

Evaluating the Potential of Vegetation Indices in Detecting Drought Impact Using Remote Sensing Data in a Mediterranean Pinewood

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Abstract. The Mediterranean ecosystem represents an important natural resource, being able to produce ecosystem services, has both economic and social repercussions, especially if located in urban and peri-urban areas.

In the last decades, increased forest vulnerability is being reflected in a larger number of severe decline episodes associated mainly with drought conditions. In this context, the Mediterranean area shows high forest vulnerability and a subsequent decline in its natural renewal rate.

In this context, the objective of this research is to evaluate the different vegetation indices to monitor the effect of drought on the health of the Castelporziano pine wood. For this purpose, we used the NDVI, NDII and NMDI, provided by ESA Sentinel-2 images and field observations, to monitor the health status of a historic pinewood that has recently been affected by a rapid spread of parasites (*Tomicus destruens Woll.*).

The application of these indices, on the scale of the entire pinewood, showed that the NDVI and NDII indices differentiate better the changes in vegetative health status for the observed period than the NMDI.

Moreover, NDVI and NDII were applied, based on the classifications made, to volume and age classes. Ultimately, these preliminary results require further studies to better understand the potential and limiting factors of the indices used in monitoring pinewoods under stress due to aridity.

Keywords: Vegetation index · Remote sensing · Sentinel-2 · Mediterranean forest · Castelporziano nature state reserve

1 Introduction

The Mediterranean region is rich in species and the bio geographical origin is the result of a combination of climate, soil and anthropic use of the landscape through the centuries, moreover it represents an attraction for tourism [1].

It is characterized by landscape fragmentation that causes an increase in environmental vulnerability, due to large increases in population, rising living standards, the development of irrigated agriculture and new activities (particularly tourism related)

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O. Gervasi et al. (Eds.): ICCSA 2020, LNCS 12253, pp. 50–62, 2020.
https://doi.org/10.1007/978-3-030-58814-4_4

which have led to an improve of anthropogenic pressure on the Mediterranean environment [2, 3]. Moreover, the Mediterranean basin is considered to be one of the most endangered environments due to climate change, which has exacerbated these pressures in a negative way, as the current rate of climate change is much faster than in the past and involves a higher risk of extreme weather events, such as prolonged periods of drought, frequent and severe storms and rising temperatures [4, 5]. The combination of the effects of climate change, anthropogenic pressures (such as overexploitation of forest resources, human-induced fire and deforestation) and other aspects, such as land use and pollution, will have an effect on Mediterrean Forest vegetation, and the impacts are expected to affect the structure and operation of forest ecosystem, as well as ecosystems services (ES) they currently provide [6, 7].

The serious negative consequences of prolonged heat waves and dry spell include forest dieback, which can be caused by starvation of carbohydrate reserves or hydraulic failure as well as result in an increased risk of pest/pathogen attacks, which might contribute to reduced productivity and increased forest mortality [8].

Drought is a complex phenomenon that cannot be traced back to a single definition, in fact there are several according to the discipline that studies it. From the literature it is possible to deduce that there are 3 main physical ways to define drought: (i) meteorological, (ii) agricultural, and (iii) hydrological [10–13]. In general, these different definitions of droughts are linked in this way: low rainfall and the consequent increase in temperature (meteorological drought), which results in a deficit of water content in the soil and stream flow, (hydrological drought) and finally affects the water content of plants, (agricultural drought), [14, 15].

In this context it is widely acknowledged that the pinewood-decline is a phenomenon that is taking place in the Mediterranean basin [8, 9]. Indeed, the increased vulnerability of forests to high temperatures combined with drought condition is a phenomenon that is well studied and coincides with the mortality of species, and this phenomenon also contributes to the expansion of other adverse phenomena, such as pathogen pest, and other disturbing events [11].

At this regard, the arrangement of replicable methodologies for the monitoring of the health conditions of forest ecosystems, especially in the Mediterranean area, is increasingly becoming an effective tool to support management decisions.

Among the different methods of monitoring forest ecosystems, remote sensing is certainly the most widely used thanks to the ability of providing synoptic information for very large areas and with frequent acquisition [9–16].

Remote sensing is a non-invasive and non-destructive tool that allows repeated survey sessions without any damage to the objects studied. It is also used in forestry for the mapping of forest areas subject to deterioration, or for the evaluation of damage caused by pathogens. Traditionally, for the study of the physiological conditions of vegetation, spectral indices from remote-sensing data are widely used to evaluate the structure and functioning of terrestrial ecosystems [17].

In the field of remote sensing applications, scientists have developed vegetation indices for qualitatively and quantitatively evaluating vegetative covers using multispectral measurements. The multispectral response of vegetated areas presents a complex

moisture of vegetation, soil brightness, environmental effects, shadow, soil color and moisture [18–20].

Several Vegetation Indices have been developed during recent decades, [18] and the most widely used in monitoring general health conditions of forestry surface is the normalized difference vegetation index (NDVI). In practice, NDVI is indicative of plant photosynthetic activity and has been found to be highly related to green leaf area index (LAI), thanks those properties NDVI can be used as an indicator of possible vegetation stress, due to water storage, indeed water availability is the main limiting factor for vegetation processes and therefore controls leaf pigment content and integrity [9].

Some specific indices have been used to detect the effects of drought, such, for instance, NDII [21] and NMDI [22].

The aim of this research is to evaluate the effectiveness of the main vegetation indices proposed in the literature, in order to monitor the effects of drought in a Mediterranean pinewood located in a peri-urban protected area in the Metropolitan area of Rome, the Nature State Reserve of Castelporziano.

2 Material and Method

2.1 Study Area

The study area is represented by the pinewood of Castelporziano (41°42'50"N - 12°24'03"E), a State Nature Reserve located in a peri-urban area of the municipality of Rome, (Fig. 1). Castelporziano presents a total surface area of 6.000 ha and its land use is characterized mainly by forest and to a lesser extent by agricultural activities.

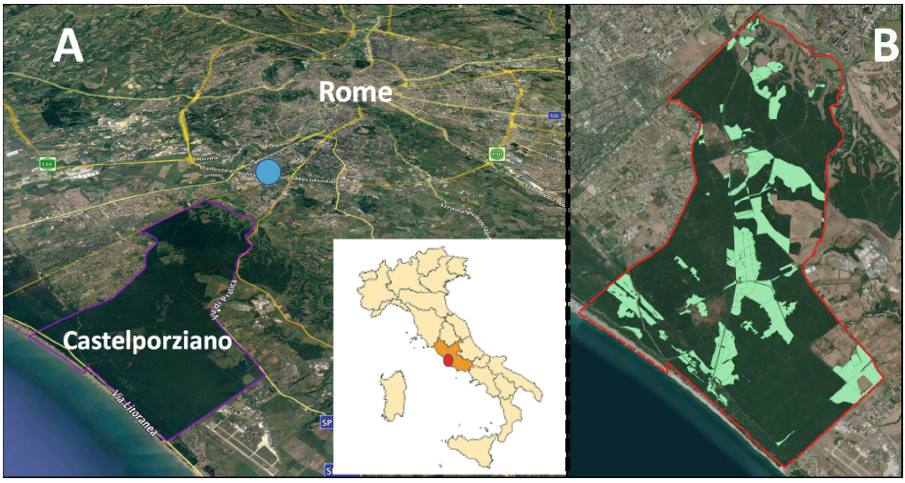


Fig. 1. Study area. [A]: The Nature State Reserve of Castelporziano and the metropolitan area of Roma. [B]: Pinewood (green) of Castelporziano. The blue dot indicate the rain gauge of EUR meteorological station. (Color figure online)

This territory is the last remnant of the ancient Mediterranean coastal forest, in which the predominant species are broadleaf oaks (4.000 ha) and Pinewood (900 ha) mainly characterized by *Pinus pinea* L. In particular, the pinewood of Castelporziano, with numerous trees aged over one hundred years or more, is the last remaining example today of mature pinewood along the Tyrrhenian coast [2, 3]. Furthermore, it is listed in the Habitat Directive with two Sites of Community Importance (SCI) and the whole territory is classified as a Special Protection Area (SPA). In October 2016, the ongoing environmental monitoring program in the Castelporziano Pinewood, carried out by remote sensing of multispectral Sentinel-2 images, allowed the detection of a diffuse dieback in several areas. This phenomenon, very probably, was caused by arid conditions that favored a sudden infestation of *Tomicus destruens* Woll, resulting, in several areas, in a severe and rapid decline of the forest.

2.2 Meteorological Data

Meteorological data were acquired from a meteorological station of the Italian National Hydrological Service located in Rome, exactly in the EUR district, 6 km far from the Estate of Castelporziano. The meteorological data set consisted of series of daily temperatures, (maximum and minimum), and precipitation from 1980 to 2018.

The Bagnouls Gaussen's diagram, (Fig. 2) shows the monthly average of temperatures and precipitation and the area between the two curves indicates the length and drought period. As can be seen from the graph, this period falls in the summer months, which makes the climate typically Mediterranean [23].

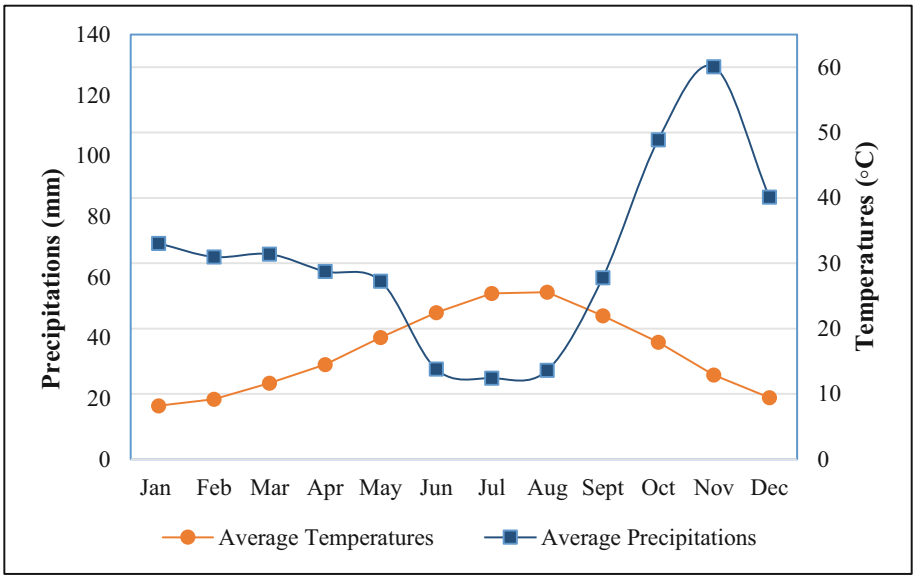


Fig. 2. Bagnouls Gaussen diagram for the years 1980–2019.

2.3 Data Set Used

We used a set of Level 1C Sentinel-2 satellite images, with top of atmosphere reflectance, (band 4, band 8, band 8a, band 11 and band 12) referring to the period: 30 August 2015, 24 August 2016, 24 August 2017, 19 August 2018 and 19 August 2019. These images are provided by Copernicus open access Hub of the European Space Agency (ESA). The Sentinel-2 images spatial resolution is 10, 20 or 60 m depending on the bands.

The acquired images were processed to level 2A Bottom of Atmosphere (BOA) using ESA Snap Sentinel-2 Toolbox with additional Sen2Cor, plug-in for atmospheric and topographic correction. Geometric distortion of the analyzed images was corrected with the rectified 10 m Digital Model Terrain (DTM) provided by the Italian Ministry of Environment.

The data concerning the forest inventory were acquired by the Observatory Laboratory of the Mediterranean ecosystem of Castelporziano [24]. It contains data related to the dendrometric characteristics of the pinewood, such as volume, age, etc.…

For this analysis, the health conditions of the pinewood were considered good in 2015 so this will be used as a reference scenario. In addition, areas inside the Pinewood were eliminated from the analysis as they were affected by silvicultural cuts (Fig. 3) carried out in 2017.



Fig. 3. Data set used. [A]: the areas affected by silvicultural cuts (in red), the border of forest units (in black) [B]: Pinewood of Castelporziano. (Color figure online)

To better understand the potential of the indices used in monitoring pinewood health conditions, we reclassified the surface according to their volume and age [24]. At this aim, the pinewood was classified according to dendrometric criteria, into 3 volume classes and 3 age classes (Fig. 4) at Forest Unit Parcel (FUP) scale.

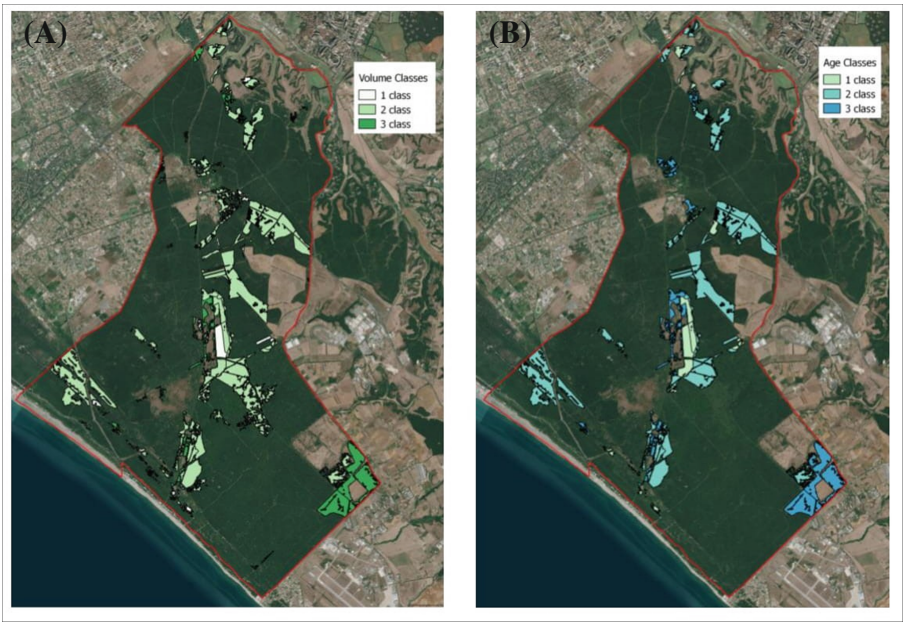


Fig. 4. Classification of Pinewood, [A]: Volume classes; [B]: Age classes

This classification is shown in Table 1.

Table 1. Classification of the pine forest according to its volume and age.

	Volume	Age
1 class	0–200 m^3 ha^{-1}	0–40 years
2 class	201–400 m^3 ha^{-1}	41–80 years
3 class	400–625 m^3 ha^{-1}	>80 years

2.4 Index Used

To assess the potential of mapping drought using Sentinel-2 data, three spectral indices were chosen to calculate: NDVI, (Normalized Difference Vegetation Index), NDII (Normalized Difference Infrared Index) and NMDI (Normalized Multi-band Drought Index).

NDVI is a remote sensing-based index that measure vegetation conditions [25] and its widely used to monitoring health vegetation condition [26]. The formula of NDVI is given in (Eq. 1):

$$NDVI = \rho B8 - \rho B4 / \rho B8 + \rho B4 \tag{1}$$

We used Sentinel 2 data, so the NIR band is ρ B8, (842 nm), and RED band is ρ B4, (665 nm).

Under healthy conditions, the light is absorbed by chlorophyll so the reflectance in the Red band decreases, increasing the value of the ratio. On the contrary, in case of low photosynthetic activity, the absorbance value in the red is higher and therefore the ratio decreases [17].

NDII, Normalized Difference Infrared Index [21], it's highly correlated with canopy and leaf water content [15]. In the case of Sentinel-2 data, the NIR band and SWIR band have different spatial resolutions, as 10 m and 20 m, so the SWIR bands were resampled to 10 m, before carrying out the calculation. NDII is defined as Eq. 2, using NIR and SWIR reflectance as 850 nm and 1610 nm [27]:

$$NDII = \rho B8a - \rho B11 / \rho B8a + \rho B11 \tag{2}$$

Finally, in this research, we used the Normalized Multi-band Drought Index, NMDI. This index was proposed for monitoring soil and vegetation moisture from space [22].

NMDI uses 860 nm channel as the reference, and to detect the absorbance of water it uses the difference between two SWIR channel, centered at 1640 nm and 2130 nm. NMDI formula is given (Eq. 3):

$$NMDI = \rho B8 - (\rho B11 - \rho B12) / \rho B8 + (\rho B11 - \rho B12) \tag{3}$$

3 Results

In the observed period, 2015–2019, the vegetation indices NDVI, NDII and NMDI were applied to the entire pinewood area and their temporal trend is shown in the following figures (Figs. 5, 6, and 7). To emphasize better the results, 2015 was taken as a reference of the health status of the pinewood as it did not show episodes of deterioration, and subsequent observations were stretched and compared to 2015.

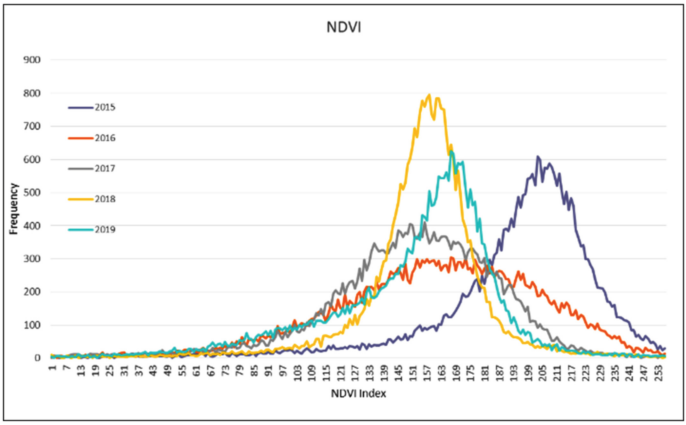


Fig. 5. NDVI index detected by Sentinel-2 satellite images (Years: 2015, 2016, 2017, 2018 and 2019).

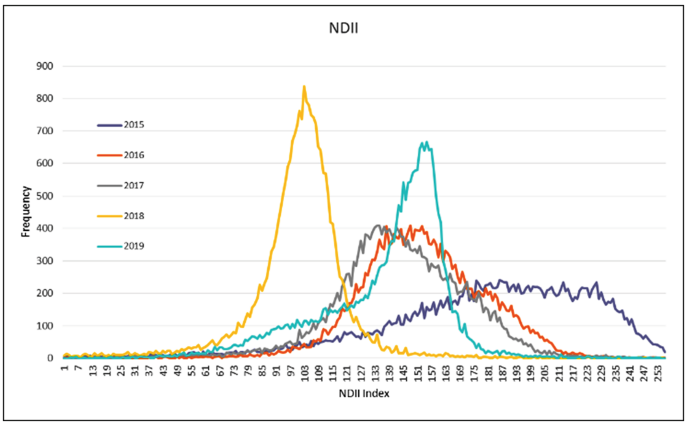


Fig. 6. NDII index detected by Sentinel-2 satellite images (Years: 2015, 2016, 2017, 2018 and 2019)

Observing preliminary results, the indices that showed the best effectiveness in terms of detecting the diachronic health conditions are the NDVI and the NDII indices. Considering that, these two indices were subsequently applied according to the classification made previously referred to volume and age classes of the pinewood, this to better investigate their capability in detecting health conditions in several forest structures phases. In Fig. 8 the results obtained are shown according to the volume classes and in Fig. 9 according to the age classes.

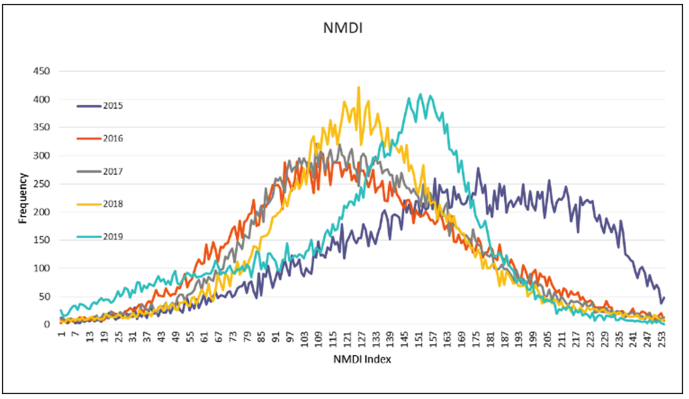


Fig. 7. NMDI index detected by Sentinel-2 satellite images (Years: 2015, 2016, 2017, 2018 and 2019)

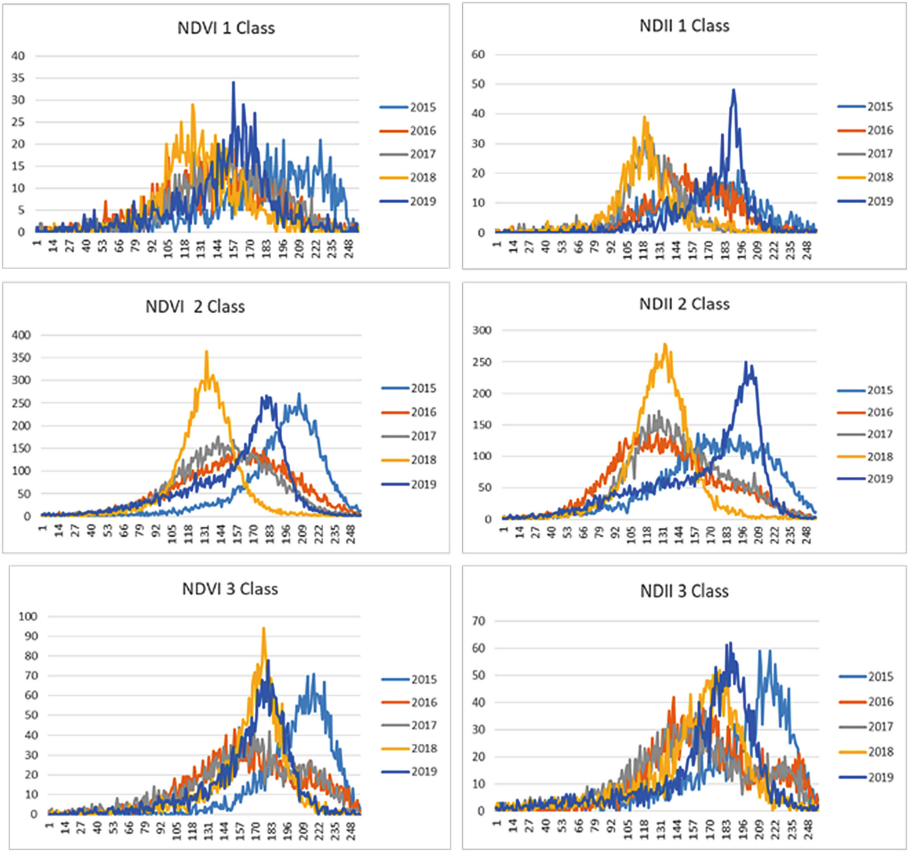


Fig. 8. Comparison of NDVI and NDII vegetation indices by volume classes.

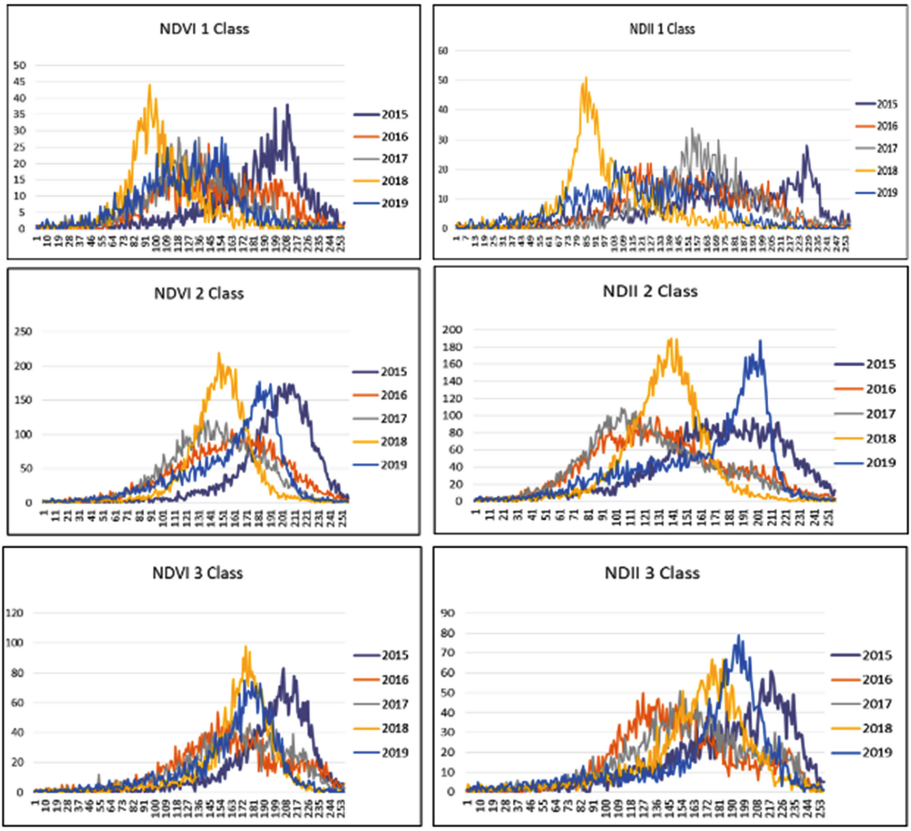


Fig. 9. Comparison of NDVI and NDII vegetation indices by age classes.

4 Discussion and Conclusion

The preliminary results obtained in this research show how the three applied vegetation indices present a different efficiency in detecting the health conditions of the studied pinewood in climatic drought conditions. At the scale of the whole pinewood it is evident that the NDVI and NDII index better differentiate the changes in vegetative health status for the observed period, this aspect emerges from the analysis of the modal values referred to the distribution of the cells frequencies based on their values. At this regard, the NDVI and NDII index, except for the years 2016 and 2017, significantly differentiate the variation in overall vegetative conditions. On the contrary, the NMDI index shows a lower variability of the data for all the years observed. This aspect clearly emerges from the over-lapping of the frequency curves in which, especially for the years: 2016, 2017, 2018 and 2019, the area of the curves presents a high overlap.

Instead, as regards the results obtained by the NDVI and NDII index applied to the different volume and age classes, it was found that: in the case of the volume classes, a better differentiation of the data is obtained for the intermediate volume class, i.e. the one included between 200 and 400 m^3 ha^{-1}. This mainly depends on two factors: (i) in

young pinewoods that present a low volume (0–200 m^3 ha^{-1}) the plants have a slightly expanded crown and, because of this, the resolution of the cell is not able to discriminate efficiently the foliage of plants from the soil surface. (ii) For pinewoods that instead have a volume greater than 400 m^3 ha^{-1}, the limiting factor is represented by a homogeneous coverage of the foliage and by an interpenetration between them, also in this case due to the resolution of the cell, that does not allow to distinguish the healthy individuals from those who have suffered a decline. Moreover, with regard to the third volume class, it was noted that the NDVI index is slightly more efficient than the NDII index since its ability to separate the values for the observed years appears more evident for the years: 2015, 2018 and 2019 while the NDII index is significant only for the years: 2018 and 2019.

Similar results have been obtained for age groups. Also for this parameter, in fact, the best results were obtained for the intermediate class, between 40 and 80 years of age, in which the foliage of the plants have a more suitable size to be analyzed with a cell of 100 m^2. The same limiting factor, found for the volume classes, is found for the first and third age classes in which the structure of the forest does not allow the two indices to be efficiently applied in diachronic way and to be able to correlate the results with each other.

In the final analysis, these preliminary results need further study and field surveys to better understand what the potentials and limiting factors of the indices used in monitoring pinewoods under stress due to aridity are.

Acknowledgments. The authors thank the General Secretariat of the Presidency of the Republic, the management of the Estate of Castelporziano, the Scientific-Technical Commission of Castelporziano that enabled these studies and the publication of the data.

Funding. This research was funded by the National Academy of Sciences (Rome), within the monitoring program of the presidential Estate of Castelporziano.

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

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