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Red-Edge Normalised Difference Vegetation Index ($NDVI_{705}$) from Sentinel-2 imagery to assess post-fire regeneration

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Abstract

Obtaining post-fire information from a burnt region is of paramount importance in applications such as examining the disturbance of natural ecosystems and in providing crucial information to local authorities that have control on policymaking. This study uses freely available data from the European Space Agency's (ESA) Sentinel-2 satellite to create a Red-Edge Normalised Difference Vegetation Index ($NDVI_{705}$) and combines the resulting layer with 30m Digital Elevation Model (DEM) from the Japanese Aerospace Exploration Agency (JAXA) to assess topographical parameters (ie. slope steepness and aspect) which may have influenced the revegetation process. Additionally, weather data is combined with the aforementioned datasets to study the revegetation dynamics. A fire event which occurred in June 2016 in Evrychou, Cyprus, was chosen, as it was one of the largest fire events in the island and happened when the Sentinel-2 was already operational, hence a period of time spanning 14 months has been studied. The results have indicated an inconsistent $NDVI_{705}$ change throughout the period. However, a significant improvement in $NDVI_{705}$ values was observed in the months of spring 2017. The improvement in vegetation health was mostly observed on north-facing and less-steep slopes, something which corresponds with previous studies in northern-hemisphere Mediterranean climates. The results have also highlighted the ability to conduct a rapid and cost-effective post-fire assessment which can be scaled up or down depending on the fire size and which can be applied to any other environment where post-fire management is required.

Keywords: Post-fire regeneration; Sentinel-2 satellite; Red-Edge Normalised Difference Vegetation Index ($NDVI_{705}$); Evrychou, Cyprus; Mediterranean Wildfires

Highlights

- A modified Normalised Difference Vegetation Index for revegetation from Sentinel-2 data was adopted.
- One of the biggest fire events in Cyprus occurred in June 2016 is used as a case study.
- Results indicate higher revegetation rates during months of spring and they show higher revegetation on north-facing and low-steepness slopes.
- Demonstrates the ability to use free-to-access data in aiding with decision making.
- The method is a cost-effective way of assessing post-fire regeneration.

1. Introduction

1.1 Background and study area

On June 19th, 2016, approximately 20 km^2 of forest were burnt near the village of Evrychou located 15 km from Mt. Olympus (the highest peak in Cyprus; figure 1). The fire started in a small dry grass and wild shrub area and led to a major loss of dry coniferous forest, but also some orchards were affected. During the wildfire, local authorities were particularly concerned due to strong winds, the fire's residence time, temperatures of around 40 ℃ and the inaccessibility to the burning region. While attempting to reach the affected area two fire trucks were overturned and caused the death of two firefighters, so the authorities decided to end terrestrial support to quench the fire due to the involved risks. Immediate post-fire attempts to obtain field observations failed due to difficult access as a result of lack of roads and the presence of steep slopes in the outskirts. In this context, obtaining remotely sensed data may provide better information more quickly and for less cost (Fox et al., 2008).

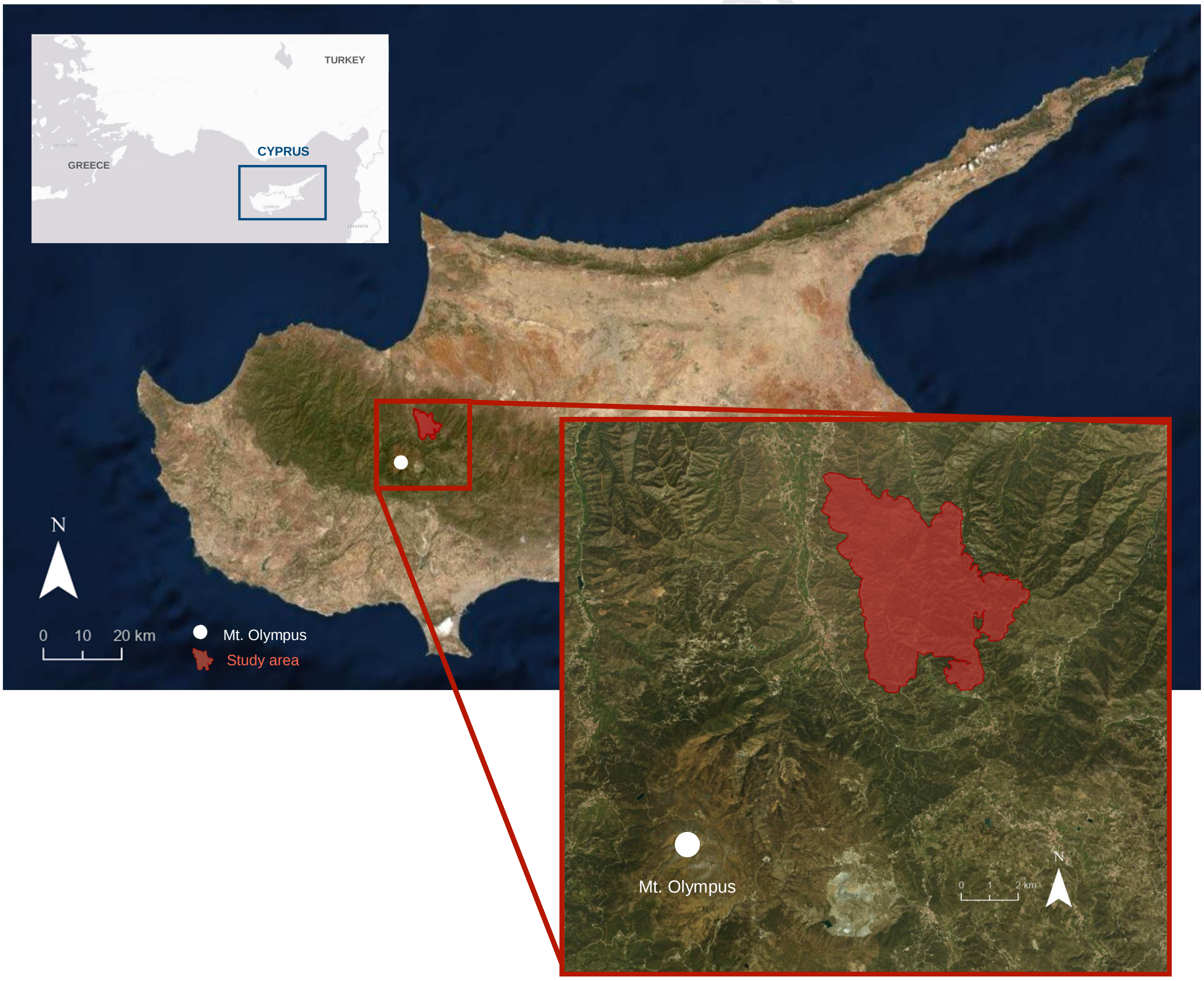

Figure 1. The study area location within Cyprus, north-west of the island's highest peak, Mt. Olympus.

1.2 Fire in the environment

Fire is an integral component of many ecosystems. It is regarded as an important natural phenomenon that has a fundamental role in the distribution, organisation and evolution of terrestrial ecosystems (Bowman et al., 2009). However, fires in forests have important biophysical and ecological consequences at multiple scales (Veraverbeke et al., 2012). At global scales, fire is a major contributor to the emission of trace gases in the atmosphere hence playing an undeniable role in global climate cycles (Andreae and Crutzen, 1997; Flannigan et al., 2000). At landscape level, fires partially or completely remove layers of vegetation thus affecting post-fire soil characteristics (Veraverbeke et al., 2012; Christopoulou et al., 2019). Fire is considered to be one of the most threatening sources of disturbance for property, infrastructure and the Mediterranean ecosystem (Petropoulos et al., 2011). In addition, fire constitutes a major threat to human life as well as leading to extremely high suppression and rehabilitation costs for local authorities (Dube, 2013). More detailed effects of fire in forests include the disturbances of below ground physical, chemical and microbial processes, leading to alterations of successional rates, mineralisation rates and above-ground biomass (Marozas et al., 2007; Ireland and Petropoulos, 2015). Such changes are also associated with soil erosion, evapotranspiration and water runoff (Cawson et al., 2013).

In Mediterranean regions, such as the one where Cyprus is located, the mean annual temperatures range between 17°C and 19 °C with temperatures higher than 40℃ in the summer and the mean annual precipitation is mainly dry and varies from 350 to 600 mm with seasonal and annual variability (Pausas, 2004). Consequently, droughts are frequent and vary between a few weeks to more than six months. Also, growth is very limited to mainly spring and autumn when ideal moisture balance takes place, leading to greater growth rates. Mediterranean forest types can be distinguished by their heterogeneity, whether that is climatic, edaphic, biogeographic or historical (Cowling et al., 2015; Gonçalves and Sousa, 2017). Fire regime dynamics are usually driven by human factors and more specifically humans are responsible for more than 95% of the fire events in the European Mediterranean Region (Moreira et al., 2012). For thousands of years, fires have been one of the most important factors shaping Mediterranean landscape where rates of post-fire recovery dynamics are usually spatio-temporal variable and contingent upon a number of factors - eg. landscape complexity, range responses and fire regimes (Mayor et al., 2007; Petropoulos et al., 2014). Mediterranean regions are responsible for approximately 90% of fires in the European Union where landscapes, recently, have undergone dramatic land abandonment (Mouillot et al., 2005). Forest fires despite being essential for the Mediterranean forest ecosystems they account for one of the most threatening natural hazards, as human existence has started to expand towards the rural and forested regions (Diakakis et al., 2017).

Several studies in the Mediterranean region emphasise on the longevity of a burnt region before returning to the pre-fire conditions. Ireland and Petropoulos (2015), for example, claimed that regions in such climatic conditions may take 50-200 years before regenerating completely. However, such studies were focused on a longer assessment period to reach the aforementioned conclusions, whereas this study was based on data of 14 months. Ireland and Petropoulos (2015), studied their region for eight years; del Pino & Ruiz-Gallard (2015) for nine years; and Mouillot et al. (2005) for even a longer period of thirty years. However, the initial stages of the recovery after the fire are crucial, so this study focuses only on the 14 months after the event.

1.3 Remote Sensing and GIS in post-fire assessments

Since the early 70s, fire events and fire severities have experienced an increasing trend, resulting in time becoming a constraining factor on assessing post-fire impacts on vegetation as well as being costlier and labour-intensive (Moreira et al., 2012). To overcome such problems as well as the limited accessibility to the affected areas, satellite remote sensing has proven to be an essential technological source for obtaining post-fire data. The ongoing improvements in spatial resolution and accessibility, and the subsequent improved image analysis techniques have allowed the assessment and evaluation of various patterns of vegetation regeneration and forest recovery after fire events (Gitas et al., 2012).

It is also important to assess the topographical characteristics of the study area, as the aspect and slope of a burnt area are factors which have a significant effect on revegetation recovery dynamics (Díaz-Delgado et al., 2003). The topography of the region, therefore, needs to be studied on the basis of aspect and slope steepness in order to identify parts of the region that are more/less prone to accumulating water and soil, which consequently has a direct effect on the revegetation dynamics (Christopoulou et al., 2019). Hence, the use of remote sensing techniques accompanied by certain GIS functions in such studies helps in presenting some important associations of these parameters to revegetation rates (Díaz-Delgado et al., 2003).

1.4 Vegetation Indices

Fundamental to post-fire regeneration assessments are the calculations of vegetation indices from remotely sensed data, as they aid with the spatio-temporal analysis and burn severity mapping (Chrysafis et al., 2019). Spectral Vegetation Indices (VIs) are implemented to assess vegetation photosynthetic activities, leaf area, biomass and physiological functioning, and to aid with post-fire assessments. VIs have the capability to reduce the effects of extraneous factors such as background substrate, atmosphere and illumination effects (Verrelst et al., 2008).

1.4.1 NDVI

The Normalised Difference Vegetation Index (NDVI) relies on the fact that spongy and healthy vegetation reflects a lot of light in the near-infrared (NIR) spectrum, in stark contrast with most non-plant objects. On the contrary, the vegetation that is dehydrated and unhealthy reflects less light in the NIR, but the same amount in the visible range. Therefore, by mathematically combining these two bands (based on reflectivity difference) and using the formula NDVI = (NIR-VIS) / (NIR+VIS), NDVI can help to highlight vegetation from other land features, and even help differentiate healthy vegetation from unhealthy vegetation (see figure 2). There is a growing body of literature that recognises the importance of NDVI and certain remote sensing techniques hence the rationale for adopting them to ascertain post-fire events (Alcaraz-Segura et al., 2010; Veraverbeke et al., 2012; Vila and Barbosa, 2010; McMichael et al., 2004). Therefore, NDVI has been receiving increasing attention of assessing burnt regions due to its great advantage of that it is easy to obtain using imagery from almost all present sensors (Salvador et al., 2000).

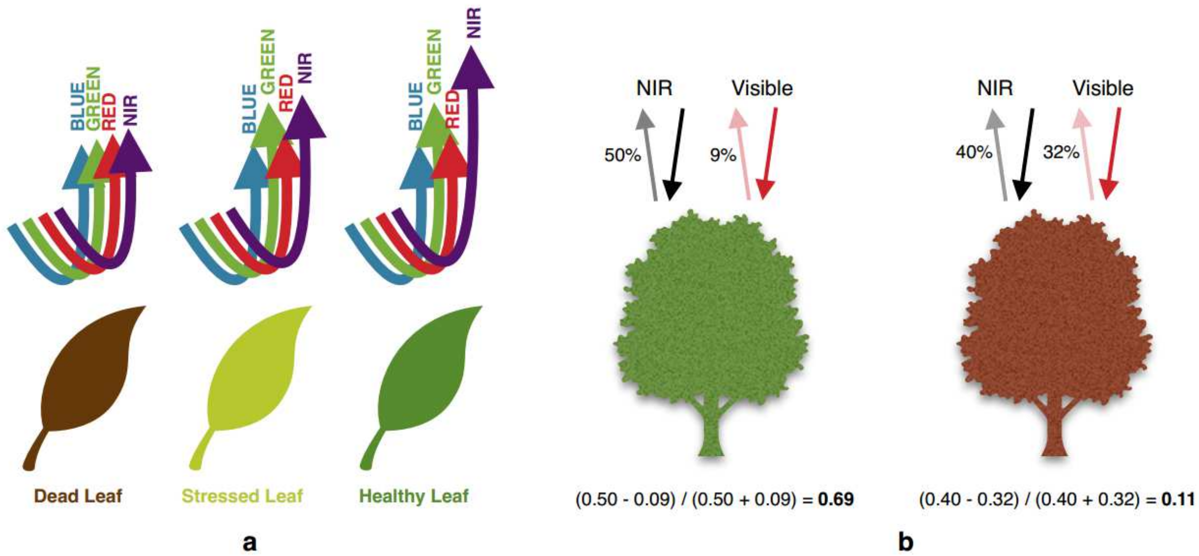

Figure 2. a shows that healthier vegetation reflects more NIR compared to the stressed vegetation where the RGB ratio is the same. However, dead vegetation shows an even lower reflectance of NIR with an even ratio of RGB. These differences can be used to distinguish vegetation from surroundings and healthy vegetation from sickly and unhealthy vegetation. **b** shows an example of NDVI calculation, noticeably the healthy tree has a higher NIR reflection than the dead tree, hence the higher value of NDVI (modified from Weier and Herring, 2000).

Since the launch of first satellite Sentinel-2 in 2015, an alternative to the also freely available data from the Landsat program has been available, and thanks to the superior resolution that Sentinel-2 offers - 10 m in bands 4 and 8 compared to 30 m and 15 m of Landsat-8's bands 4 and 5 respectively (Law et al., 2018; U.S. Geological Survey, 2017) it has become an increasingly popular source for remotely sensed data. In addition, Sentinel-2 carries a Multi-Spectral Instrument (MSI) providing the opportunity for an improved moderate spatial resolution burned area mapping.

The MSI consists of 13 spectral bands with a range of 0.443-2.19 μm in the electromagnetic spectrum.

1.4.2 NBR

Some studies (ie. Frazier et al., 2018; Yang et al., 2017) have adopted the Normalised Burn Ratio (NBR) for post-fire regeneration assessments. The ratio has gained considerable attention, especially in the United States, for detecting burnt scars (Miller and Thode, 2007). The NBR is formulated similarly to the NDVI where the only difference is the use of band 7 (from Landsat) - instead of band 8 for NDVI - which replaces the red band. This is because band 7, which records infrared in the range of 2.08-2.35 μm, is sensitive to water content in both soil and vegetation and along with band 4's (from Landsat) sensitivity for chlorophyll content they make a good combination for detecting changes in live green vegetation, moisture content, and some soil conditions which may take place after a fire event (Jia et al., 2006; Miller and Thode, 2007). Veraverbeke et al. (2010), claimed that NBR is mostly adopted for burnt scars with varying fire-severity. In theory, NBR would be ideal for quantifying fire severity if the trajectory in spectral feature caused by various levels of severity occurred perpendicular to the NBR isoline. On the contrary, Roy et al. (2006), suggested that NBR does not provide optimal evidence for describing fire severity shortly after a fire occurrence. More specifically, the NBR is less sensitive to burning changes as most of the spectral range lies in the NIR and MID (middle-infrared) reflectance - in essence being less sensitive to chlorophyll change, hence the decision of not using this index to evaluate recent post-fire dynamics.

1.4.3 $NDVI_{705}$

The Red Edge Normalised Difference Vegetation Index ($NDVI_{705}$) is a slight alteration to the traditional NDVI and is adopted for use with high spectral resolution reflectance data such as data from Sentinel-2 (Potter et al., 2012). Unlike standard NDVI, $NDVI_{705}$ takes into account a narrower waveband at the edge of the chlorophyll absorption feature (e.g. 705 nm) rather than at the middle (Gamon and Surfus, 1999; Moroni et al., 2013; Sims and Gamon, 2002). $NDVI_{705}$ is more affected by chlorophyll content when compared to the NDVI and common applications include precision agriculture, forest monitoring, forest fires and vegetation stress detection (Cundill et al., 2015). This ultimately leads to more reliable VI mapping, especially in dryer areas such as Cyprus, where due to climatic reasons water content is a more sensitive factor in revegetation dynamics (Moreira et al., 2012; Fyllas et al., 2017). Table 1 presents the Sentinel-2 bands' properties.

Table 1: The spectral and spatial resolution of Sentinel-2's bands. Noticeably bands 5 and 6 are the ones that concern chlorophyll change, as chlorophyll is more sensitive around that region of the electromagnetic spectrum. Data acquired from Huang et al., 2016.

Sentinel-2 bands	*Spatial resolution*	*Central Wavelength*	*Band width*
Band 1: Coastal Aerosol	60	443	20
Band 2: Blue	10	490	65
Band 3: Green	10	560	35
Band 4: Red	10	665	30
Band 5: Vegetation Red	20	705	15
Band 6: Vegetation Red	20	740	15
Band 7: NIR	20	783	20
Band 8: NIR	10	842	115
Band 8A: NIR	20	865	20
Band 9: Water vapour	60	945	20
Band 10: SWIR Cirrus	60	1375	30
Band 11: SWIR	20	1610	90
Band 12: SWIR	20	2190	180

2. Materials and methods

2.1 DEM

The main purpose for the processing of a DEM was understanding the topographical parameters that may have been associated with the post-fire revegetation dynamics (aspect and slope). The aspect map was created by separating the slopes into two groups - based on the direction they face (ie. North and South) and by identifying which ones have greater regeneration rates (according to Mouillot et al. (2005) and Petropoulos et al. (2014). The slope steepness map was created by utilising the elevation (altitude of each pixel) attribute. The DEM was created using data from JAXA's (Japanese Aerospace Exploration Agency) data from the Advanced Land Observing Satellite "DAICHI" (ALOS as it offered the most precise elevation data freely available for the study area. Resolution of the dataset is of 30 m, and tiles N035E032 and N034E032 were used, as the area affected by the fire straddles between both (figure 3 aids this statement by presenting the tiles adopted for the DEM). The elevation data adopted were used to generate two derived datasets, an aspect map and a slope map, in order to account for the influence factors such as insolation (aspect) or water retention (slope steepness map) may have on revegetation processes (Nobajas et al, 2017). For the aspect map, north was defined as all pixels with an orientation between NW (315°) and NE (45°) while all pixels with an orientation between SE (135°) and SW (225°) were classified as south-facing slopes and all remaining pixels were not considered as either (Fox et al., 2008; Ireland and Petropoulos, 2015; Wittenberg et al., 2007). The slopes (in degrees) were classified in five categories ranging from 0° (flat surface) and 45°.

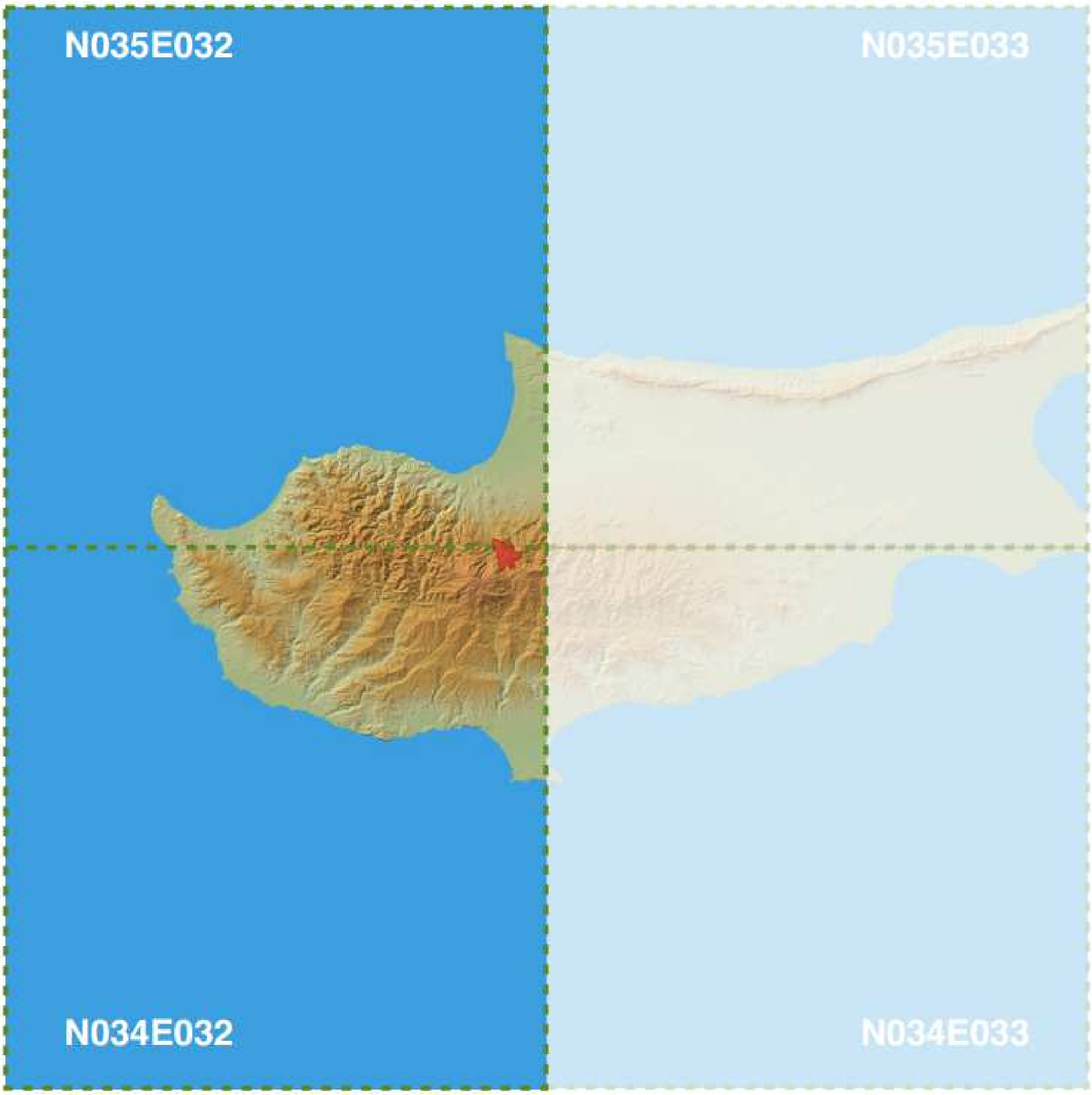

Figure 3. The tiles from JAXA used for the topographical analysis. As can be noticed the study area is split between the N035E032 and N034E032 tiles, hence the adoption of these two tiles.

2.2 Adopting $NDVI_{705}$ in this study

$NDVI_{705}$ using Sentinel-2 imagery can be calculated by using bands 5 (705 nm) and 6 (750 nm) and it ranges between -1 to +1, where $NDVI_{705}$ decreases when the vegetation is subject to a state of stress (Piro et al., 2017). $NDVI_{705}$ is calculated from the following formula: $NDVI_{705} = (B_6 - B_5) / (B_6 + B_5)$. Although the study period ranges from May 2016 - before the fire occurred - to July 2017 and a monthly interval is used, it was not possible to obtain data for all months as even with Sentinel-2's 10-day revisit time (European Space Agency, 2018) the amount of cloud cover impeded obtaining adequate data for December 2016 and January and June 2017. In order to create the vegetation index, a supervised image classification method was used with the image from June 2016 when the fire had just been extinguished as the benchmark. For comparison between the different months of the study period three classes were generated depending on the $NDVI_{705}$ where Severely Burnt refers to the mostly burnt patches within the region, Less Burnt to the less affected and Healthy Forest to the unchanged pixels based on $NDVI_{705}$ - the latter was not included in the analysis and was just used to delineate the study area's limits. Severely and Less burnt regions should not be misinterpreted to be based on the Normalised Burnt Ratio (NBR) which focuses on fire intensity (where a low value indicates bare ground & recently burnt areas and non-burnt areas have a value of zero; Sunderman and Weisberg, 2011).

2.3 Temperature and rainfall data of the affected area

Historical climate data were obtained from the Department of Meteorology of Cyprus (2018). The data obtained included the average rainfall (mm) and the average temperature derived from the average maximum and average minimum temperatures of each studied month. The downloaded data (rainfall and temperature) are considered to be very significant factors on chlorophyll content, hence affecting the $NDVI_{705}$. These were measured from the nearest weather stations - specifically, the rainfall data from Platania (4 km south of the burnt region) and temperature data from Prodromos (10 km southwest of the burnt region). The particular choice of attributes has been chosen in accordance with other short-term post-fire assessments, as higher rainfall can lead to higher $NDVI_{705}$ values, hence a faster vegetation recovery (Meng et al., 2015).

3. Results

3.1 Vegetation regeneration area dynamics

As the results presented in figure 4 show, there is an inconsistent change in the $NDVI_{705}$ values throughout the fourteen months studied - not signifying an overall increase or decrease. This is evident in the first 6 post-fire months where the severely burnt region increases (from 11.28 km^2 to 13.65 km^2), followed by a decrease in the months of spring (from 13.86 km^2 in February to 12.68 km^2 in April) and, lastly, by an increase in the last studied month (15.39 km^2). Therefore, the trend seen in figure 5 is the improvement of $NDVI_{705}$ in the months of spring, as in all the remaining months the severely burnt region increases in area, with greater improvements on the western part of the burnt scar. It is important to stress the fact that the change in severely-burnt region area does not indicate the degree of vegetation health improvement - this is due to the classification of severity (severely burnt and less burnt) against the VI (which can have any value between -1 and +1).

3.2 DEM, Aspect and Slope Steepness

According to the aims set in this study a DEM was constructed in order to further analyse the reasoning behind the revegetation observed in the months of spring - March and April 2017. Therefore, figure 5 was plotted where the spring months' burnt scars (5b and 5c) were superimposed on the DEM - the first post-fire months (June 2016) and the last post-fire month (July 2017) are also presented for comparison purposes in the same figure (5).

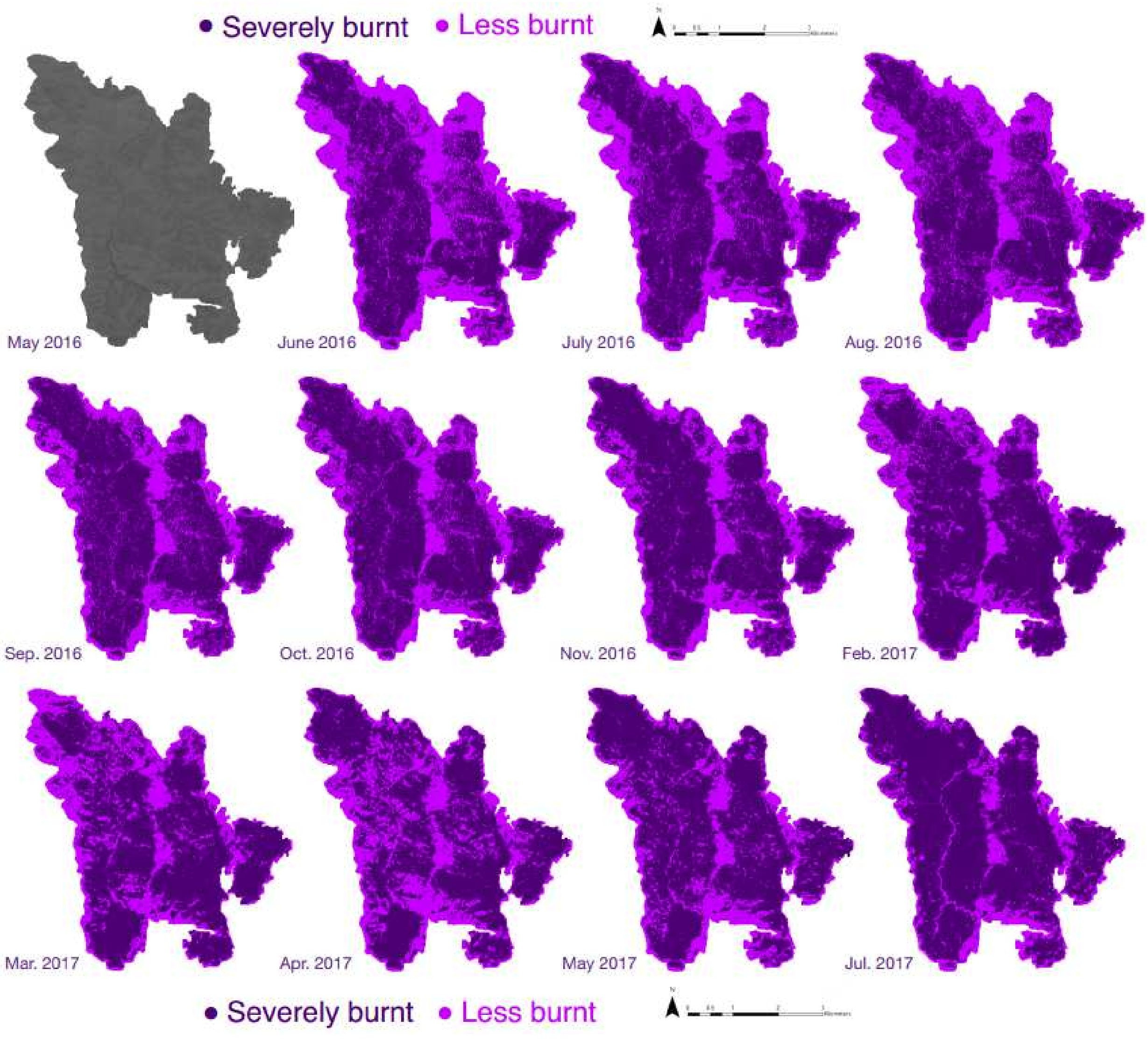

Figure 4. A multi-temporal visual representation for the studied months, indicating the two types of burnt regions based on the pixel ($NDVI_{705}$) classification of June 2016 - the first post-fire month.

The second part of the topographical analysis involved the creation of the aspect and slope steepness maps. The aspect map was classified according to many similar examples in literature (ie. Fox et al., 2008; Ireland and Petropoulos, 2015; Wittenberg et al., 2007) and can be seen along with the slope steepness map (based on elevation data of adjacent pixels) in figure 6.

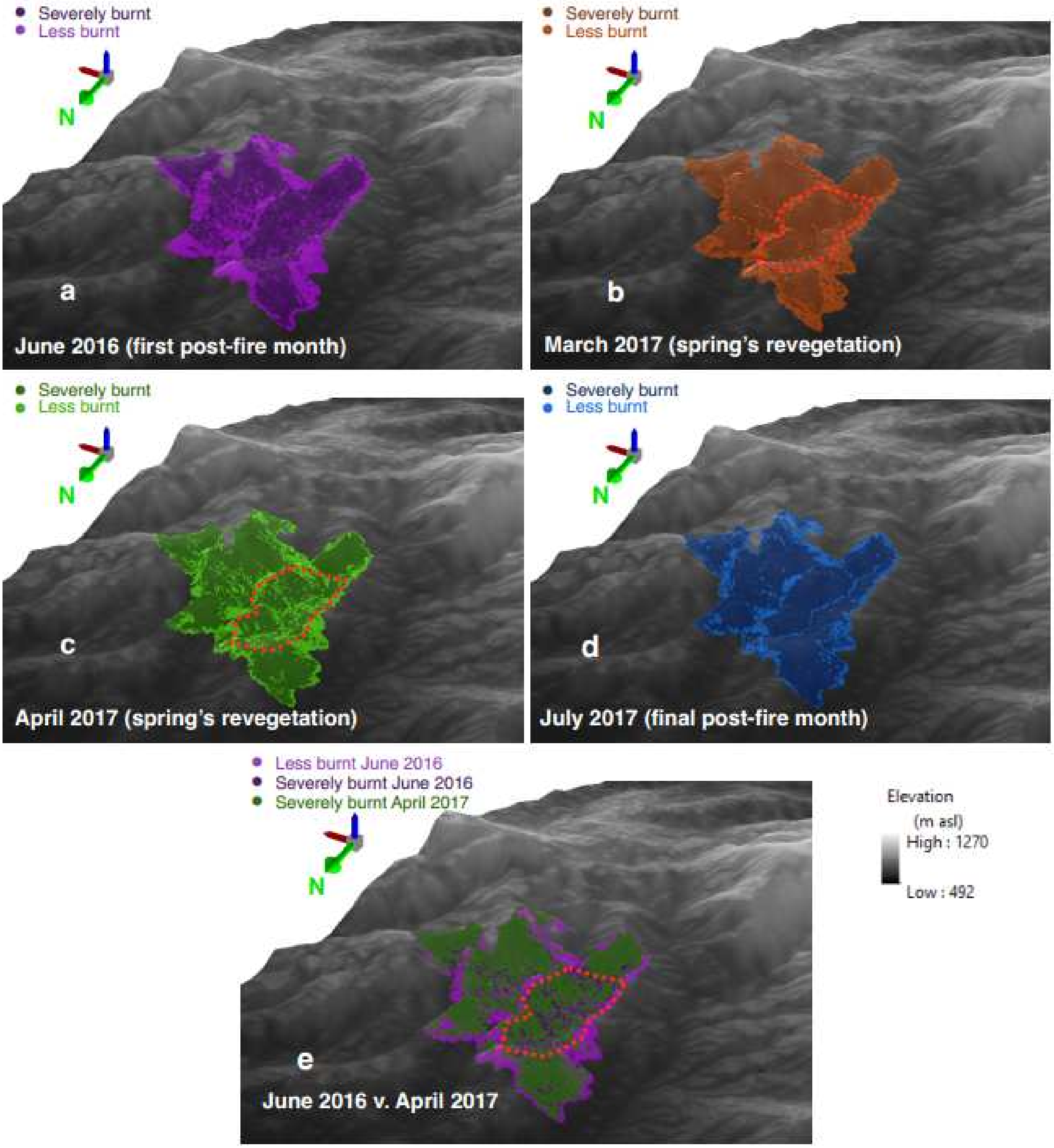

Figure 5. The four $NDVI_{705}$ maps superimposed on the constructed DEM are depicted in **a**, **b**, **c** and **d** (**a**=first post-fire month, **b** and **c**=two months in spring and **d**=last post-fire month), whereas the comparison of the first post-fire map and April 2017 is shown **e**. The difference in the darker pixels for the spring months of the $NDVI_{705}$ maps is evident in the months of spring but also in the comparison with the first post-fire map in **e**. To aid this statement the areas in dotted red show the higher revegetation in spring - this is clearer when spring is compared to the first post-fire month - seen by the absence of dark green pixels in **e**.

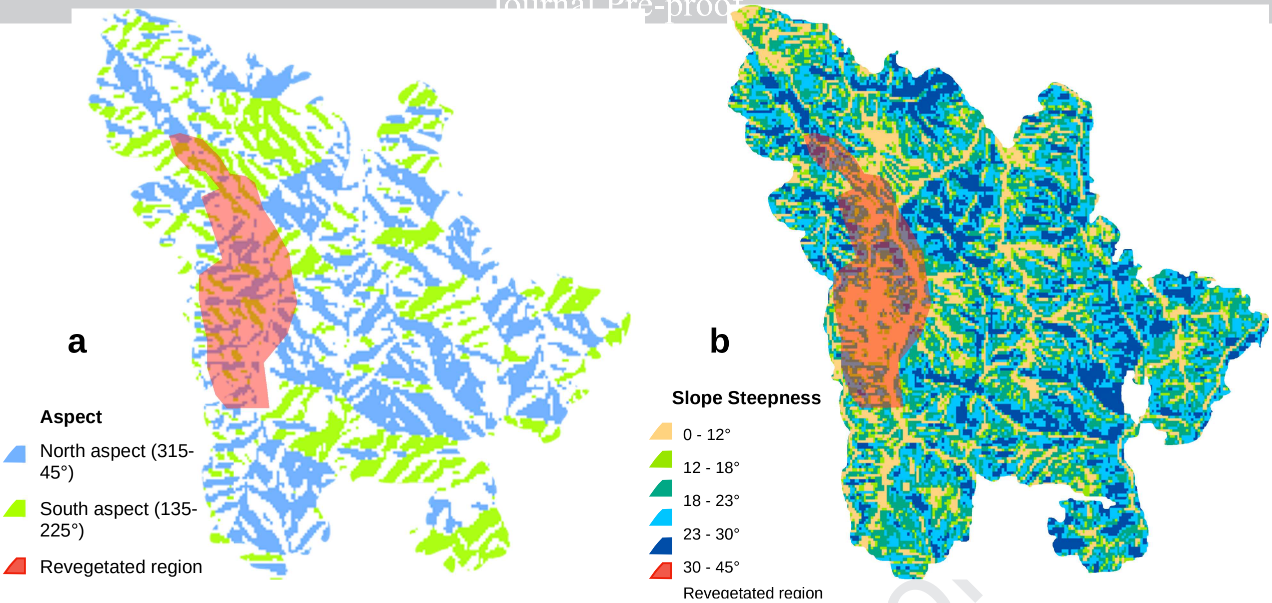

Figure 6. The Northern and Southern aspects covering the burnt scar are shown in **a**. The region of vegetation recovery (same as dotted red in figure 5) is shown in transparent red. **b** presents the more detailed slope map of the burnt region. The slope has been calculated in degrees (°) and is divided into 5 classes. From these derived maps it can be noticed that revegetation took place on north-facing slopes (from **a**) and on slopes which are almost flat (from **b**).

The results of the aspect map indicate that the western region where vegetation seemed to have recovered the most, has a north-facing slope. Furthermore, the slope map shows the same region of revegetation to have slopes with low steepness (the larger area of the region has slopes between 0 and 18°).

3.3 Climate Data

Meteorological data of the area helps in providing important information when assessing the dynamics of the burnt region, as it has an impact on the rate of recovery - due to temperature and rainfall variability which affect water content (as chlorophyll) in the revegetated region. The study area presented two very distinct thermal seasons, with winter months being the coldest, and with overall temperatures being colder than other areas at similar latitudes due to its elevation (figure 7). Additionally, most of the precipitation has taken place between November and March, including an unusually wet month in December 2016 with 145% of the normal rainfall for that month from that specific weather station and a dryer than a usual month of February (Department of Meteorology of Cyprus, 2018).

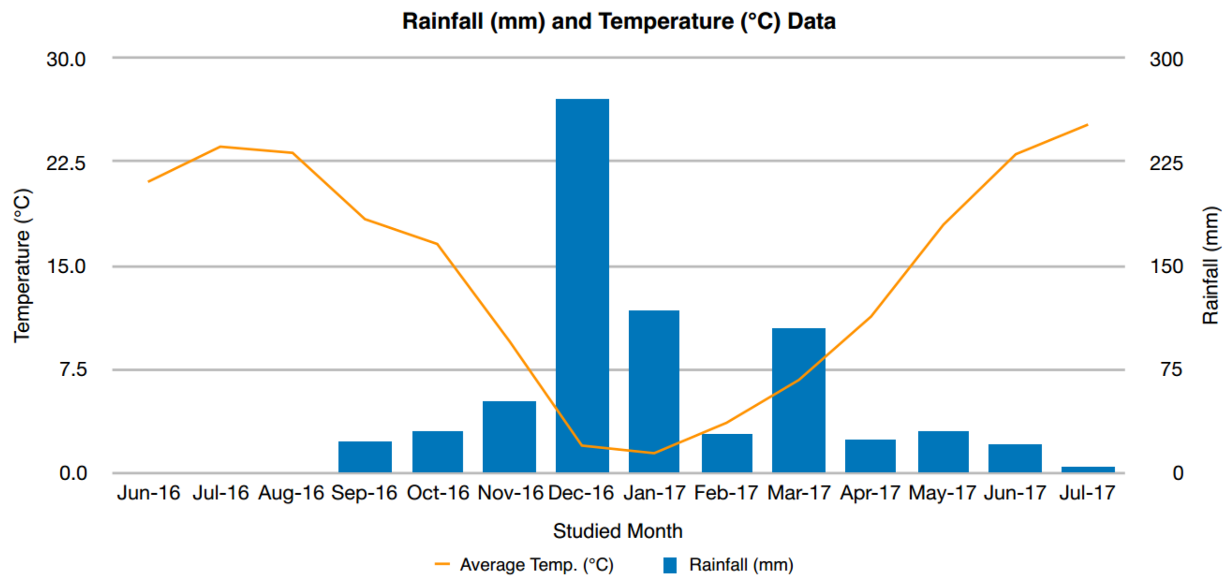

Figure 7. Rainfall (mm) and average temperature (°C) data for the period of study.

4. Discussion

The importance of fire in many terrestrial ecosystems and its role in global climatic cycles via emissions of gases into the atmosphere are well documented (Andreae and Crutzen, 1997; Bowman et al., 2009; Flannigan et al., 2000), and this is even more relevant to Mediterranean climate environments, where low precipitation, high temperatures and pyrophyte plant species have led to fires becoming one of the most important factors in shaping the landscape (Mayor et al., 2007). Various climate models have reiterated the aforementioned and projected an increase in ecosystem susceptibility as a result of increased fire occurrences (Ireland and Petropoulos, 2015). As Mouillot et al. (2005) claimed, Mediterranean regions are responsible for approximately 90% of fires in the European Union leading to increased number of studies in the Mediterranean - especially in Spain (Cerda et al., 1995; del Pino and Ruiz-Gallardo, 2015) and in Greece (Arianoutsou et al., 2010; Diakakis et al., 2017; Kalivas et al., 2013). However, the island of Cyprus is usually neglected from such studies despite the frequent fire events, but thanks to the accessibility to remotely sensed data and to the use of $NDVI_{705}$ it is now possible to study fire events in almost any region at an unprecedented level of detail while keeping costs down. Although this multi-temporal study spans through a relatively short period of time (Marozas et al., 2007; Mouillot et al. 2005) due to how recently the fire occurred, it offers an insight to how forested areas behave right after catastrophic fires.

4.1 Burn severity and $NDVI_{705}$

The combination of remotely sensed data, GIS methods and multi-temporal analysis has enabled to identify important insights. Results show that the two different levels of severity generated by using $NDVI_{705}$ - severely burnt and less burnt - show an inconsistent trend throughout the studied period, which is contrary to what one would expect, as it means vegetation regrowth is nonlinear. It can be noticed, however, that the severely burnt region decreases in area for the first two months of spring. The reason for this may arise due to seasonality. Cyprus, as mentioned before, is associated with high temperatures during summer and cold and rainy winters. The first 6 months of the study showed an increasing trend in the severely burnt region whereas the first two months of spring indicated a decreasing trend for the same region. This is a characteristic to post-fire dynamics in Mediterranean ecosystems as rainfall during winter and the time until spring (where the ideal moisture conditions take place) are responsible for the resprouting of vegetation (Mayor et al., 2007). This affects the $NDVI_{705}$ values, which are based on water content hence affect chlorophyll. Therefore, the combination of the absence of hot temperatures and increased rainfall provided the ideal conditions for revegetation during spring months. This identified trend can be seen more clearly in figure 8, as peak rainfall (Dec-16) and average $NDVI_{705}$ per month (Apr-17) take place 3-4 months apart since it takes some time for vegetation to grow after the rain. Similarly, areas classified as severely burnt seem to increase during summer months even if no new fires occurred. This is due to higher evapotranspiration rates as high temperatures and low rainfall cause vegetation to wither and therefore their signature is similar to that one of severely burnt areas (Fox et al. 2008).

4.2 Topography

Soil availability is a key element in order to regenerate vegetation after a catastrophic fire event, so its preservation is a key element in order to guarantee a full and quick recovery. Together with precipitation, two topographic variables have a key influence in soil retention, slope steepness and slope aspect, as they are predictors to model soil erosion risk in Mediterranean areas (del Pino & Ruiz-Gallard, 2015).

Aspect refers to the cardinal direction slopes face, and the results of this study show that the burnt region is almost equally split between north-facing and south-facing slopes. However, the revegetation recovery is greater in north-facing slopes (see the green region in figure 6a). These results support the findings of del Pino & Ruiz-Gallard (2015) in a Mediterranean basin, as they indicated that north-facing slopes usually have higher moisture contents, hence increasing plant cover, soil organic matter contents, soil structural stability, and therefore resistance against water erosion (Cerdà, 1998). This is because south-facing slopes have greater insolation and evapotranspiration rates, so vegetation tends to grow back more quickly on north-facing slopes with better moisture conditions (Fox et al., 2008). Supporting del Pino & Ruiz-Gallard's (2015) findings, Cerdà et al. (1995) claimed that soil erosion rates over north-facing slopes are expected to be lower due to evolution and maintenance of soil aggregate stability that is better than sunny slopes, which coincides with the results in this case, where plant recovery was greater and soil erosion rates lower for north-facing slopes. Such differences have repercussions regarding post-fire erosion as vegetation recovery is the major factor influencing future post-fire erosion rates.

The second topographic variable, slope, helps to better explain soil degradability, as steeper slopes are associated with holding fewer soil horizons, hence vegetation is more difficult to regrow (Diakakis et al., 2017). The steepness assessment complemented the aspect findings by providing more insights into the recovered region located at the western sub-region and in the two months of spring. Steeper slopes are associated with holding less water and more likelihood of erosion due to gravity and therefore the recovery rates are expected to be lower in these slopes (Diakakis et al., 2017). Unsurprisingly, the results from this study support this statement, as the red region from figure 6b indicated that most of the recovered region lies on less steep slopes. Therefore, both the steepness and the aspect assessments support the literature findings as north-facing slopes and less steep slopes recovered during spring when the ideal conditions for vegetation regrowth in a Mediterranean environment take place.

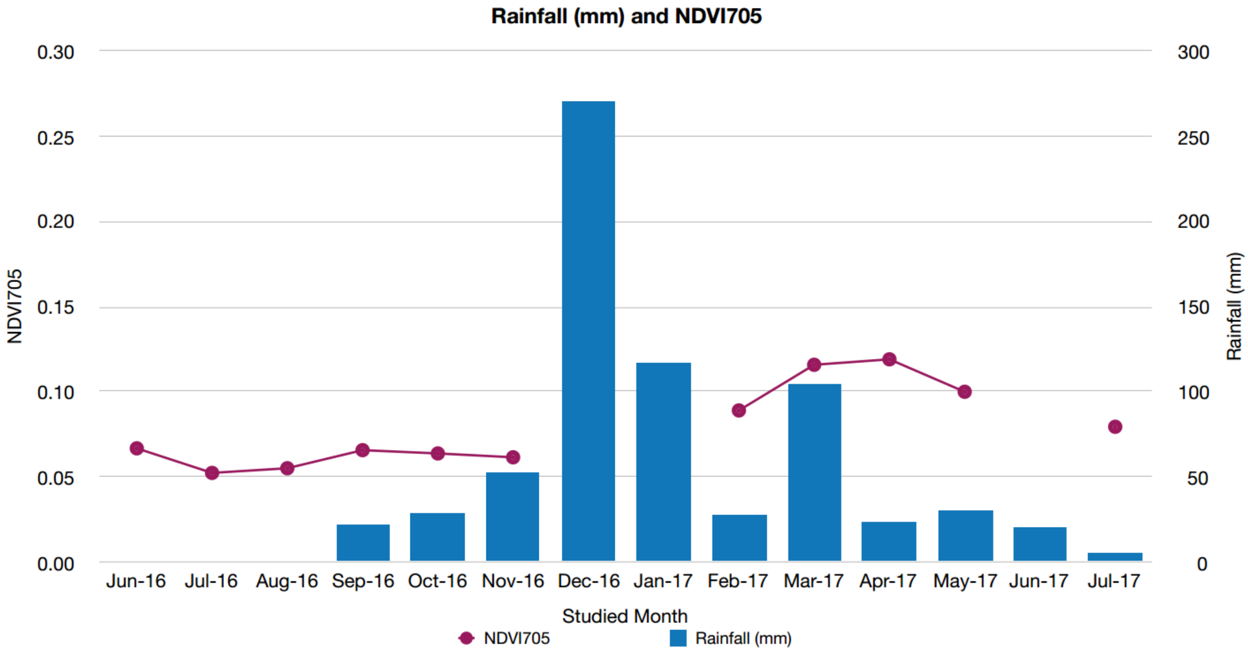

Figure 8. The results of the rainfall (mm) data and the mean NDVI705 values of each month

5. <u>Conclusions</u>

The extraction of $NDVI_{705}$ from Sentinel-2 provides a fast and cost-efficient way of monitoring post-fire regeneration; while combining these data with digital elevation models allows gaining a deeper understanding of how such regeneration is influenced by topography. Despite the fact that this study focused on a short time period of 14 months, it was able to reveal important insights for the revegetation dynamics of the burnt area. More importantly, the methodological approach enables the establishment of a study protocol for similar studies in the future which concern rapid post-fire regeneration assessments (Miller et al., 2016; Robichaud et al., 2009).

The protocol followed can be easily be applied in other regions, as the used datasets are almost global in their coverage and freely available, making their use an option to take into account by any studies interested in studying and managing post-fire events.

In the case of the studied Cypriot fire, it was found that when comparing burnt severity maps, the severely burnt region does not decrease in area during the studied period due to the higher temperatures Mediterranean regions tend to have, which have an impact in the chlorophyll content of plants, the element measured by $NDVI_{705}$. The results indicated, however, that there was a vegetation recovery in the spring, which coincides with similar studies in the Mediterranean basin (Pizarro-Tobías et al., 2015), although it would be interesting to continue monitoring the affected area for several years to observe how the recovery evolves year-on-year.

When the results of the vegetation index are combined with the DEM for the study area, it is clear that the most exuberant recovery takes place in the north-facing slopes and where the slopes are less steep, as south-facing slopes receive more insolation leading to higher evapotranspiration rates and that steeper slopes have less-deep soils and higher rates of water runoff. Although not the main focus of this study, the inclusion of a local DEM also provided insights as to why certain areas were so severely burnt. Those areas were almost inaccessible to ground fire-fighting forces such as fire-trucks due to the steep slopes, so local authorities should consider building new ways to access the area, as they will also have the potential to act as firebreaks too.

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Highlights

- A modified Normalised Difference Vegetation Index for revegetation from Sentinel-2 data was adopted.
- One of the biggest fire events in Cyprus occurred in June 2016 is used as a case study.
- Results indicate higher revegetation rates during months of spring and they show higher revegetation on north-facing and low-steepness slopes.
- Demonstrates the ability to use free-to-access data in aiding with decision making.
- Method is a cost-effective way of assessing post-fire regeneration.

The authors declare that all ethical practices have been followed in relation to the development, writing, and publication of the article.

The authors declare that they are submitting the manuscript to the journal without any known conflicts of interest.