in the ecotones of these mountains are of the *Pinaceae* family which are also the dominant species in the Southern, Central and Eastern Europe treelines (Boratyńska et al. 2005). *Pinacea* family species are commonly stressed by herbivory (Cherubini et al. 2002; Todaro et al. 2007). *Quercus* which is found in the Lefka Ori treeline ecotones shares the same characteristics as the pine species in the Northern hemisphere (Keeley 2012). This supports the likely contribution of herbivory on treeline ecotone dynamics.

Herbivory in the mountain ecosystems is not only confined to the upper edge of the treeline ecotone but rather across the ecotone. This can thus imply that canopy cover increase is majorly due to tree crown diameter increase and foliation rather than growth in tree population. Treeline shifting in some few locations reflects a few trees which manage to reach the grazing escape height and thus flourished in the ecosystem. However, this observation needs further investigations for firmer conclusions.

Significant treeline movement can only occur when establishment, growth and survival of seedlings are successful (Kambo & Danby 2018). In this study, other site-specific factors which were not accounted for by the independent variables used could be inhibiting changes. Such factors include but not limited to snow slides, avalanches, snow creeps, lack of viable seeds, high sapling and seedling mortality, land use changes, the limited ability of tree species to adapt to new environments, pathogens and diseases, severe wildfires and nutrient deficiency (Holtmeier & Broll 2017).

There exist probable sources of the uncertainties in this study. The low variance explained by the predictors used could be due to the small sample size of the data providing lower statistical power. Secondly, lack of reliable climatic data hindered the analysis of climatic parameters on treeline ecotones and their changes, especially that temperature is probably the main parameter influencing treeline ecotone formation and modifications. Historical images quality could also be the possible causes of uncertainties in the analysis. Identifying tree limits from the images was difficult. Finally, the lack of data on grazing intensity and other human-induced impacts is also another possible source of uncertainty in the study sites.

Nonetheless, the interplay of a diversity of factors within sites makes modeling treeline ecotone limit, canopy cover and their changes more complex. This hence calls for a robust statistical analysis incorporating a multitude of influential variables of treeline ecotone and their alterations.

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

Treeline altitudinal limits are not entirely explained by the latitudinal positions but also depends on the mass elevation effects and the continentality with tall mountains and those farther away from the oceanic influences having treeline positions at higher elevations.

Canopy cover expansion and treeline upslope migration are quite negligible in the study sites. Contrary to the obvious expectations of treeline ecotones colonizing the alpine zones, this study proves that treeline ecotone changes are not ubiquitous. Due to the commonly documented cases of herbivory in the European mountains, it is reasonable that the increase of canopy cover in treeline ecotones is more likely due to the increased tree foliage more than tree population increase.

Topo-climatic variables marginally explain the occurrence and variation of treeline ecotones in these study areas. Lower altitudes of the ecotone are more conducive for treeline ecotone establishment and changes. TPI negatively correlates with treeline establishment. Furthermore, concave terrains at lower slopes of the ecotones are more favorable for tree canopy cover intensification. However, there remains a large amount of variation not accounted for by the variables used in this study. The unexplained gap might be due to other site-specific factors. Investigation of treeline ecotones and their changes is complicated due to the intricate interactions among multiple feasible variables within the ecosystem and thus requires multifactorial statistical analyses.

5.2. Recommendations

The study endeavored to map and find out factors affecting treeline ecotones and their changes. There remain quite apparent gaps which could be addressed further. The study found out that latitude, continentality and MEE are the modulators of treeline elevations in the sites. More sites need to be considered to make substantial deductions on the effects of these factors at a larger scale. The exploratory variables used explained a little variation of the treeline ecotones establishment and modifications. For better understanding, other factors affecting treeline ecotones could be included in the creation of the models to reveal the factors influencing treeline ecotones along a latitudinal gradient.

Weather stations are found at lower altitudes and sometimes far from the mountains. Even with the temperature decrease of 6º C per 1000 m upslope, temperature estimations will still be unreliable due to the effects of microclimate. It is, therefore, expedient that temperature is measured and monitored at the treeline ecotones. Finally, the study concluded that the canopy increase is mainly due to increased canopy cover rather than the tree population. However, this claim can be better explained by setting up monitoring sites where changes in tree population and canopy cover could be monitored.

LIST OF REFERENCES

Abuckley. (2010). 'Understanding curvature rasters'. *Esri*. Retrieved December 15, 2018, from <https://www.esri.com/arcgis-blog/products/product/imagery/understanding-curvature-rasters/>

Amatulli, G., Domisch, S., Parmentier, B., Tuanmu, M., Jetz, W., Ranipeta, A., & Malczyk, J. (2017). 'A suite of global, cross-scale topographic variables for environmental and biodiversity modeling', *Scientific Data*, In press: 1–15. DOI: 10.1038/sdata.2018.40

de Andrés, E. G., Camarero, J. J., & Büntgen, U. (2015). 'Complex climate constraints of upper treeline formation in the Pyrenees', *Springer*. DOI: 10.1007/s00468-015-1176-5

Bader, M. Y., Rietkerk, M., & Bregt, A. K. (2008). 'A Simple Spatial Model Exploring Positive Feedbacks at Tropical Alpine Treelines', *Arctic, Antarctic, and Alpine Research*. DOI: 10.1657/1523-0430(07-024)[BADER]2.0.CO;2

Bader, M. Y., & Ruijten, J. J. A. (2008). 'A topography-based model of forest cover at the alpine tree line in the tropical Andes', *Journal of Biogeography*. DOI: 10.1111/j.1365-2699.2007.01818.x

Barbeito, I., Dawes, M. A., Rixen, C., Senn, J., & Bebi, P. (2012). 'Factors driving mortality and growth at treeline: A 30-year experiment of 92 000 conifers', *Ecology*. DOI: 10.1890/11-0384.1

Bareja, B. (2011). 'Abiotic Factors Affecting Plant Growth: Topography and Soil'. *Cropsreview*. Retrieved December 15, 2018, from <https://www.cropsreview.com/abiotic-factors.html>

Bebi, P., Kienast, F., & Schönenberger, W. (2001). 'Assessing structures in mountain forests as a basis for investigating the forests' dynamics and protective function', *Forest Ecology and Management*. DOI: 10.1016/S0378-1127(00)00570-3

Belgiu, M., & Drăguţ, L. (2014). 'Comparing supervised and unsupervised multiresolution segmentation approaches for extracting buildings from very high resolution imagery', *ISPRS Journal of Photogrammetry and Remote Sensing*. DOI: 10.1016/j.isprsjprs.2014.07.002

Berdanier, A. (2010). 'Global Treeline Position | Learn Science at Scitable'. *thenatureEDUCATION*. Retrieved January 13, 2019, from <https://www.nature.com/scitable/knowledge/library/global-treeline-position-15897370>

Blaga, L. (2012). 'Aspects regarding the significance of the Curvature Types and Values in the Studies of Geomorphometry assissted by GIS', *Studies in Mathematical Sciences*.

Blaschke, T. (2010). 'Object based image analysis for remote sensing'. *ISPRS Journal of Photogrammetry and Remote Sensing*. DOI: 10.1016/j.isprsjprs.2009.06.004

Boll, T., Svenning, J. C., Vormisto, J., Normand, S., Grández, C., & Balslev, H. (2005). 'Spatial distribution and environmental preferences of the piassaba palm Aphandra natalia (Arecaceae) along the Pastaza and Urituyacu rivers in Peru', *Forest Ecology and Management*. DOI: 10.1016/j.foreco.2005.03.020

Bolli, J. C., Rigling, A., & Bugmann, H. (2007). 'The influence of changes in climate and land-use on regeneration dynamics of Norway spruce at the treeline in the swiss alps', *Silva Fennica*. DOI: 10.14214/sf.307

Boratyńska, K., Marcysiak, K., & Boratynski, A. (2005). 'Pinus mugo (Pinaceae) in the Abruzzi Mountains: High morphological variation in isolated populations', *Botanical Journal of the Linnean Society*. DOI: 10.1111/j.1095-8339.2005.00374.x

Broll, G., & Keplin, B. (2005). *Mountain ecosystems: Studies in treeline ecology*. *Springer*. DOI: 10.1007/b138976

Caccianiga, M., Andreis, C., Armiraglio, S., Leonelli, G., Pelfini, M., & Sala, D. (2008). 'Climate continentality and treeline species distribution in the Alps', *Plant Biosystems*. DOI: 10.1080/11263500701872416

Callaway, R. M. (1998). 'Competition and Facilitation on Elevation Gradients in Subalpine Forests of the Northern Rocky Mountains, USA', *Oikos*. DOI: 10.2307/3546376

Cansler, C. A., McKenzie, D., & Halpern, C. B. (2018). 'Fire enhances the complexity of forest structure in alpine treeline ecotones':, *Ecosphere*. DOI: 10.1002/ecs2.2091

Casana, J., & Jackson Cothren. (2013). 'The Corona Atlas Project: Orthorectification of Corona Satellite Imagery and regional-Scale Archaeological Exploration in the Near East'. *Springer*. DOI: 10.1007/978-1-4614-6074-9

Cermak, J., Opgenoorth, L., & Miehe, G. (2005). 'Isolated mountain forests in central Asian deserts: A case study from the Govi Altay, Mongolia'. *Springer*. DOI: 10.1007/3-540-27365-4_11

Chen, I., Hill, J. K., Ohlemüller, R., Roy, D. B., & Thomas, C. D. (2011). 'Rapid range shifts of species associated with high levels of climate warming.', *Science (New York, N.Y.)*. DOI: 10.1126/science.1206432

Cherubini, P., Fontana, G., Rigling, D., Dobbertin, M., Brang, P., & Innes, J. L. (2002). 'Tree-life history prior to death: Two fungal root pathogens affect tree-ring growth differently', *Journal of Ecology*. DOI: 10.1046/j.1365-2745.2002.00715.x

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., et al. (2013). 'The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change', *IPCC*. DOI: 10.1017/CBO9781107415324.015

Clark, D. B., Palmer, M. W., & Clark, D. A. (1999). 'Edaphic factors and the landscape-scale distributions of tropical rain forest trees', *Ecology*. DOI: 10.1890/0012-9658(1999)080[2662:EFATLS]2.0.CO;2

Congalton, R. G., & Green, K. (1999). 'Assessing the accuracy of remotely sensed data: principles and applications', *Lewis Publishers, Boca Raton, Flalishers*.

Cooley, S. (2016). 'Terrain Roughness - 13 Ways'. *GIS 4 Geomorphology*. Retrieved December 15, 2018, from <http://gis4geomorphology.com/roughness-topographic-position/>

Coomes, D. A., & Allen, R. B. (2007). 'Effects of size, competition and altitude on tree growth', *Journal of Ecology*. DOI: 10.1111/j.1365-2745.2007.01280.x

Cresswell, I., & Murphy Hellen. (2016). 'Importance of biodiversity | Australia State of the Environment Report'. *Australia State of Environment*. Retrieved June 4, 2018, from <https://soe.environment.gov.au/theme/biodiversity/topic/2016/importance-biodiversity>

Cudlín, P., Klopčič, M., Tognetti, R., Mališ, F., Alados, C. L., Bebi, P., Grunewald, K., et al. (2017). 'Drivers of treeline shift in different European mountains', *Climate Research*. DOI: 10.3354/cr01465

Czortek, P. (2018). 'Changes in vegetation of the Tatry Mountains related to climate change and change in land use', *Faculty of Biology of the University of Warsaw*.

Dai, L., Luo, G., Palombo, C., Rossiter, D. G., Tognetti, R., & van Gils, H. (2017). 'Pinus mugo Krummholz Dynamics During Concomitant Change in Pastoralism and Climate in the Central Apennines ', *Mountain Research and Development*, 37/1: 75–86. DOI: 10.1659/mrd-journal-d-14-00104.1

Danby, R. K. (2011). 'Monitoring forest-tundra ecotones at multiple scales', *Geography Compass*. DOI: 10.1111/j.1749-8198.2011.00447.x

Danby, R. K., & Hik, D. S. (2007). 'Variability, contingency and rapid change in recent subarctic alpine tree line dynamics', *Journal of Ecology*. DOI: 10.1111/j.1365-2745.2006.01200.x

Das, A., Nagendra, H., Anand, M., & Bunyan, M. (2015). 'Topographic and bioclimatic determinants of the occurrence of forest and grassland in tropical montane forest-grassland mosaics of the Western Ghats, India', *PLoS ONE*. DOI: 10.1371/journal.pone.0130566

Diaz, H. F., Eischeid, J. K., Duncan, C., & Bradley, R. S. (2003). 'Variability of freezing levels, melting season indicators, and snow cover for selected high-elevation and continental regions in the last 50 years'. *Springer*. DOI: 10.1023/A:1024460010140

Dinca, L., Nita, M. D., Hofgaard, A., Alados, C. L., Broll, G., Borz, S. A., Wertz, B., et al. (2017). 'Forests dynamics in the montane – alpine boundary : a comparative study using satellite imagery and climate data', *Climate Research*. DOI: https://doi.org/10.3354/cr01452

Dirnböck, T., Dullinger, S., & Grabherr, G. (2003). 'A regional impact assessment of climate and land-use change on alpine vegetation', *Journal of Biogeography*. DOI: 10.1046/j.1365-2699.2003.00839.x

Dobrowski, S. Z. (2011). 'A climatic basis for microrefugia: The influence of terrain on climate'. *Global Change Biology*. DOI: 10.1111/j.1365-2486.2010.02263.x

Ebert, K. (2015). 'GIS analyses of ice-sheet erosional impacts on the exposed shield of Baffin Island, eastern Canadian Arctic', *Canadian Journal of Earth Sciences*. DOI: 10.1139/cjes-2015-0063

Fagre, D. B. (2008). 'Chapter 1 Introduction. Understanding the Importance of Alpine Treeline Ecotones in Mountain Ecosystems'. *Developments in Earth Surface Processes*. DOI: 10.1016/S0928-2025(08)00201-0

FAO. (2000). *On definitions of forest and forest change. FRA Working Paper No. 33.FAO*. Retrieved August 28, 2018, from <http://www.fao.org/docrep/006/ad665e/ad665e06.htm>

Filippidis, E. I., & Mitsopoulos, I. D. (2004). 'Mapping forest fire risk zones based on historical fire data in Mount Olympus, Greece, using Geographical Information Systems', *WITPRESS*, 9: 613–25.

Fletcher, M. S., Wood, S. W., & Haberle, S. G. (2014). 'A fire-driven shift from forest to non-forest: Evidence for alternative stable states?', *Ecology*. DOI: 10.1890/12-1766.1

Gamache, I., & Payette, S. (2005). 'Latitudinal response of subarctic tree lines to recent climate change in eastern Canada', *Journal of Biogeography*, 32/5: 849–62. DOI: 10.1111/j.1365-2699.2004.01182.x

Geoffrey, S., Nance, R. D., & Genes, A. N. (1997). 'Quaternary glacial history of Mount Olympus, Greece', *The Geological Society of America*. DOI: 10.1130/0016-7606(1997)109<0809:QGHOMO>2.3.CO;2

Goulden, M. L., Anderson, R. G., Bales, R. C., Kelly, A. E., Meadows, M., & Winston, G. C. (2012). 'Evapotranspiration along an elevation gradient in California's Sierra Nevada', *Journal of Geophysical Research: Biogeosciences*. DOI: 10.1029/2012JG002027

Grabherr, G., Gottfried, M., & Pauli, H. (1994). 'Climate effects on mountain plants', *Nature*. DOI: 10.1038/369448a0

Greenwood, S., & Jump, A. S. (2014). 'Consequences of Treeline Shifts for the Diversity and Function of High Altitude Ecosystems', *Arctic, Antarctic, and Alpine Research*, 46/4: 829–40. DOI: 10.1657/1938-4246-46.4.829

Grodzki, W., Jakuš, R., & Gazda, M. (2003). 'Patterns of bark beetle occurrence in Norway spruce stands of national parks in Tatra Mts. in Poland and Slovakia', *Anzeiger fur Schadlingskunde*. DOI: 10.1046/j.1439-0280.2003.03018.x

Groen, T. A., Fanta, H. G., Hinkov, G., Velichkov, I., Van Duren, I., & Zlatanov, T. (2012). 'Tree Line Change Detection Using Historical Hexagon Mapping Camera Imagery and Google Earth Data', *GIScience & Remote Sensing*. DOI: 10.2747/1548-1603.49.6.933

Haeberli, W., Hoelzle, M., Paul, F., & Zemp, M. (2007). 'Integreted monitoring of mountain glaciers as key indicators of global climate change: the European Alps', *Annals of Glaciology*. DOI: 10.3189/172756407782871512

Hagedorn, F., Schweingruber, F. H., Rigling, A., & Moiseev, P. A. (2004). 'Alpine timberline dynamics in the Southern Urals (Russia)', *Die Erde*.

Hajduk, G. (2017). 'Introduction to linear mixed models'. *Coding Club*. Retrieved January 5, 2019, from <https://ourcodingclub.github.io/2017/03/15/mixed-models.html>

Hammer, E. S., & Walsh, S. J. (2008). 'Chapter 7 Canopy Structure in the Krummholz and Patch Forest Zones'. *Developments in Earth Surface Processes*. DOI: 10.1016/S0928-2025(08)00207-1

Harsch, M. A., Hulme, P. E., McGlone, M. S., & Duncan, R. P. (2009). 'Are treelines advancing? A global meta-analysis of treeline response to climate warming', *Ecology Letters*. DOI: 10.1111/j.1461-0248.2009.01355.x

Heydari, M., & Mahdavi, A. (2009). 'Pattern of Plant Species Diversity in Related to Physiographic Factors in Melah Gavan Protected Area, Iran', *Asian Journal of Biological Sciences*, 2/1: 21–8. DOI: 10.3923/ajbs.2009.21.28

Hoersch, B., Braun, G., & Schmidt, U. (2002). 'Relation between landform and vegetation in alpine regions of Wallis, Switzerland. A multiscale remote sensing and GIS approach', *Computers, Environment and Urban Systems*. DOI: 10.1016/S0198-9715(01)00039-4

Holland, P. G., & Steyn, D. G. (1975). 'Vegetational Responses to Latitudinal Variations in Slope Angle and Aspect', *Journal of Biogeography*. DOI: 10.2307/3037989

Holtmeier, F. K., & Broll, G. (2005). 'Sensitivity and response of northern hemisphere altitudinal and polar treelines to environmental change at landscape and local scales', *Global Ecology and Biogeography*. DOI: 10.1111/j.1466-822X.2005.00168.x

Holtmeier, F. K., & Broll, G. (2007). 'Treeline advance - driving processes and adverse factors', *Landscape Online*. DOI: 10.3097/LO.200701

Holtmeier, F. K., & Broll, G. (2009). 'Altitudinal and polar treelines in the northern hemisphere causes and response to climate change', *Polarforschung*. DOI: 10.1371/journal.pmed.0020359

Holtmeier, F. K., & Broll, G. (2017). 'Treelines-approaches at different scales', *Sustainability (Switzerland)*. DOI: 10.3390/su9050808

Hsieh, Y.-T., Chen, C.-T., & Chen, J.-C. (2017). 'Applying object-based image analysis and knowledge-based classification to ADS-40 digital aerial photographs to facilitate complex forest land cover classification', *Journal of Applied Remote Sensing*. DOI: 10.1117/1.JRS.11.015001

Inouye, D. W. (2000). 'The ecological and evolutionary significance of frost in the context of climate change', *Ecology Letters*. DOI: 10.1046/j.1461-0248.2000.00165.x

Isioye, O. A., & Yang, I. C. (2013). 'Comparison and validation of ASTER-GDEM and SRTM elevation models over parts of Kaduna State, Nigeria', *SA Surveying and Geomatics Indaba (SASGI)*, 11.

Jump, A. S., Huang, T. J., & Chou, C. H. (2012). 'Rapid altitudinal migration of mountain plants in Taiwan and its implications for high altitude biodiversity', *Ecography*. DOI: 10.1111/j.1600-0587.2011.06984.x

Kambo, D., & Danby, R. K. (2018). 'Factors influencing the establishment and growth of tree seedlings at Subarctic alpine treelines', *Ecosphere*. DOI: 10.1002/ecs2.2176

Kazakis, G., Ghosn, D., Vogiatzakis, I. N., & Papanastasis, V. P. (2007). 'Vascular plant diversity and climate change in the alpine zone of the Lefka Ori, Crete', *Biodiversity and Conservation*. DOI: 10.1007/s10531-006-9021-1

Keeley, J. E. (2012). 'Ecology and evolution of pine life histories'. *Annals of Forest Science*. DOI: 10.1007/s13595-012-0201-8

Kjallgren, L., & Kullman, L. (1998). 'Spatial Patterns and Structure of the Mountain Birch Tree-Limit in the Southern Swedish Scandes - A Regional Perspective', *Geografiska Annaler, Series A: Physical Geography*. DOI: 10.1111/1468-0459.00023

Körner, C. (2003). *Alpine plant life: functional plant ecology of high mountain ecosystems*. *Springer*. Springer. DOI: 10.1659/0276-4741(2001)021[0202:APLFPE]2.0.CO;2

Körner, C. (2012). *Alpine Treelines: Functional Ecology of the High Elevation Treelines*. *Springer*. London: Library of Congress Control.

Körner, C., & Paulsen, J. (2004). 'A world-wide study of high altitude treeline temperatures', *Journal of Biogeography*. DOI: 10.1111/j.1365-2699.2003.01043.x

Kucsicsa, G. (2011). 'Considerations on the Timberline in the', *Romanian Academy/Institute of Geography*, 12: 57–61.

Kucsicsa, G. (2015). 'Global climate change-related particularities in the rodnei mountains national park GLOBAL CLIMATE CHANGE – RELATED PARTICULARITIES IN THE RODNEI MOUNTAINS NATIONAL PARK', *Carpathian journal of earth and environmental sciences*, February 2011.

Kuemmerle, T., Chaskovskyy, O., Knorn, J., Radeloff, V. C., Kruhlov, I., Keeton, W. S., & Hostert, P. (2009). 'Forest cover change and illegal logging in the Ukrainian Carpathians in the transition period from 1988 to 2007', *Remote Sensing of Environment*. DOI: 10.1016/j.rse.2009.02.006

Kullman, L. (1998). 'Tree-limits and montane forests in the Swedish Scandes: Sensitive biomonitors of climate change and variability', *Ambio*.

Kullman, L. (2001). '20th century climate warming and tree-limit rise in the southern Scandes of Sweden.', *Ambio*. DOI: 10.1579/0044-7447-30.2.72

Kullman, L. (2007). 'Tree line population monitoring of Pinus sylvestris in the Swedish Scandes, 1973-2005: Implications for tree line theory and climate change ecology', *Journal of Ecology*. DOI: 10.1111/j.1365-2745.2006.01190.x

Landis, J. R., & Koch, G. G. (1977). 'The Measurement of Observer Agreement for Categorical Data', *Biometrics*. DOI: 10.2307/2529310

Lee, R. (1969). 'Latitude, elevation, and mean temperature in the northeast', *Professional Geographer*, 21/4: 227–31. DOI: 10.1111/j.0033-0124.1969.00227.x

Lloyd, A. H., & Fastie, C. L. (2002). 'Spatial and temporal variability in the growth and climate response of treeline trees in alaska', *Springer*. DOI: 10.1023/A:1014278819094

Lookingbill, T., & Urban, D. (2004). 'An empirical approach towards improved spatial estimates of soil moisture for vegetation analysis', *Landscape Ecology*. DOI: 10.1023/B:LAND.0000030451.29571.8b

Lu, D., Hetrick, S., & Moran, E. (2010). 'Land Cover Classification in a Complex Urban-Rural Landscape with QuickBird Imagery', *Photogrammetric Engineering & Remote Sensing*. DOI: 10.14358/PERS.76.10.1159

Maggi, M., Estreguil, C., & Soille, P. (2007). 'Woody vegetation increase in Alpine areas: A proposal for a classification and validation scheme', *International Journal of Remote Sensing*. DOI: 10.1080/01431160600851785

Malanson, G. P. (1997). 'Effects of feedbacks and seed rain on ecotone patterns', *Landscape Ecology*. DOI: 10.1007/BF02698205

Martorell, C., & Peters, E. M. (2005). 'The measurement of chronic disturbance and its effects on the threatened cactus Mammillaria pectinifera', *Biological Conservation*. DOI: 10.1016/j.biocon.2005.01.025

Mokarram, M., Roshan, G., & Negahban, S. (2015). 'Landform classification using topography position index (case study: salt dome of Korsia-Darab plain, Iran)', *Modeling Earth Systems and Environment*, 1/4: 40. Springer International Publishing. DOI: 10.1007/s40808-015-0055-9

Mondal, A., Kundu, S., Chandniha, S. K., Shukla, R., & Mishra, P. K. (2012). 'Comparison of Support Vector Machine and Maximum Likelihood Classification Technique using Satellite Imagery', *International Journal of Remote Sensing and GIS*, 1/2: 116–23.

Montgomery, K. (2006). 'Variation in Temperature With Altitude and Latitude', *Journal of Geography*. DOI: 10.1080/00221340608978675

Morley, P. J., Donoghue, D. N. M., Chen, J. C., & Jump, A. S. (2018). 'Integrating remote sensing and demography for more efficient and effective assessment of changing mountain forest distribution'. *Ecological Informatics*. DOI: 10.1016/j.ecoinf.2017.12.002

Mowbray, T. B., & Oosting, H. J. (1968). 'Vegetation Gradients in Relation to Environment and Phenology in a Southern Blue Ridge Gorge', *Ecological Monographs*. DOI: 10.2307/1948531

Myers, N., Mittermeler, R. A., Mittermeler, C. G., Da Fonseca, G. A. B., & Kent, J. (2000). 'Biodiversity hotspots for conservation priorities', *Nature*. DOI: 10.1038/35002501

Nagy, L., & Grabherr, G. (2009). 'The Biology of Alpine Habitats', *Oxford University Press 2009*, 3.

Nyktas, P. (2012). 'DYNAMIC FEEDBACKS BETWEEN LANDFORM, LANDSCAPE PROCESSES AND VEGETATION PATTERNS', *EThOS*.

Odland, A. (2010). 'Importance of mountain height and latitude for the altitudinal distribution limits of vascular plants in Scandinavia : are the mountains high enough ?', *Fennia*, 188/2: 149–162.

Odland, A. (2015). 'Effect of latitude and mountain height on the timberline (Betula pubescens ssp. czerpanovii) elevation along the central Scandinavian mountain range', *Fennia*. DOI: 10.11143/48291

Okeke, F., & Karnieli, A. (2006). 'Methods for fuzzy classification and accuracy assessment of historical aerial photographs for vegetation change analyses. Part I: Algorithm development', *International Journal of Remote Sensing*. DOI: 10.1080/01431160500166540

Organization of the National Forest Management of Olympus. (2018). 'Vegetation Zones & Types of Habitats - Organization of the National Forest Management of Olympus'. *National Forest of Olympus* . Retrieved February 9, 2019, from <https://olympusfd.gr/ζώνες-βλάστησης-τύποι-οικοτόπων/>

Parmesan, C., & Yohe, G. (2003). 'A globally coherent fingerprint of climate change impacts across natural systems', *Nature*. DOI: 10.1038/nature01286

Payette, S., & Filion, L. (1985). 'White spruce expansion at the tree line and recent climatic change', *Canadian Journal of Forest Research*, 15/1: 241–51. DOI: 10.1139/x85-042

Peng, C., Zhou, X., Zhao, S., Wang, X., Zhu, B., Piao, S., & Fang, J. (2009). 'Quantifying the response of forest carbon balance to future climate change in Northeastern China: Model validation and prediction', *Global and Planetary Change*. DOI: 10.1016/j.gloplacha.2008.12.001

Platt, R. V., & Schoennagel, T. (2009). 'An object-oriented approach to assessing changes in tree cover in the Colorado Front Range 1938-1999', *Forest Ecology and Management*, 258/7: 1342–9. DOI: 10.1016/j.foreco.2009.06.039

Presas, E. B., Camarero, J. J., Ninot, J. M., & Gutiérrez, E. (2009). 'Seedling recruitment, survival and facilitation in alpine Pinus uncinata tree line ecotones. Implications and potential responses to climate warming', *Global Ecology and Biogeography*. DOI: 10.1111/j.1466-8238.2009.00464.x

Pungetti, G., Marini, A. M., & Vogiatzakis, I. N. (2008). *Mediterranean Island Landscapes: Natural and Cultural Approaches*. *Springer*. DOI: 10.1076/vesd.36.4.359.3546

R Core Team. (2018). 'R: The R Project for Statistical Computing'. *R Foundation for Statistical computing, Vienna, Austria*. Retrieved February 19, 2019, from <https://www.r-project.org/>

Roberts, D. W. (1986). 'Ordination on the basis of fuzzy set theory', *Vegetatio*. DOI: 10.1007/BF00039905

Schenk, T., Csatho, B., & Shin, S. (2003). 'Rigorous panoramic camera model for DISP imagery', *The Ohio State University*.

Schickhoff, U. (2005). 'The upper timberline in the Himalayas, Hindu Kush and Karakorum: A review of geographical and ecological aspects'. *Springer*. DOI: 10.1007/3-540-27365-4_12

Schwab, N., Kaczka, R. J., Janecka, K., Böhner, J., Chaudhary, R. P., Scholten, T., & Schickhoff, U. (2018). 'Climate change-induced shift of tree growth sensitivity at a central Himalayan treeline ecotone',

Forests. DOI: 10.3390/f9050267
Shi, P., & Wu, N. (2013). 'The timberline ecotone in the Himalayan region: An ecological review', *Chinese Academy of Sciences*, 108–16.
Singh, C. P., Panigrahy, S., & Parihar, J. S. (2012). 'Alpine Vegetation Ecotone Dynamics in Gangotri Catchment Using Remote Sensing Techniques', *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. DOI: 10.5194/isprsarchives-XXXVIII-8-W20-162-2011
Smith, J. M. B. (1977). 'Vegetation and Microclimate of East- and West-Facing Slopes in the Grasslands of MT Wilhelm, Papua New Guinea', *Journal of Ecology*. DOI: 10.2307/2259061
Sohn, H. G., Kim, G. I. H., & Yom, J. H. (2004). 'Mathematical modelling of historical reconnaissance CORONA KH-4B imagery'. *Photogrammetric Record*. DOI: 10.1046/j.0031-868X.2003.00257.x
Stocker, T. F., Qin, D., Plattner, G. K., Tignor, M. M. B., Allen, S. K., Boschung, J., Nauels, A., et al. (2013). *Climate change 2013 the physical science basis: Working Group I contribution to the fifth assessment report of the intergovernmental panel on climate change*. *IPCC*, Vol. 9781107057. DOI: 10.1017/CBO9781107415324
Stoffel, M., Wehrli, A., Kühne, R., Dorren, L. K. A., Perret, S., & Kienholz, H. (2006). 'Assessing the protective effect of mountain forests against rockfall using a 3D simulation model', *Forest Ecology and Management*. DOI: 10.1016/j.foreco.2005.12.030
Styllas, M. (2017). 'Mount Olympus Massif - Olympus Climbing Mount Olympus On-line Guide'. *Olympus Climbing*. Retrieved February 9, 2019, from <https://www.olympus-climbing.gr/index.php?page=articles&id=24>
Švajda, J., Solár, J., Janiga, M., & Buliak, M. (2011). 'Dwarf Pine (Pinus mugo) and Selected Abiotic Habitat Conditions in the Western Tatra Mountains', *Mountain Research and Development*. DOI: 10.1659/MRD-JOURNAL-D-09-00032.1
Tchoukanski, I. (n.d.). 'RasterCurvature'. *ESRI*. Retrieved December 15, 2018, from <http://www.et-st.com/et_surface/userguide/Raster/ETG_RasterCurvature.htm>
Tenow, O. (1996). 'Hazards to a mountain birch forest- Abisko in perspective.', *Ecological Bulletins*.
Tilahun, A. (2015). 'Accuracy Assessment of Land Use Land Cover Classification using Google Earth', *American Journal of Environmental Protection*, 4/4: 193. DOI: 10.11648/j.ajep.20150404.14
Todaro, L., Andreu, L., D'Alessandro, C. M., Gutiérrez, E., Cherubini, P., & Saracino, A. (2007). 'Response of Pinus leucodermis to climate and anthropogenic activity in the National Park of Pollino (Basilicata, Southern Italy)', *Biological Conservation*, 137/4: 507–19. DOI: 10.1016/j.biocon.2007.03.010
Treml, V., & Chuman, T. (2015). 'Ecotonal Dynamics of the Altitudinal Forest Limit are Affected by Terrain and Vegetation Structure Variables: An Example from the Sudetes Mountains in Central Europe', *Arctic Antarctic and Alpine Research*. DOI: 10.1657/AAAR0013-108
Truong, C., Palmé, A. E., & Felber, F. (2007). 'Recent invasion of the mountain birch Betula pubescens ssp. tortuosa above the treeline due to climate change: Genetic and ecological study in northern Sweden', *Journal of Evolutionary Biology*. DOI: 10.1111/j.1420-9101.2006.01190.x
Tukhanen, S. (1984). 'A circumboreal system of climatic-phytogeographical regions', *Acta Botanica Fennica*.
Vogiatzakis, I. N., Griffiths, G. H., & Mannion, A. M. (2003). 'Environmental factors and vegetation composition, Lefka Ori massif, Crete, S. Aegean', *Global Ecology and Biogeography*. DOI: 10.1046/j.1466-822X.2003.00021.x
Walther, G. R., Beißner, S., & Pott, R. (2005). 'Climate change and high mountain vegetation shifts'. *Mountain Ecosystems: Studies in Treeline Ecology*. DOI: 10.1007/3-540-27365-4_3
Weiss, D. J., & Walsh, S. J. (2009). 'Remote sensing of mountain environments', *Geography Compass*. DOI: 10.1111/j.1749-8198.2008.00200.x
White, A., Cannell, M. G. R., & Friend, A. D. (2000). 'The high-latitude terrestrial carbon sink: A model analysis', *Global Change Biology*. DOI: 10.1046/j.1365-2486.2000.00302.x
Wiersum, K. F. (1995). '200 years of sustainability in forestry: Lessons from history'. *Environmental Management*. DOI: 10.1007/BF02471975
Yu, Q., Gong, P., Clinton, N., Biging, G., Kelly, M., & Schirokauer, D. (2006). 'Object-based Detailed Vegetation Classification with Airborne High Spatial Resolution Remote Sensing Imagery', *Photogrammetric Engineering & Remote Sensing*. DOI: 10.14358/PERS.72.7.799
Zhang, Y., Xu, M., Adams, J., & Wang, X. (2009). 'Can Landsat imagery detect tree line dynamics?', *International Journal of Remote Sensing*. DOI: 10.1080/01431160802509009

Zhao, F., Zhang, B., Pang, Y., & Yao, Y. (2014). 'A study of the contribution of mass elevation effect to the altitudinal distribution of timberline in the Northern Hemisphere', *Journal of Geographical Sciences*. DOI: 10.1007/s11442-014-1084-4