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Oak decline in the Mediterranean basin: a study case from the southern Apennines (Italy)

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Abstract
It is known that the decline of oaks forest can be triggered by an increase of climatic anomalies such as heat waves, droughts, and extreme cold. The present study aims to deepen the relationships between climate anomalies and oak decline basing on in-field observations made in the Lucanian Apennine (southern Italy) during summer 2017. Remote sensing was used to identify those areas affected by vegetation decline. A comparison of the climatic conditions recorded in 2015 and 2017 was carried out, these years being the hottest and the driest, respectively, since 1800. Satellite images and remote sensing data [Normalized Difference Water Index (NDWI), Temperature Condition Index (TCI)], and ground-based collected data [(Decline Severity (DES), Deficit/Surplus (D/S), Rainfall Anomaly Index (RAI), Standardized Precipitation Index (SPI)] were processed using GIS techniques to evaluate spatial distribution and time-scale evolution of the damage by oak decline. The results show that despite the heat peaks reached in 2015, it was not possible to highlight any clear sign of oak decline based on satellite images for that year. On the contrary, these signs were found to be evident by observing the satellite images of 2017 and confirmed by the Decline Severity assessment made in the field and further supported by NDWI and DNDWI indexes. Regarding possible factors that may have triggered the 2017' oak decline in the study area, it is not possible to provide a definite answer, at present. In this work it was hypothesized that an important role could have been played by the drastic reduction of rainfalls during the first semester of the year.

Key words: DES, Italy, Lucanian Apennine, NDWI, oak decline, Sentinel 2 (ESA).

Introduction

During the last forty years, the oak-decline phenomenon has affected the forests of the northern hemisphere, causing the death of hundreds of hectares of oak forest (Gottschalk & Wargo, 1997; Gentilesca *et al*., 2017). Although this has often been considered the result of local or regional episodic events, the interest in the oak decline has grown exponentially over time and, today, it is one of the most studied issues in the field of forest conservation (González-Alonso, 2008; Bussotti & Pollastrini, 2017; Hierro *et al*., 2017).

Oak decline is generally defined as a syndrome affecting individuals and populations of species belonging to *Quercus* genus, which manifests itself with clear signs of plant suffering, such as leaf yellowing, summer defoliation, death of the terminal axis of the branches (died-back), secretion of dark exudates from the trunk, thinning of the crown, and the production of epicormic branches along the trunk (Ciesla & Donaubauer, 1994; Ragazzi *et al*., 2000). Studies carried out on this topic over the past two decades have shown that the oak decline is to be related to the single or combined effects of many factors, such as climatic anomalies, hydraulic failures, carbon deficiency, and attack from defoliant insects and other pests (Manion, 1991; Ragazzi *et al*., 2000; Thomas *et al*., 2002; Choat *et al*., 2012; Keča *et al*., 2016; Colangelo *et al*., 2017). However, in recent years, much of the attention has focused on the climate and on rapid changes in temperature and rainfalls trends. Since 1950, many extreme climatic events have been recorded (IPCC, 2014) in various parts of the world, and, according to some worrying scenarios hypothesised for the near future (2020-2049), heat waves and periods of drought will happen with greater frequency and through progressively higher heat peaks (Allen *et al*., 2010; Mariotti *et al*., 2015; Lhotka *et al*., 2018).

In Europe, an increasing risk of drought moving along a W-E gradient is expected (Lindner *et al*., 2010). In the Mediterranean region, a decline in forest productivity is expected within a relatively short period of time due to a sharp increase in the length and intensity of drought periods and fire episodes (Lindner *et al*., 2010). In fact, a climatic deterioration has already

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occurred since the end of the last century, in which the climate of the Mediterranean basin has shown a general tendency to become warmer and drier (Mariotti *et al*., 2015; Polade *et al*., 2017). Alongside, the beginning of the new millennium has been identified as a general period of Mediterranean forest decline related to drought (Di Filippo *et al*., 2010; Gentilesca *et al*., 2015).

Regarding the Italian Peninsula, climatic anomalies have occurred several times in the last twenty years with rainfalls far below the national average. Very low rainfalls, if compared to the rainfalls recorded during the period 1961-1990, were recorded in 2001, 2006, 2011, and, especially, in 2017 (Brunetti, 2017; Desiato *et al*., 2018; CNR-ISAC, 2019). On the other hand, very high temperatures have been recorded since 2000, with the high peaks in 2015 (Desiato *et al*., 2016-2018; CNR-ISAC 2019).

During the summer of 2017, large areas of the Lucanian Apennine (southern Italy) characterized by mixed oak woods exhibited an anomalous 'morphological status' with a yellow-brown colouring of the foliage and evident defoliation of the crown (Online Appendix I). All these symptoms are pertinent with the oak decline, which, among other things, had already been reported for several other areas of the Lucanian Apennines since the 1980s (Sicoli *et al*., 1992; Ragazzi *et al*., 2000; Gentilesca *et al*., 2015). Already then, it was assumed that anomalous climatic phenomena were responsible, although the relationships among the climatic and biotic factors involved in the decline phenomenon were not examined in depth.

It is certain, however, that the cases of oak decline have gone up during the past thirty years (González-Alonso, 2008; Gentilesca *et al*., 2015; Michel *et al*., 2018). Thus, it would be of primary importance to establish a shared methodological protocol of field and laboratory investigations for monitoring the spatial distribution and time-scale evolutions of the oak decline. This would certainly help to promote a global strategy of actions and policies to carry out effective management plans to preserve the functionality of forest ecosystems.

The aim of this study is to investigate the relationships between the climate anomalies that occurred in the last years in southern Italy and the oak decline phenomena observed in the Lucanian Apennine during summer 2017. The study was carried out combining detailed climatic data, remote sensing, and field surveys.

Materials and methods

Study area

The study area is located in the Lucanian Apennine, Potenza administrative province (~660,000 ha), western Basilicata; 15° 40' E, 40° 00' N (vertex SW), 16° 30' E, 41° 00' N (vertex NE). The Lucanian Apennine is part of Southern Apennine, which extends for about 120 km along an NW-SE direction in southern Italy. The lithological backbone is formed by calcareous rocks which are bordered, in the east side, by silicoclastic sediments and flyschoid deposits whereas the hilly areas at lower altitudes are characterised by conglomerates, and Plio-Pleistocene deposits (Patacca & Scandone, 2007). In this area, the oak forests mainly occur in the submontane and lower montane belts and are dominated by *Quercus cerris* L., *Q. pubescens* Willd. and *Q. frainetto* Ten. in the form of the following potential vegetation types: *Lathyro digitati-Quercetum cerridis*, *Lathyro jordani-Quercetum cerridis*, *Echinopo siculi-Quercetum frainetto*, *Centaureo centaurii-Quercetum pubescentis* (Di Pietro *et al*., 2010).

Satellite image interpretation (visible image) and GIS analysis

Satellite images in the visible band (spatial resolution: 10 × 10 m) for the periods March-October 2015 and March-October 2017 were examined (QGIS Development Team, 2018). These images were provided by the Sentinel 2 satellite, belonging to the European Space Agency's Copernicus monitoring system (ECMWF, 2018). The satellite data were available through the Climate Engine portal (Climate Engine, 2019; Huntington *et al*., 2017). The list of the parameters used in our analyses was reported in Table 1. The interpretation of satellite images allowed us to observe the spatial-temporal distribution of oak decline and select field survey areas (forest stands). To improve our dataset and avoid possible errors in the interpretation of the visible image (e.g. to consider the effects of recent fires or human activities on the vegetation cover as signs of oak decline episodes), we also analyzed the available satellite images from a longer period (2000-2017) taken from the Landsat 4/5/7/8 (NASA) satellites and RSDI Basilicata portal (Climate Engine, 2019; RSDI, 2019).

For the monitoring of the vegetation response to climate stresses the Normalized Difference Water Index (NDWI) was used. NDWI (Gao, 1996) is a satellite-derived index from Near-Infrared (NIR) and Short Wave Infrared (SWIR). This index allows removing variations induced by leaf internal structure and leaf dry matter content, improving the accuracy in retrieving vegetation water content (Ceccato *et al*., 2001; Wang *et al*., 2007). The NDWI values range between -0.4 and 0.4, where negative values represent oaks dying back due to the loss in leaf moisture content and positive values are considered a recovery of the leaves that grow back (see Wang *et al*., 2007). NDWI data were obtained for the period 2000-2017 by Landsat system and for the period 2015-2017 by Sentinel 2 system (Climate Engine, 2019) and they have been used to arrange a rectangular surface raster file including the whole study area. This file was converted to

Tab. 1 - List of data set used (Dat). Time series data available (Ts). Timescale resolution (Tr). Spatial scale resolution (Sr). Data supply (Das).

Parameter	Dat	Ts	Tr	Sr	Das
Rainfall	ALSIA Basilicata	> 2000	Monthly	Punctual	ALSIA Basilicata
Rainfall	CFD Basilicata	> 2001	Daily - Monthly	Punctual	Centro Funzionale Decentrato Basilicata
Temperature and Rainfall	Climatic Research Unit (CRU)	1901 - 2017	Monthly	0.5° x 0.5° or finer grid	Climatic Research Unit. University of East Anglia (www.cru.uea.ac.uk)
Visible Images	True colours. based on Red/Green/Blue bands	> 2015 Sentinel2 > 2000 Landsat	Daily	10 m 30 m	Sentinel 2 (ESA) and Landsat 4/5/7/8. Climate Hazard Group (https://clim-engine-development.appspot.com/fewsNet)
NDWI	NIR. SWIR	> 2015 Sentinel2 > 2000 Landsat	Daily	10 m 30 m	Sentinel 2 (ESA) and Landsat 4/5/7/8. Climate Hazard Group (https://clim-engine-development.appspot.com/fewsNet)
LST	MODIS	> 2000	8 days	1000 m	MODIS Terra 8-day. Climate Hazard Group (https://clim-engine-development.appspot.com/fewsNet)

a point-vector file using the GIS program ESRI ArcMap 10.1. Subsequently, the polygon-vector file of the borders of the forest stands was used to clip the NDWI's point-vector file. Finally, NDWI was used for mapping the died-back degree which followed the oak decline episodes in order to distinguish the areas where trees effectively died from those in which an active trend of tree canopy recovery was occurring. The differential NDWI (DNDWI) was calculated as $NDWI_{2015}–NDWI_{2017}$ (using Qgis Raster Calculator tool). Furthermore, we extracted all the NDWI point-vectors included in each stands area and on these, we performed statistics (mean, median, standard deviation, normal distribution).

The Temperature Condition Index (TCI) allowed the assessment of temperature stress conditions for vegetation (Kogan, 1995). TCI was calculated on the basis of the surface temperature (LST) datasets (Sun & Kafatos, 2007) from MODIS satellite (AVHRR thermal bands MODIS Terra 8 day, NASA) using the following formula: $TCI = [(LST_{max} - LST_{i}) / (LST_{max} - LST_{min})] \times 100$, where LST_i is the last LST image available belonging to the period 24-31 August 2015 and 2017. While LST_{min} is the last LST image available of the absolute minimum, LST_{max} the last LST image available of the absolute maximum values. LST images were obtained from the Climate Engine Portal (Huntington *et al*., 2017; Magno *et al*., 2018).

Field survey

Field surveys were carried out at the end of summer 2017 only. The health status of oak's forest communities was defined using the Decline Severity scale (DES) modified from Mannerucci and Sicoli (2006), and Cullotta *et al*. (2016) (Tab. 2). We also assessed the defoliation of the crown by the oak decline's damage pattern: 'tree-to-tree' dieback (each adjacent individual is affected) or 'salt and pepper' dieback (several sick trees found in a healthy tree matrix) according to Ciesla and Donaubauer (1994). In addition, the phytosociological method (Braun-Blanquet, 1964) was used to identify the plant community type in issue.

Tab. 2 - Decline Severity damage observed scale (DES) used during summer 2017 field analyses. Dieback*: the condition of a tree that begins to die from the apex of its leaves towards the base of the branch due to an illness.

DES	Description of the symptoms observed
0	Healthy plants
1	Trees with crown damaged by dieback* for more than 20%
2	Trees with crown damaged by the dieback from 21 to 50%
3	Trees with crown damaged by dieback from 51 to 99%
4	Trees with 100% dieback with presence of epicormic shoots
5	Trees with crown and dead apical branches, secondary branches still alive with or without buds
6	Completely dead plant

Pluviometric data (D/S, RAI, and SPI)

Pluviometric data from 17 climatic stations were provided by the Decentralised Functional Centre of Basilicata (CFD Basilicata) and Lucanian Agency for Development and Innovation in Agriculture (ALSIA) (Online Appendix II). Pluviometric maps (isolines for general data and pluviometric indexes; D/S, RAI, and SPI, see below) were generated from a rainfall database (CSV file) interpolated with the ESRI ArcMap 10.1, using the Inverse Distance Weighted (IDW) method and fitting on the borders of the Potenza's province using the contour tool. Owing to oak species having a growth response proportional to the amount of spring rainfall (Tessier *et al*., 1994; Corcuera *et al*., 2006; Di Filippo *et al*., 2010), we have used the first semester of each year as the pluviometric period of reference. Accordingly, we have arranged a further rainfalls dataset (using CRUTS 3.21; Online Appendix III) in which the monthly values and those summing the rainfalls of both the 1st and the 2nd semester of the year were shown (Harris *et al*., 2014 updated).

The Deficit/Surplus (D/S) is a measure of the difference between the rainfall value recorded during a given period (cumulative values) and the rainfall value recorded during a reference period (see e.g., Berterame *et al*., 2017). The D/S formula, which was calculated for each pluviometric station (ALSIA-CFD data set), is $D/S = P_{ij} - P_{ik}$, where P_{ij} is the cumulated rainfall of the *i*-semester of *j*-year and P_{ik} is the average of the average cumulative rainfall in the *i*-semester for the *k*-period.

The Rainfall Anomaly Index (RAI), proposed by Van Rooy (1965), is one of the most effective indexes to identify climatic anomalies (Keyantash & Dracup, 2002). The RAI values were obtained by comparing the first semesters of 2015 and 2017 (ALSIA-CFD data set) with an average of the 2001-2017 first semesters' series. The RAI was calculated using the equation $RAI = (R - \mu) / \sigma$, where R is the rainfall refers to the first semester of 2015 and 2017, μ is the long-term average rainfall (first semester of 2001 and 2017), and σ is the standard deviation. Low rainfalls values correspond to negative RAI values (Dutta *et al*., 2015).

The Standardised Precipitation Index (SPI) was used to identify and characterize drought periods (Mckee *et al*., 1993; Edwards, 1997) at different time scales (usually 1, 3, 6, 12, 24, and 48 months). In the present paper, SPI was computed on a time scale of 6 months, using the database of ALSIA and CFD Basilicata from 2001 to 2017. SPI values ranging from -1.0 to 1.0 reflect normal rainfalls. A dry regime (rainfall deficit) is indicated by SPI values lower than -1.0, whereas a wet regime (excess rainfall) by SPI values higher than 1.0.

Results

Satellite image interpretation (visible image) and GIS analysis

The satellite images interpretation made on an extended period (2000-2017) highlighted the occurrence of a severe episode of the oak decline for summer 2017. For this year (2017), satellite images allowed to identify 24 areas of the Lucanian Apennines in which the oak decline manifested itself clearly. Accordingly five forest stands (ST) which exhibited a situation of homogeneus oak decline were selected in order to analyze the monthly time evolution of this phenomenon (Fig. 1; Online Appendix IV). The results showed that the oak decline started during the first week of July in stands ST1, ST4, and ST5 and at the end of August in stands ST2 and ST3. The highest degree of damage for all the analysed stands was observed in the middle of September.

Normalised Difference Water Index (NDWI)

The NDWI analysis for the period 2000-2017 (Landsat dataset) showed that years 2000, 2001, 2008 and 2017 exhibited low NDWI values. However, the Sentinel 2 data, which were available for the period 2015-2017 only, showed that 2017 registered the lowest NDWI values (Tab. 3). In fact, during summer 2017 a widespread oak decline was found to be occurring in the whole study area with more than 500 hectares of

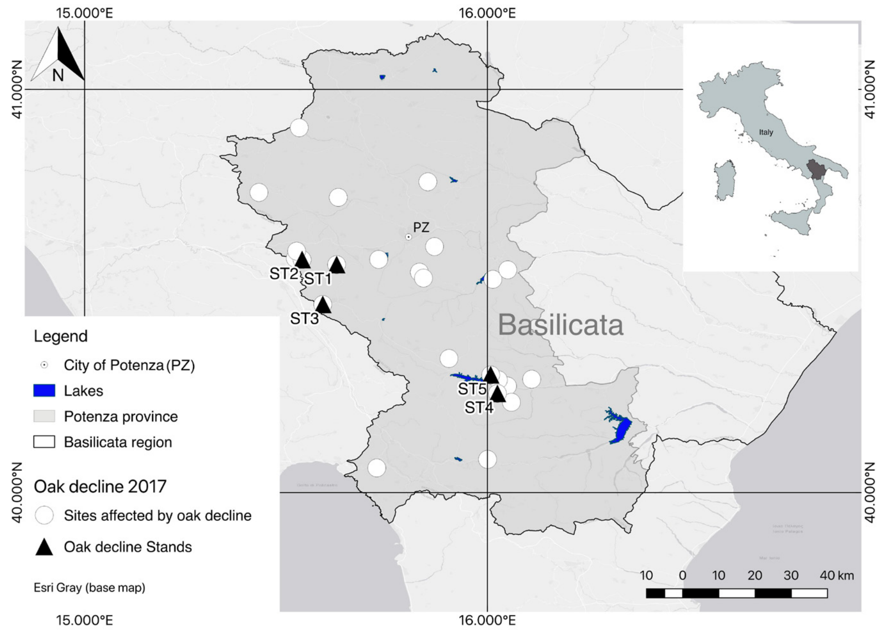

Fig. 1 - Map of the oak decline stands (ST1-5) subjected to the 2017 field investigations (see Online Appendix IV).

woods involved. The NDWI average values extracted from Sentinel 2 for the forest stands in issue (period 2015-2017) showed the following mean trend: 0.29 ±0.03 (2015), 0.30 ± 0.04 (2016), 0.21 ± 0.07 (2017).

The DNDWI ($NDWI_{2015}$–$NDWI_{2017}$) showed that although patches of various size of vegetation recovery were found over the Region, the large majority of the study area was characterized by extensive died-back patches (Fig. 2; Tab. 3).

Temperature Condition Index (TCI)

The TCI values recorded for 2015 and 2017 were found to be averagely similar, showing that the thermic stress suffered by the forest vegetation was severe on both dates. However, a different spatial distribution of TCI emerged comparing 2015 and 2017. In 2015 the TCI was uniformly widespread in the northern part of the study area, whereas, in 2017, a discountinous distribution was observed (Fig. 3). For this reason, in 2015, the stands ST1 and ST2 exhibited higher thermic stress (dark-red colour) than in 2017, with stress values ranging from 7.51% to 10.49% (vs. 14.59% ST1 to 15.02% ST2 in 2017). On the other hand, stations ST3, ST4, and ST5 exhibited similar TCI stress values (or slightly lower) in 2015 and 2017 (Tab. 4).

Vegetation response

The DES highlighted that the degree of crown's damage was classified as “4” in three stands (ST1, ST4, ST5), while in the remaining two stands (ST2, ST3), it was classified as “3” (according to the scale reported in Tab. 2). The ‘salt and pepper’ dieback pattern was detected in three out of the five stands (ST1, ST2, ST4) and the ‘tree-to-tree’ dieback in stands ST3 and ST5 (Tab. 5). The phytosociological sampling showed that ST1 and ST5 were dominated by *Q. pubescens* and that in ST3 *Q. pubescens* was co-dominant with *Q. cerris*. Differently in ST2 and ST4 the dominant oak species were found to be *Q. cerris* and *Q. frainetto* respectively (Tab. 5). During the field sampling, we observed that the forest decline appeared more marked at the woody edge of the forest stands. These edges were mainly composed of shrubby species (e.g. *Spartium junceum* L., *Cornus sanguinea* L., *Rosa canina* L. s.l., *Crataegus monogyna* Jacq., *Prunus spinosa* L., *Rubus* L. spp.) or medium-sized trees (*Acer mospessulanum* L., *A. campestre* L., *Pyrus pyraster* Burgsd., *Fraxinus ornus* L., and *Carpinus orientalis* Mill.).

Pluviometric data, D/S, RAI, and SPI

The rainfall data for the whole study area (Online Appendix III) showed that 2017 was the second driest year considering the period 2000-2017 and that, together with 2012, it was the only year showing rainfalls lower than 500 mm. If only the first semester was considered, then 2017 was found to be the driest year with only 213.75 mm of total rainfalls. A comparison with 2015 (the hottest year ever) showed that 2015 had yearly rainfalls about 46% higher than 2017. However, when the two semesters of the year were analyzed singularly, the total rainfalls of the first semester for 2015 (69.02 ± 46.15 mm) were found

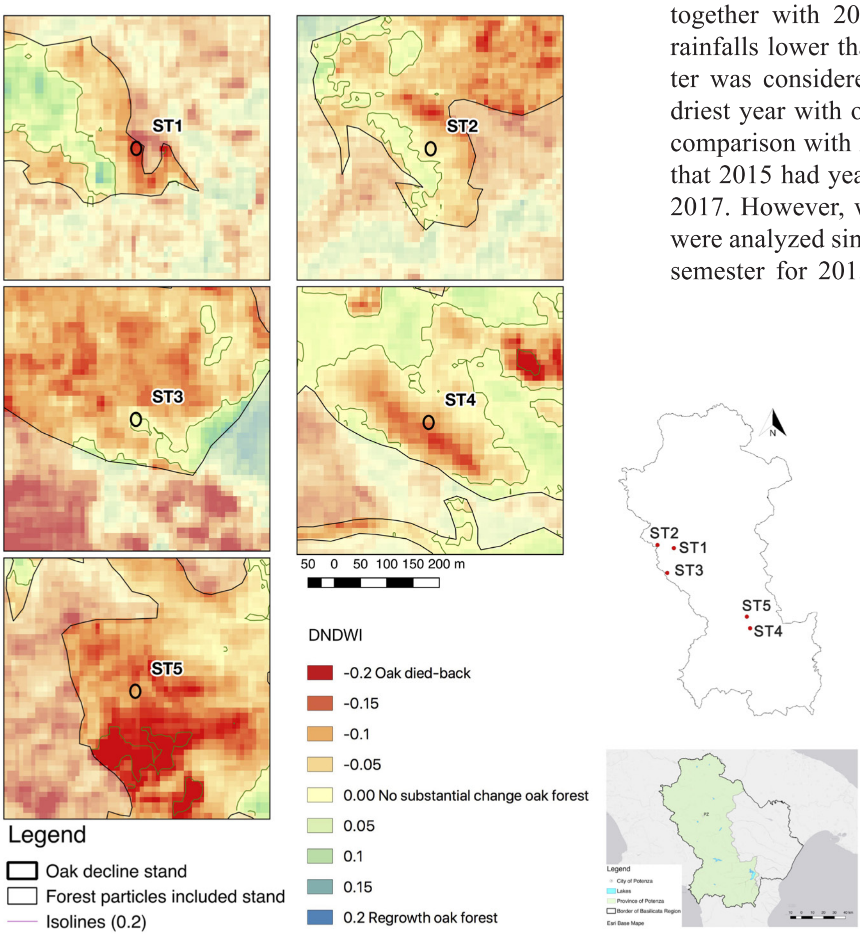

Fig. 2 - Details map of the stands affected by the oak decline (based on the Normalised Difference Water Index (DNDWI 2015-2017) = differential NDWI; $NDWI_{2015}$ $-NDWI_{2017}$ using Raster Calculator tool of Qgis). The decline areas are evidenced by the values under -0.05. For each stand reported in the small map in the lower right side of the figure (see Online Appendix IV) it is shown an enlargement of the wooded stands to highlight the degree of decline.

Tab. 3 - NDWI values for each stand based on the Landsat data set (time series 2000-2017) and Sentinel 2 (time series 2015-2017). SD = standard deviation. Data source Climate Engine. 2019. Desert Research Institute and University of Idaho. Accessed on (September 2019) http://climateengine.org

	Time scale 15 August to 17 September											
	LANDSAT 4/5/7/8											
Year	**ST1**	**SD**	**ST2**	**SD**	**ST3**	**SD**	**ST4**	**SD**	**ST5**	**SD**	**Annual Mean**	**SD**
Mean 2000	0.16	± 0.10	0.29	± 0.07	0.23	± 0.07	0.12	± 0.11	-0.04	± 0.01	0.15	± 0.12
Mean 2001	0.22	± 0.01	-0.03	± 0.03	-0.03	± 0.03	0.29	± 0.11	0.15	± 0.17	0.12	± 0.14
Mean 2008	0.23	± 0.20	0.27	± 0.23	0.22	± 0.18	0.21	± 0.10	0.15	± 0.15	0.22	± 0.04
Mean 2015	0.33	± 0.04	0.31	± 0.03	0.32	± 0.06	0.34	± 0.03	0.32	± 0.03	0.32	± 0.01
Mean 2016	0.29	± 0.01	0.36	± 0.03	0.37	± 0.02	0.30	± 0.00	0.29	± 0.01	0.32	± 0.04
Mean 2017	0.18	± 0.02	0.33	± 0.02	0.27	± 0.01	0.23	± 0.10	0.15	± 0.12	0.23	± 0.07
	SENTINEL 2											
Mean 2015	0.30	± 0.05	0.26	± 0.03	0.31	± 0.06	0.25	± 0.05	0.32	± 0.04	0.29	± 0.03
Mean 2016	0.30	± 0.04	0.30	± 0.04	0.37	± 0.06	0.28	± 0.08	0.26	± 0.06	0.30	± 0.04
Mean 2017	0.27	± 0.02	0.25	± 0.02	0.24	± 0.03	0.11	± 0.04	0.17	± 0.06	0.21	± 0.07

to be about twice those of 2017 (35.62 ± 30.55 mm), whereas the second semester displayed about similar rainfalls values for the two years.

The rainfall average of the ground-based collected data of first-semester (ALSIA-CFD data set) for the period 2001–2017 was 68.89 mm (± 16.40), and ranging from 34.55 mm (Genzano di Lucania locality, NE-Basilicata) to 132.78 mm (Nemoli locality, SW-Basilicata).

The lowest and the highest first-semester rainfall values during the 2001-2017 period occurred in 2008 (49.44 mm on average, ± 21.66) and 2009 (100.16 mm on average ± 45.50), respectively. In 2015, there was a surplus of rainfall of 28.03% compared to the average of the first semester of the 2001-2017 period (88.20 vs. 68.89 mm), whereas, in 2017, this rainfall average was 25.79% lower (51.12 vs. 68.89 mm).

Regarding the D/S index, a rainfall deficit occurred across in most of the Potenza administrative area during the first semester of 2017 (almost all values of D/S < 0, average to 17.77 mm ± 22.83), whereas no deficit occurred in 2015 (almost all D/S values were found to be > 0, average 19.31 mm ± 17.75). On the basis of the pluviometric maps generated (Fig. 4), the five stands were found to be characterized by positive values of D/S in 2015 and, therefore, by a surplus of precipitations, D/S values ranging from 24.43% for ST1

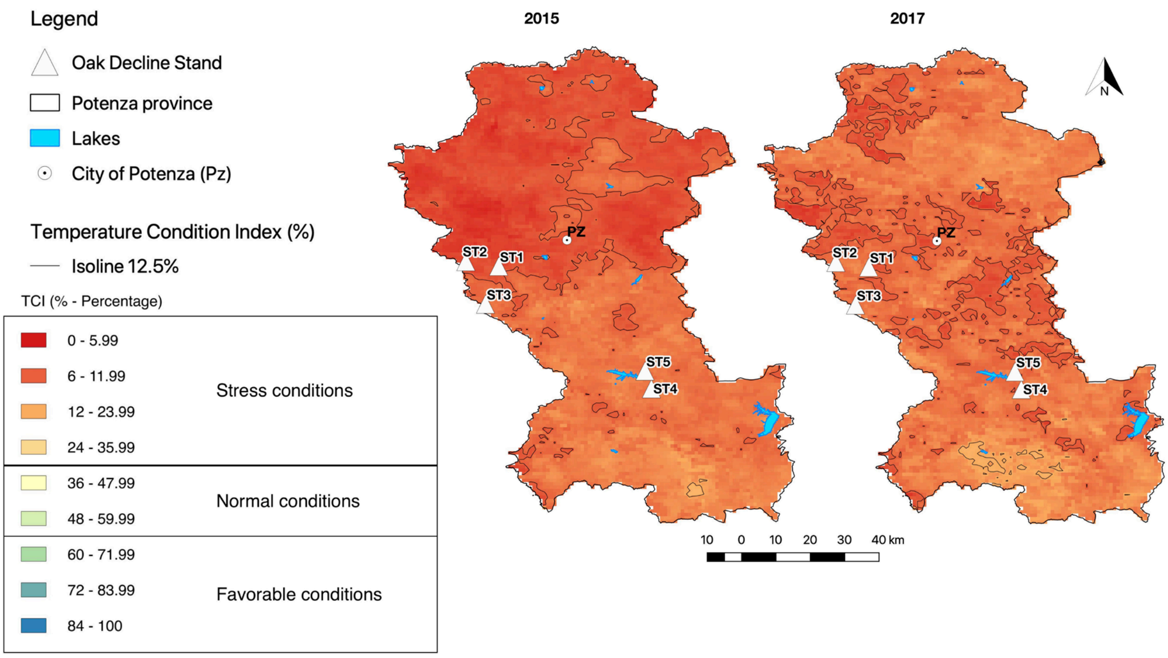

Fig. 3 - Distribution of the Temperature Condition Index (TCI) in summer 2015 and 2017.

to 27.38% of ST5, passing from ST2 with 26.31%, ST3 26.49%, and ST4 24.86%. In contrast, in 2017 these stands were characterised by negative values of D/S and, therefore, by a deficit of precipitations, D/S values ranging from -13.74% of ST5 to -20.34% for ST3 passing from -18.85% ST1, -18.58% ST2, and -17.13% ST4 (Tab. 4).

RAI values that referred to the first semester of 2017 were averagely lower when compared to those of the first semester of 2015 (Fig. 5). This result confirms that, in the first semester of 2017, the deficit was higher than during the same period in 2015 and of the average for the period 2001-2017. In 2017, the RAI values were mostly negative (14 out of 17 climatic stations), ranging from -0.44 to -1.61 (average -0.56 ± 0.66), whereas in 2015, almost all the RAI values were found to be positive and ranging from -0.16 and 1.84 (average 0.95 ± 0.65). The ST1 stand showed RAI = 0.78 for 2015, while both ST2 and ST3 RAI = 0.83. For both the stands located in the southernmost part of the study area (ST4 and ST5), the RAI 2015 values were found to be 0.80. In 2017 stands ST1, ST2, and ST3 exhibited low values of RAI (-0.75, -0.70, and -0.73, respectively), while stands ST4 and ST5 RAI of -0.53 and -0.44 respectively (Tab. 4; Online Appendix V).

SPI values for the year 2015 were found to be all positive, ranging from 0.202 to 1.881 (average 1.510 ± 0.533), whereas in 2017, these also exhibited negative values (up to -1.04) (Online Appendix V). On the basis of the Copernicus Europe an Drought Observatory drought scale (ECMWF, 2018), the precipitation regime in 2015 ranged from 'normal' to 'extremely wet' (most of the examined stations were included in the SPI categories 'moderately wet' and 'very wet'), whereas they ranged from 'moderately wet' to 'moderately dry' in 2017 (most of the examined stations are included in the 'normal' SPI category).

Tab. 4 - Stand's dataset extrapolate from GIS. Percentage values of Deficit Surplus 2015 (D/S 2015 %). Percentage values of Deficit Surplus 2017 (D/S 2017 %). Values of Rainfall Anomaly Index 2015 (RAI 2015). Values of Rainfall Anomaly Index 2017 (RAI 2017). Percentage values of Temperature Condition Index 2015 (TCI 2015 %). Percentage values of Temperature Condition Index 2017 (TCI 2017 %).

Stand Code	D/S 2015 (%)	D/S 2017 (%)	RAI 2015	RAI 2017	TCI 2015 (%)	TCI 2017 (%)
ST1	24.43	-18.85	0.7817	-0.7531	10.4991	14.5951
ST2	26.31	-18.58	0.8371	-0.7003	7.5122	15.0245
ST3	26.49	-20.34	0.8312	-0.7303	15.2904	14.4737
ST4	24.86	-17.13	0.8049	-0.5323	15.3533	14.0824
ST5	27.38	-13.74	0.8049	-0.4497	15.3592	15.0756

Discussion

In the present study, which concerned local episodes of oak forests decline in the Lucanian Apennines, we focused on the possible role of climatic anomalies in influencing this phenomenon.

We have found that the temperature anomalies recorded for 2015, the hottest year ever (CNR-ISAC, 2019), was not sufficient to trigger oak decline events. In fact, the year 2015, in addition to the high temperatures and possible heat waves, was characterized by a water surplus if compared to the average rainfalls calculated for the period 2000-2017 (as shown by D/S, RAI and SPI). It is therefore conceivable that precipitations that are not exceptional but at least not too deficient (especially in the first semester) have allowed the forest vegetation not to manifest an evident oak decline.

The oak decline observed during summer 2017 occurred concurrently to a general decrease in rainfall of about 20-30% compared to the period 2001-2017.

Tab. 5 - Vegetation features. Data collected on the field surveys in summer 2017 (*): Dominant species, Decline Severity (DES 2017), Pattern of decline, Vegetation series data.

Stand Code	Dominant species*	DES* 2017	Pattern of decline*	Vegetation series	Phytoclimate	Soil
ST1	*Q. pubescens*	4	Salt and pepper dieback	South-Appennines mesophilous neutro-subacidophilous (*Physospermo verticillati-Quercetum cerridis*)	Temperate oceanic semi-continental	Calcaric Cambisol, Calcaric Regosol
ST2	*Q. cerris*	3	Salt and pepper dieback	Centre-southern sub-Mediterranean and meso-Mediterranean Appennines neutro-basiphilous (*Roso sempervirentis-Quercetum pubescentis*)	Temperate oceanic semi-continental	Haplic Andosol Molli-Vitric Andosol Epilepti-Vitric Ando
ST3	*Q. cerris - Q. pubescens*	3	Tree to tree dieback	South-Appennines mesophilous neutro-subacidophilous (*Physospermo verticillati-Quercetum cerridis*)	Semi-continental oceanic transition	Haplic Andosol Molli-Vitric Andosol Epilepti-Vitric Ando
ST4	*Q. frainetto*	4	Salt and pepper dieback	South Appennines thermophilous neutro-subacidophilous (*Lathyro digitati-Quercetum cerridis*)	Temperate oceanic semi-continental	Calcaric Cambisol Skeleti-Calcaric Haplic Calcisol
ST5	*Q. pubescens*	4	Salt and pepper dieback	South-Appennines mesophilous neutro-subacidophilous (*Physospermo verticillati-Quercetum cerridis*)	Temperate Oceanic transition	Calcaric Cambisol, Calcaric Leptosol

This observation agrees with averages of the D/S and RAI, which were negative in 2017 (-17.77 mm and -0.56, respectively), whereas they were positive in 2015 (19.31 mm and 0.95, respectively). Also, the SPI index highlighted a difference in rainfall, which was up to extremely wet in 2015 and up to moderately dry in 2017. These evidences indicate that drought stress is probably the factor that is majorly involved in triggering oak decline more than temperature anomalies. However, it is not to be excluded that although extremely high temperatures are not sufficient, on their own, to trigger the oak decline, they may not have acted negatively in 2017 by widening the discomfort for a forest vegetation which was already exhausted by the water deficit. In fact, it should not be forgotten that, in addition to being the driest year since 1800, the year 2017 was also classified as the fourth warmest (CNR-ISAC, 2019). Our analyses regarding rainfall, carried out on both raw data and combined-indexes, revealed that a rainfall deficit occurred during the first semester of 2017 and it was absent during the same period of 2015. In addition, the temperature data did

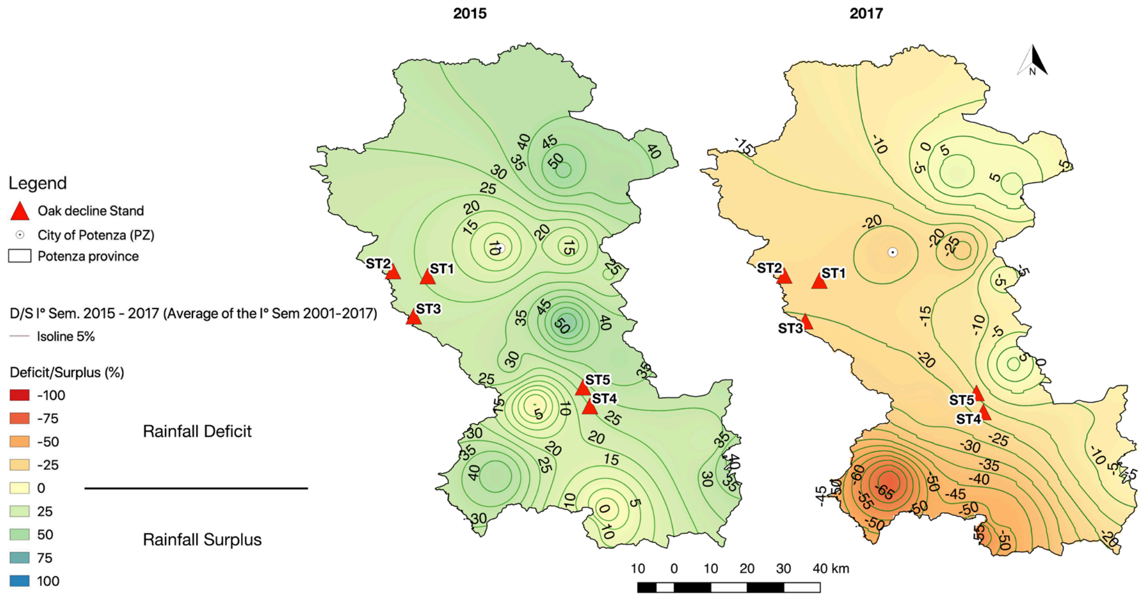

Fig. 4 - Deficit/Surplus (D/S) values for each Pluvio station in the 1st semester 2015 and 2017. D/S values reported in %. Pluviometric station code number (PS) in Online Appendix II.

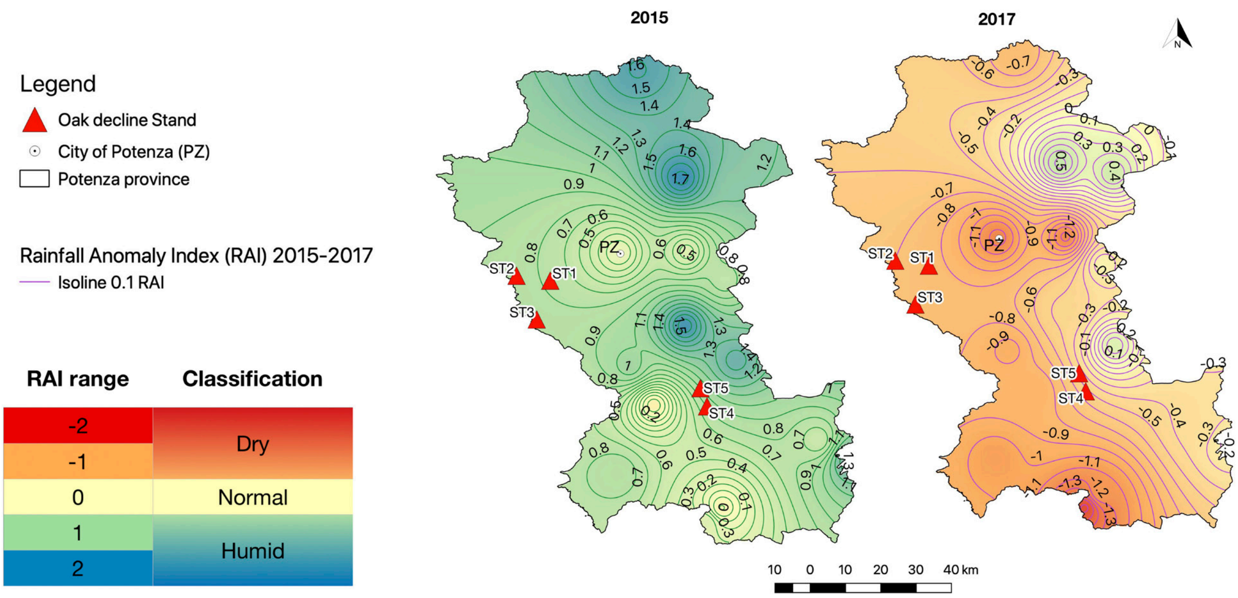

Fig. 5 - Rainfall Anomalies Index (RAI) in summer 2015 and 2017.

not provide significant differences between 2015 and 2017 in terms of thermic stress (TCI).

A worsening of the tree canopy conditions, which occurred passing from 2015 to 2017, was testified also by DNDWI and confirmed by DES. It is to be excluded any possible contribution of 2016 in determining the oak decline in 2017 being the NDWI values for 2016 even higher than those observed for 2015.

Vautard *et al*. (2007) observed that very hot summers (potentially able to trigger decline), are often preceded by dry winters. From what emerged in our work this statements cannot be confirmed or at least not completely. In fact, the correlation between hot summer and dry winters was pertinent with 2013, 2014 and 2017 and not pertinent with 2015 and 2016.

The fact that 2017 exhibited the lowest rainfall amount only for the first semester of the year would confirm that spring to early summer water availability is probably crucial in the seasonal cycle of the *Quercus* species and that climate anomalies occurring in this period could play a major role in triggering the oak forest decline. In broad terms, the oak decline could be viewed as a delayed response to spring drought conditions (see also Di Filippo *et al*., 2010; Natalini *et al*., 2016; Sánchez-Salguero *et al*., 2017) although according to other authors (see Gottschalk & Wargo 1997; Kabrick *et al*., 2008; Allen *et al*., 2010) drought, taken alone, would not be sufficient to cause decline and would require the action of other contributing factors such as heat stress, previous winter wind and frost damage, nutrient-deficiency and competition.

Concerning the distribution pattern of the oak decline, Mueller-Dombois (1992) argues that a possible cause of the decline is the synchronous senescence of the trees (called 'cohort senescence'), which would be able to spread rapidly from one area to its neighbouring ones. However, in the stands investigated, we have observed many dying trees occurring in a matrix of healthy trees, i.e. 'salt and pepper'.

Several authors (e.g., Camarero *et al*., 2016; Gentilesca *et al*., 2017; Colangelo *et al*., 2017) reported that the oak decline in mixed forests of the hilly and submontane belts of southern Italy involved *Q. cerris* more frequently than *Q. pubescens*. However, in our study area *Q. pubescens* would appear to be the most affected species (see Tab. 5). When the levels of drought stress become particularly severe, prolonged over time and possibly associated with other negative climatic anomalies concerning the winter or spring period, the fact that *Q. pubescens* woods tends to occupy the south-facing slopes, here as in the rest of the Apennines (see for example Ubaldi *et al*. 1984; Di Pietro & Blasi 1998; Allegrezza *et al*. 2003), makes them particularly exposed to undergo a more extensive and intense oak decline. As regards the observed evidence that the woody edges of the forest stands appeared to be more subjected to the negative effects of the decline we have not a definitive answer. As suggested by some authors (e.g., Van Gunst *et al*., 2016; Colangelo *et al*., 2017) it is possible that the shrub species forming the forest woody edges are more likely to die due to their inability to obtain water from great depths. At the same time it cannot be a-priori excluded that the woody edges acted more sensitively to oak decline, owing to the extremely severe drought conditions experienced by the ecotonal fringes when compared to those of the core areas where almost only dominant oak tree species are found.

Concluding remarks

The oak decline events in summer 2017 had a widespread effect throughout the Lucanian Apennine and involved more than 500 hectares of woods. The oak decline events observed in the field and assessed with DES were also confirmed by the NDWI datum. Our results suggest that the forest decline that we observed in 2017 in southern Italy could be majorly linked to the rainfall deficit that characterized the first semester of this year more than possible temperature anomalies.

The oak decline evidenced in the Lucanian Apennines is to be viewed as the local emergence of a phenomenon that is actually affecting the entire Mediterranean basin. The results obtained in our paper are pertinent with those published for other Mediterranean areas, where several other species of trees were involved. Similar cases of oak decline have recently been documented for some deciduous oak forests of central Italy (Castelporziano protected area in the Lazio Region), where the nefarious effects of the oak decline were found to be particularly significant in summer 2017 (Recanatesi *et al*., 2018). In other studies regarding the near East and Spain (Hosseini *et al*., 2017; Sánchez-Salguero *et al*., 2017) other species such as conifers (*Pinus halepensis* Mill., *P. nigra* J.F. Arnold), other deciduous (*Q. faginea* Lam.), semideciduous (*Q. brantii* var. *persica* (Jaub. & Spach) O.Schwarz), and evergreen oaks (*Q. ilex* L., *Q. suber* L.) were found to be involved in the oak decline phenomenon.

As already observed in the majority of the papers published over the last few years on the oak decline topic, the cause-effect relationships are still not clear and the role of the ecological factors involved not yet established.

A protocol of analyses, based on the combination of remote sensing techniques and field surveys would seem the only way forward although it will be probably necessary to implement the detail of the analysis carried out in the field. A new and shared sampling protocol could become an important tool in order to carry out oak decline risk maps at large scale useful for preserving the forest heritage in the whole Mediterranean area.

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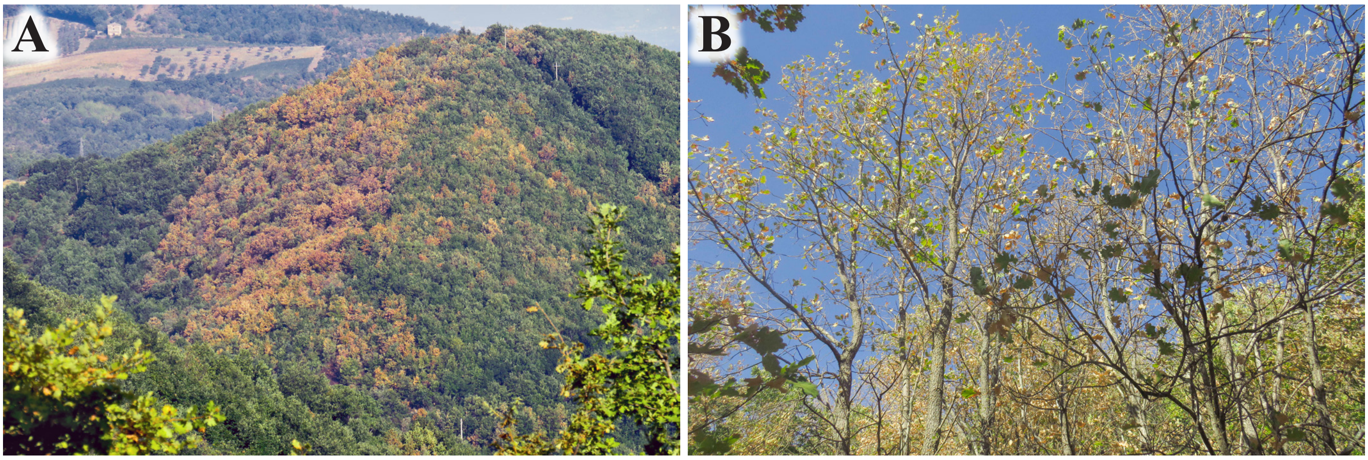
Appendix I

(A) The oak decline at the 2017-08-27. San Martino d'Agri (Pz). (B) Defoliation of trees at the 2017-09-17. Montemurro (Pz).



Appendix II

Climatic stations located in the administrative Provinces of Potenza and Matera. Pluviometric station code number (PS). Longitude and Latitude of DD UTM WGS84 (Data base from ALSIA and CFD Basilicata).

PS	Climate Station	Municipality	Altitude m asl	Longitude	Latitude
1	C.da Ripa D'api	Genzano di L. (PZ)	320	16.09416666	40.7991667
2	Loc. Abetina	Laurenzana (PZ)	938	15.96861111	40.4508333
3	Az. Bosco Galdo	Villa D'Agri (PZ)	595	15.82861111	40.3494444
4	C.da Pipoli	Acerenza (PZ)	420	15.95999999	40.8255556
5	Grassano scalo	Grassano (MT)	190	16.23638888	40.5969444
6	Piano delle Rose	S. Giorgio L.(MT)	455	16.38777777	40.1102778
7	C.da Montecrispo	Campomaggiore (PZ)	824	16.07138888	40.5688889
8	C.da Lupara	Guardia Perticara (PZ)	616	16.09833333	40.3627778
9	Az. Agr. Ventrona	Nemoli (PZ)	500	15.79666666	40.0750000
10	Loc. Serra del Ponte	Brindisi di Montagna (PZ)	820	15.97361111	40.6388889
11	C.da Torre	Stigliano (MT)	240	16.33416666	40.3950000
12	C. da Pedali	Viggianello (Pz)	616	16.06250000	39.9875000
13	AASD Pollino	Rotonda (Pz)	566	16.02222222	39.9491667
14	C. da Trutolo	Sarconi (Pz)	662	15.88944444	40.2488889
15	AASD Gaudiano	Lavello (Pz)	180	15.84861111	41.1016667
16	Piano delle Maniche	Senise (Pz)	270	16.30750000	40.1600000
17	Potenza	Potenza (Pz)	829	15.80153900	40.6369020

Appendix III
Rainfall data of the study area. Data source from Climatic Research Unit, University of East Anglia, CRU TS 3.21 (Data available on September 2019; https://www.globalclimatemonitor.org/).

	Rainfall of I Semester			**Rainfall of II Semester**			**Annual Rainfall**		
	Monthly average (mm)	**Standard Deviation**	**Total (mm)**	**Monthly average (mm)**	**Standard Deviation**	**Total (mm)**	**Monthly Average (mm)**	**Standard Deviation**	**Total (mm)**
2000	37.95	± 21.49	227.70	61.10	± 40.34	366.65	49.52	± 33.75	594.35
2001	77.80	± 49.28	466.80	30.25	± 33.57	181.50	54.02	± 47.86	648.30
2002	43.43	± 37.69	260.60	80.55	± 43.40	483.30	61.99	± 44.04	743.90
2003	55.90	± 40.83	335.40	90.90	± 77.07	545.45	73.40	± 62.91	880.85
2004	70.61	± 23.35	423.70	69.04	± 55.64	414.25	69.82	± 41.74	837.95
2005	66.29	± 37.34	397.75	97.18	± 65.06	583.10	81.73	± 54.22	980.85
2006	76.22	± 36.03	457.35	68.87	± 37.27	383.25	70.05	± 36.40	840.60
2007	70.30	± 29.70	421.85	68.90	± 49.85	413.40	69.60	± 40.14	835.25
2008	47.15	± 26.31	282.90	90.48	± 81.94	542.90	68.81	± 63.50	825.80
2009	107.53	± 73.46	645.20	68.11	± 59.20	408.70	87.82	± 68.28	1053.90
2010	73.65	± 26.95	441.90	81.49	± 75.94	488.95	77.57	± 55.87	930.85
2011	70.55	± 29.30	423.35	46.19	± 35.44	277.15	58.37	± 34.15	700.50
2012	46.00	± 41.73	276.00	28.87	± 26.67	173.25	37.43	± 35.35	449.25
2013	71.15	± 39.44	426.95	55.09	± 41.29	330.55	63.12	± 40.33	757.50
2014	58.07	± 27.28	348.45	42.57	± 23.47	255.45	50.32	± 26.11	603.90
2015	69.02	± 46.15	414.15	48.07	± 47.41	288.45	58.55	± 46.99	702.60
2016	69.15	± 27.73	414.90	55.78	± 42.12	334.70	62.46	± 35.54	749.60
2017	35.62	± 30.55	213.75	46.93	± 44.47	268.10	41.27	± 37.76	481.85
Mean	65.20	± 35.81		62.80	± 48.90		63.10	± 44.72	756.54
Standard Deviation	± 17.45			± 20.32			± 13.40		± 162.10

ID Points: 33624-33625. CRU TS 3.21 Data source:@Climatic Research Unit. University of East Anglia:CRU TS 3.21@NOAA:GHCN@DWD:GPCC made available under the ODL

Appendix IV
Characteristics of the five stands monitored with field survey.

Stand Code	Municipality and Province	Coordinates UTM-WGS84	Altitude m a.s.l.	Aspect (degrees)	Slope (%)	Stand's Area m^2
ST1	Tito (Pz)	552979.00 E - 4490728.00 N	785	155°	43	400
ST2	Savoia di Lucania (Pz)	545712.00 E - 4492057.00 N	574	230°	67	400
ST3	Brienza (Pz)	550099.00 E - 4479755.00 N	958	180°	50	400
ST4	San Martino d'Agri (Pz)	587075.81 E - 4455612.61 N	756	170°	28	400
ST5	Montemurro (Pz)	585744.44 E - 4460624.09 N	843	230°	36	400

Appendix V
Standardised Precipitation Index (SPI). Deficit/Surplus (D/S) and Rainfall Anomaly Index (RAI) values for each Pluvio station in the 1st semester 2015 and 2017. PS = numbers of Pluvio stations in Online Appendix 2.

PS	SPI		D/S				RAI	
	2015	2017	2015 (mm)	2015 (%)	2017 (mm)	2017 (%)	RAI 15	RAI 17
1	1.751	0.674	15.91	44.44	6.51	18.18	1.210	0.495
2	1.405	-1.036	44.65	58.86	-12.25	-16.15	1.765	-0.484
3	1.341	0.305	23.24	31.20	-20.56	-27.62	1.057	-0.935
4	0.202	-0.524	25.59	51.08	8.69	17.35	1.843	0.626
5	1.881	-0.739	25.15	47.06	-13.95	-26.10	1.710	-0.949
6	2.326	1.175	23.71	42.73	-3.09	-5.57	1.386	-0.181
7	-	0.994	13.66	24.61	-2.34	-4.21	0.722	-0.124
8	1.405	-0.643	24.13	39.97	6.13	10.15	1.448	0.368
9	0.000	0.994	59.65	43.59	-73.45	-53.67	0.881	-1.084
10	0.000	0.000	7.66	12.14	-26.84	-42.50	0.351	-1.230
11	0.000	0.842	19.56	38.79	-2.24	-4.43	1.265	-0.145
12	1.881	0.332	-4.43	-4.80	-43.18	-46.79	-0.114	-1.115
13	1.881	0.253	14.39	13.33	-58.91	-54.59	0.395	-1.615
14	1.405	-0.050	-4.28	-5.07	-23.57	-27.90	-0.163	-0.900
15	-	0.025	19.71	39.12	-9.59	-19.03	1.613	-0.785
16	-	0.358	15.88	25.23	-9.32	-14.82	0.616	-0.361
17	1.126	-0.915	4.09	6.64	-24.11	-39.09	0.211	-1.242