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ORIGINAL ARTICLE

Square-grid sampling to address the vegetation patterns of declined Mediterranean forest ecosystems

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Abstract

Palo Laziale Wood is a relatively small biotope (129 ha) situated along the coast of the Metropolitan Area of Rome, Lazio region, Italy. Despite being one of the region's remaining patches of an ancient oak floodplain broad-leaved forest, it conserves numerous priority habitats and species of high conservation interest. The vegetation consists mainly of Turkey oak stands with small temporary ponds and flooded meadows. The forest underwent a dieback in 2003, triggered by a significantly hot and dry summer. In 2018, an ecological restoration project (LIFE PRIMED LIFE17 NAT/GR/000511) was initiated to restore Palo Laziale's ecosystems. This paper presents the methodological approach employed to assess the vegetation ecology of a degraded forest ecosystem. Such an investigation was a key component of the Adaptative Restoration Plan of the Project. It provided the baseline necessary for designing and calibrating the planned direct conservation actions on the target habitat types (91M0: Pannonian-Balkanic turkey oak-sessile oak forests, 3170*: Mediterranean temporary ponds, 5230*: Arborescent matorral with *Laurus nobilis*, etc.) and establishing reference values to enable long-term monitoring. Plant taxa comparison from 1 ha square-grid sampling and multivariate analyses were carried out to group species and identify environmental and Ellenberg-based drivers. Six ecologically distinct units were found, eventually confirming the distinctive ecological heterogeneity of Mediterranean ecosystems. Amongst these, the hygrophilous vegetation has resulted to be the one mainly affected by the dieback outbreak. Due to the high heterogeneity, introduced by the massive tree mortality, the method of regular 1 ha squares turned out to be a reliable alternative to random vegetation sampling plots (e.g., phytosociological relevés) to disentangle ecological patterns of fragmented and disturbed habitats.

Keywords Square-grid sampling · Mediterranean ecosystems · Ecological patterns · Ellenberg indicators · Forest dieback

Introduction

Monitoring of plant species and vegetation types is getting a huge response in Europe and around the world (Bruelheide et al., 2019; Chytrý et al., 2016; Resurvey Europe, etc.), also to support restoration, conservation and management practices (Lindenmayer, 2020; Wortley et al., 2013). Monitoring a given biome at the level of habitats or ecosystems allows the achievement of information on the status of lower levels of biodiversity organisation, including the most characteristic species of a plant coenosis (Bunce et al., 2013; Noss, 1990). Once the link between species and habitat types is established, this approach can be used to monitor different species or vegetation types simultaneously (Gottschalk et al., 2005). One of the most important factors when studying the vegetation and habitat types of a natural or semi-natural area is the choice of the assessment approach. The assessment and monitoring of vegetation can be approached with single or combined methods. The monitoring way is increasingly gaining momentum in the scientific arena and is welcomed by the competent institutions for the Natura 2000 network and the Habitats Directive (Gigante et al., 2016).

The Natura 2000 site 'Bosco di Palo 'Laziale' is a coastal woodland ecosystem located in the surroundings of Rome. Over the last twenty years, the forest has been subject to a rapid decline in vitality, leading to several direful events of tree decay. Both direct and indirect anthropogenic pressures have been responsible for such dieback, including local implications of climate change, inappropriate forest and water management and endophytic fungi diseases of *Biscogniauxia mediterranea*, *Discula quercina* and *Diploidia corticola* (Beccaccioli et al.,

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2021; Natili et al., 2014). Thus, from a dense coppice forest with occasional clearings, the wood of Palo Laziale turned nowadays into a scrubland with mostly isolated adult trees and a few islands of forest stands.

LIFE PRIMED was one of the first ecological restoration projects in Europe which harmonised the incorporation of ecosystem-based knowledge in the design process of practices for the restoration, conservation and management practices of declined Mediterranean habitats. Determining the vegetation structure was one of the key tasks in the holistic and interdisciplinary decision-making and conservation process of Palo Laziale's ecosystems. The identification of the plant assemblages, their spatial distribution, and the peculiar ecological features of certain taxa or groups, including their conservation status and needs, are fundamental steps in the adaptative restoration and management of the site (Bunnefeld et al., 2017).

In Palo Laziale, it was employed an alternative method to characterise plant communities and identify their ecology. It consisted of an adaptation of the square grid floristic census. Square grids have been widely used to survey the flora and certain macroecological and functional patterns in many European countries and regions since the 1960s, usually using grids of a few kilometres wide (Perring & Walters 1990; Schönfelder, 1999; Biesmeijer et al., 2006; Stešević et al., 2014; Jogan et al., 2022). On the contrary, fine-scale mapping has rarely been employed.

In this study, we divided the Palo Laziale area into 37 squares (1 ha). In each plot, the presence of all the plant species was detected by ground mapping. Data from pedological, topographical and functional field surveys were also integrated to develop a set of indicators which defines the ecological features of the species of group of species.

The study aimed at (1) identifying the ecological units of species that persist in the area of interest, (2) regionalising the study site at a fine scale, i.e., finding the distribution of the ecological units, and (3) investigating the ecological factors that shaped the current vegetation patterns. This is an integrated experimental design to disentangle the ecological complexity of a natural ecosystem based on the presence of certain taxa and their interaction with the various abiotic parameters. The work embraces further integration of other data sources and types of analysis, including remote sensing and comparison with high-resolution mapping methods, to draw possible clues on the degradation process and causes of an ecosystem.

Materials and methods

Study area

The Palo Laziale wood is located along the coastline of the Lazio Region, in the province of Rome, about 40 km NW of Italy's capital, within the Municipality of Ladispoli. It is set within an entirely fenced-off private property and is embedded in the SAC IT6030022 "Bosco di Palo Laziale." The forest extends over a flat area of about 50 hectares, with an altitude of between 3 and 10 m above sea level and about 100 m far from the coastline.

According to the bioclimatic features, the area is located within the Mediterranean region, as defined by the compensated summer ombrothermic index (Rivas Martìnez 2008). During the summer, the high temperatures and the low precipitation give rise to a dry period and negative soil water balance due to the high evapotranspiration.

Lithology shows an alternation of alluvial and deltaic sediments with different permeability. Sands and biocalcarenites of the Middle Pliocene (Macco formation), alluvial deposits and sand layers of the Pleistocene, coastal sand and polygenic pebbles reworked with volcanic elements of the Holocene are all more permeable. In contrast, the quaternary deposits consisting of clay, silt and clay of lakes and marshes, peat and cemented sand may be considered of low permeability (Compagnoni et al., 1988; Ventriglia, 1988). The differences in permeability create areas with water stagnation, a reminder of the marshes that covered this area before the land reclamations.

The predominant vegetation of Palo Laziale is represented by a deciduous forest, with a prevalence of *Quercus cerris* and rare individuals of *Q. petraea* and *Q. frainetto*. In the depressed areas, where there is water stagnation and formations of freshwater pools, the vegetation changes drastically, with *Fraxinus angustifolia* subsp. *oxycarpa* and *Quercus robur*. In drier and warmer areas, Mediterranean sclerophyllous scrub can be found with a predominance of *Quercus ilex*, *Pistacia lentiscus* and *Phillyrea latifolia*. Mediterranean meadows occupy small patches of the SAC with very rich flora. In late spring and summer, annual herbaceous and xerophilous communities of the Habitat 6220* (Pseudo-steppe with grasses and annuals of the *Thero-Brachypodietea*) dominate the dry topsoil. In the same area, during late winter and early spring, Mediterranean temporary ponds (habitat code 3170*) burgeoning in the meadows. They form ephemeral habitats of priority importance from a conservation point of view. The coastal vegetation has been heavily impacted by sea erosion, erasing hundreds of metres of coastline over time. The vegetation is very poor, with species mainly from embryonic mobile dunes.

Sampling methods and datasets

Sampling for the study of plant assemblages was carried out in 2020 by ground sampling taking the presence/absence data of plant species on an alternating grid square base (100 m side) according to Bullock (2006) and Fratarcangeli

et al. (2022) arranged following the UTM WGS84 33 T reference system and built with QGIS software (QGIS Development Team, 2023) and the "TomBio tools" plugin, for a total of 37 squares (Fig. 1). The choice of 1 ha plots it seemed to match the grain of the vegetation, and it is based on preliminary surveys in the area. An exception to this scheme is the I9 plot, which was chosen due to the presence of the biggest temporary pool in the area. The grid does not include other plots (e.g., the entire column A) for the impossibility of entering those areas because are private property.

These squares are a baseline for future monitoring works to assess the changes. The taxonomic and syntaxonomic nomenclature of the present work follows Bartolucci et al. (2018) and Mucina et al. (2016), respectively.

Environmental data were included to allow an ecological analysis of the vegetation (Table 1). We implemented

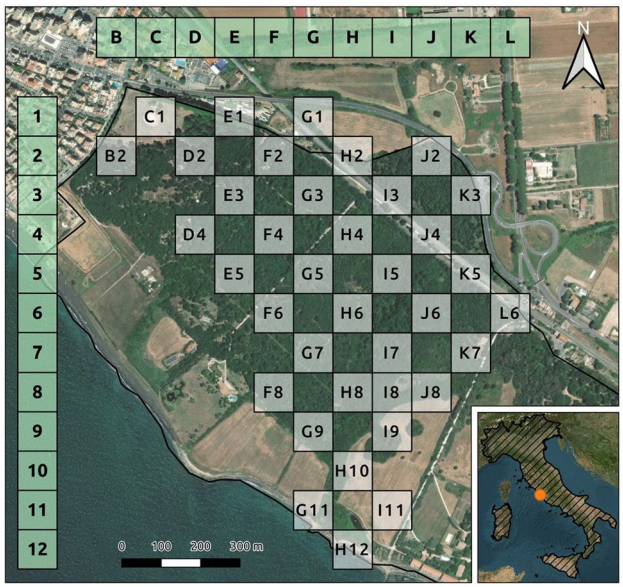


Fig. 1 Map of the study area with the grid-cells investigated

28 soil surveys carried out and spatialised over the area. In addition to the soil variables in Table 1, some measured parameters (cation-exchange capacity, exchangeable sodium, exchangeable bases and calcium carbonate percentage) were not included because their ecological meaning is redundant with respect to electrical conductivity.

Soil data retrieved from 28 pits were integrated into the analysis. Since measurements were point-like, they were spatially analysed using IDW (Inverse Distance Weighted) interpolation with a distance coefficient P of 4.

Topographic data of the area were also included to develop a Digital Terrain Model (DTM) to investigate whether ground depressions might influence vegetation (variable Altitude). The distance of each plot from the sea was also included as an additional spatial variable to verify if there is an influence of the sea and marine aerosol on the species composition of the vegetation. Normalised Difference Vegetation Index (NDVI) used in Lombardi et al. (2023) was employed to measure vegetation density and identify changes in plant health. For a better understanding of the structural differences of the vegetation in the area, a Canopy Height Model (CHM) was calculated from the difference between the Digital Surface Model (DSM; from UAV pictures of the area) and DTM.

The same mapping procedure was carried out with the Ellenberg indicators (Pignatti, 2005) for each 1 ha plot to identify differences with the measured environmental variables and to discern the ecological conditions encountered in the plots.

Data analysis

The distribution of species "within" and "between" the squares and their correlation to abiotic factors was investigated.

Table 1 Environmental variables used for the ecological analysis of the area

Variable	Description	Unit
Sand	Sand content	%
AWC	Average water capacity, the amount of water that can be stored	mm/m
pH	pH of the soil in aqueous suspension measured with a pH metre	pH*10
Clay	Clay content	%
OM	Organic matter content	%
Silt	Silt content	%
Altitude	Actual elevation above mean sea level	m
EC	Electrical conductivity measured on soil in aqueous suspension using a conductivity metre	µS/cm
NDVI	Normalised Difference Vegetation Index	
Sea distance	Distance from the seashore	m
CHM	Canopy height model	m

As a first step, a dissimilarity matrix was created through Ochiai's method using the "vegan" R package (Oksanen et al., 2017) to have the distances between pairs of squares.

Afterwards, a cluster analysis was carried out to find divisions into groups. The package "cluster" (Maechler et al., 2022) allows hierarchical aggregations with the *full link* method to define the distance between groups. The optimal number of groups was chosen based on the "average silhouette width."

Then, we moved to the study of the species composition of each square. Turboveg software (Hennekens & Schaminée, 2001) was used to create a database of the plots of Palo Laziale and to create an output file for the vegetation study. Juice (Tichý, 2002) was used to create a synoptic table of the species, to assign the diagnostic and constant species to each group, setting the "fidelity threshold" at 50 and the "frequency threshold" at 70.

Hence, it was possible to apply a multivariate sorting analysis using NMDS (Non-metric Multidimensional Scaling). The same dissimilarity matrix used for the cluster analysis was adopted for this ordination to ensure continuity between the two types of analysis. Before starting the computation in Rstudio software (R Core Team, 2022), a seed value was set for the generation of random number sequences equal to "123."

The dissimilarity matrix was analysed with a limited number of dimensions ($k = 2$) and with several random starts equal to 100 to avoid reaching a local minimum. Subsequently, to further ensure that the latter type of problem was avoided, the same analysis was repeated using the solutions of the previous analysis as a starting point. The goodness was assessed by looking at the "stress" value and for further confirmation, the Shepard diagram was also evaluated.

Once the community data had been sorted based on the species occurrences, we overlayed the previously obtained environmental variables. The same procedure was done with the Ellenberg indicators of each plot. These steps were also tested through a permutation test to try out all possible combinations of the pairing of variables and sorting points. Finally, the results grouped according to the cluster analysis were reported on two graphs, one with the environmental variables as a whole and one with the Ellenberg indicators.

Following this, nonparametric statistical tests were carried out to understand how much the environmental variables are related to the group differentiation of the plots. The choice of using a nonparametric test is because the total number of observations of the variables is too small. The nonparametric test chosen is the Kruskal–Wallis test.

Once the Kruskal–Wallis test was performed, Dunn's post hoc test was implemented for groups with a significant difference ($p < 0.05$) for a given ecological variable. The *p-value* adjustment method used in this work is that of Benjamini and Hochberg. Finally, the same tests were performed to assess the presence of significant differences between groups and the values of incidence of forest dieback in the area, as assessed by Natili et al. (2014).

Results

Cluster analysis and species composition

The cluster analysis shows clear differentiation into groups of the floristic plots. There are two main groups with different physiognomy (woodlands and grasslands) and six groups with specific differences in plant composition (Fig. 2). The silhouette test confirmed that the optimal number of groups was 2, and the following optimal number of groups is 6, the second point of relative maximum.

Thanks to the use of Juice and Turboveg software, we were able to identify the diagnostic and constant species for

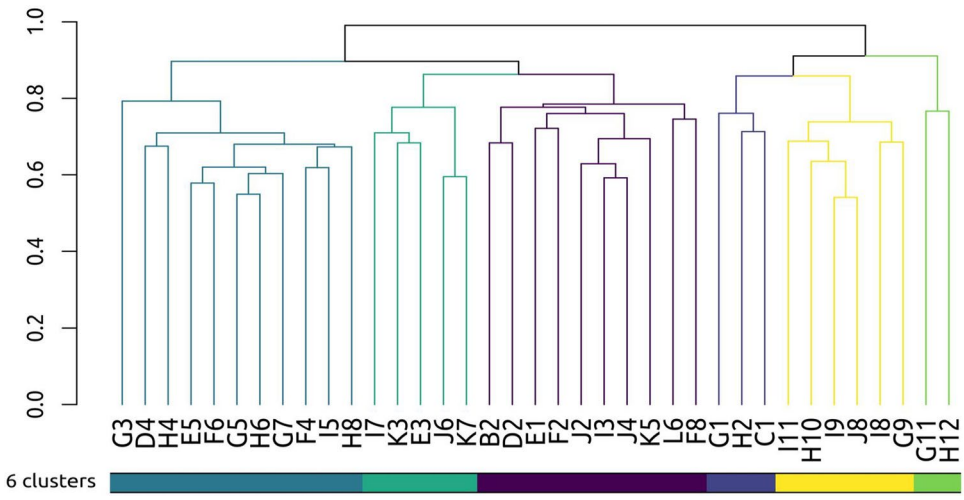


Fig. 2 Dendrogram showing the six clusters identified during the analysis

each group, as illustrated in the synoptic table in Appendix S1.

NMDS and statistical tests

The multivariate sorting analysis "NMDS" conducted on the dissimilarity matrix presents remarkable results. Then, we checked the goodness of the analysis by the Shepard diagram (Appendix S1) with a non-metric fit of 0.977 (R^2) and a linear fit of 0.894 (R^2).

From the sorting analysis, we have a stress value of 0.1523829. In the biplot (Fig. 3), the groups are clearly divided, except for the grassland groups. There is a clear differentiation in the forest main groups (clusters 1,3 and 4). The environmental variables that seem to explain the most the disposition of the plots in the graph seem to be altitude ($p=0.005$), AWC ($p=0.021$), mean sand and clay in the soil (respectively, $p=0.034$ and $p=0.010$), NDVI ($p=0.001$), and finally CHM ($p=0.001$) whilst some physicochemical and soil variables do not seem to have a great influence on the determination of groups.

Groups 2, 3, and 6 are separated from the remaining by the amount of clay in the soils and the water in them. Groups 1, 4, and 5 seem to follow the amount of sand in the soil. On the other hand, the vertical axis partially subdivides them into the two main groups previously identified, which follow the trend of the NDVI and CHM variables.

However, if we look at the biplot of the surveys with the Ellenberg indicator variables (Fig. 4), we see that they are arranged differently.

From the p-value reading, all variables, except the pH indicator, are highly significant (L $p=0.0009$; T $p=0.001$; K $p=0.0009$; F $p=0.0009$; N $p=0.001$; S $p=0.0009$; H $p=0.0009$) and therefore explain well the pattern and arrangement of the groups illustrated. In particular, it is observed that the variables S, L, K, and H tend towards a single direction in the second quadrant, subdividing the groups at the top left (grassland main group) from those at the bottom left (grassland main group) from those in the lower right (forest main group). The variable F tends to go opposite to those previously described, whilst T and N point towards the third quadrant.

After completing the sorting analysis, we statistically tested it to confirm how closely the environmental variables are linked to the identified groups (Table 2).

Subsequently, Dunn's post hoc test was applied to the variables with the highest significance. Using the boxplots, it is possible to see which groups differ significantly from the others for the environmental variable.

From the boxplots (Fig. 5) representing the different variables related to groups, there are several differences for the soil clay variable, some of which are very marked and significant (statistical values are summarised in Appendix S1). Turning to the sand percentage boxplots there are significant differences between the groups, lesser than those found with the clay variable. For the AWC edaphic variable, a similar, but not the same, pattern can be seen as for the clay variable. On the other hand, the variable NDVI does not differ significantly between groups, although the Kruskal–Wallis test showed a significant difference. Then, the CHM showed a high significant difference with groups 1, 3 and 4 having higher values than the other three. Finally, the topographic variables analysed with this post hoc test are the last two variables. The test for the

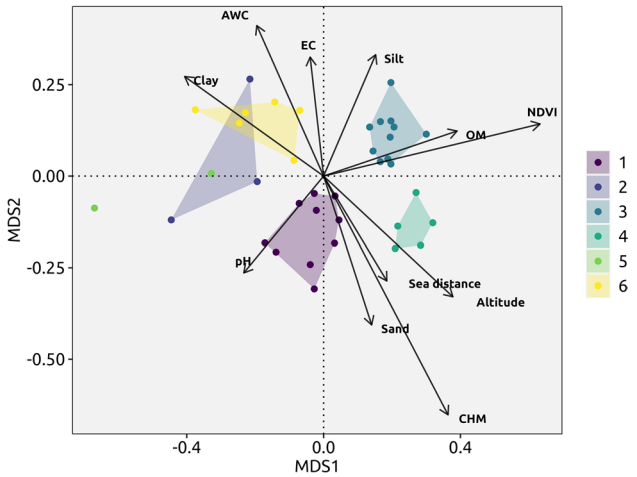


Fig. 3 NMDS ordination analysis depicting separation of the six different groups with the measured environmental variables. The direction of the arrows indicates a positive or negative correlation with the ordination axes and the length reflects the correlation between the environmental factors and the ordination biplot

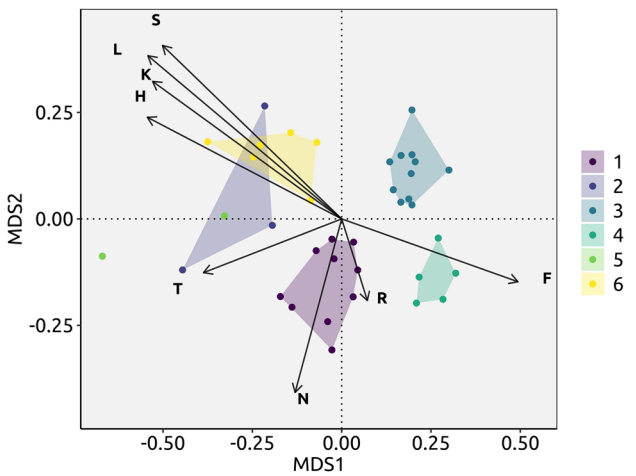


Fig. 4 NMDS ordination analysis depicting separation of the six different groups with the Ellenberg indicator. The direction of the arrows indicates a positive or negative correlation with the ordination axes and the length reflects the correlation between the indicators and the ordination biplot

Table 2 Summary of the nonparametric Kruskal–Wallis tests, including the chi-square, the degrees of freedom and *p*-value

Environmental variables	Chi-square	Degrees of freedom	*p*-value
Sand	17.607	5	0.003481**
AWC	20.428	5	0.001038***
pH	5.5306	5	0.3546
Clay	16.509	5	0.005531**
OM	5.7452	5	0.3318
Silt	7.6937	5	0.1739
Altitude	16.131	5	0.006481**
EC	8.7084	5	0.1213
NDVI	12.636	5	0.02704*
Sea distance	16.197	5	0.006305**
CHM	24.274	5	0.000192***

Of the 11 variables tested, only 6 shows a significant difference in the various groups identified. NDVI is the only variable with a slightly higher p value than the others, but still significant (* *p*-value <0.05; ** *p*-value <0.01; *** *p*-value <0.001)

variable "altitude" shows a significant difference between some groups as well as the variable "distance to the sea".

With this method, six ecological units were highlighted. These units are thoughtfully explained by environmental variables directly measured (soil, etc.) and inferred through bio-indicators (light, temperature, humidity, etc.).

The dendrogram developed shows the plots sorted into the six groups identified above (Fig. 2). They can be clearly distinguished into two main groups, referred to as forest and grassland plots, since the species are predominantly, respectively, mainly forest and grassland species, both of which consist of three distinct groups. Given the results, we can define them as ecological units divided into forest-dominated groups (1, 3 and 4) and grassland-dominated groups (2, 5 and 6).

From these results, we chose the forest main group plots to perform the Kruskal–Wallis test and Dunn's post hoc test to assess if the incidence of the dieback is higher in one or more groups. This analysis revealed that group 3 coincides with the area more affected by the dieback with a significant difference (Kruskal–Wallis test $p = 0.01$) compared to the other two (groups 1 and 4). Results are shown in Appendix S1.

Discussion

In Italy, oak forests, from north to south of the Peninsula, have been subject to decline, reduction, and death of plant populations under a wide range of environmental conditions (Bertini et al., 2011; Conte et al., 2019; Di Filippo et al., 2010). The environmental phenomena that mainly cause these oak forest declines range from severe droughts to prolonged flooding or rapid fluctuations in soil water levels (Brasier, 1996; McDowell et al., 2022), which cause ecophysiological stress to the plants and make them more susceptible to attack by pathogens (Moricca et al., 2012). Forecasts of future climate trends suggest that the Mediterranean region will be increasingly exposed to extreme weather events and long-lasting drought over the forthcoming years (Beniston et al., 2007; Giorgi & Lionello,

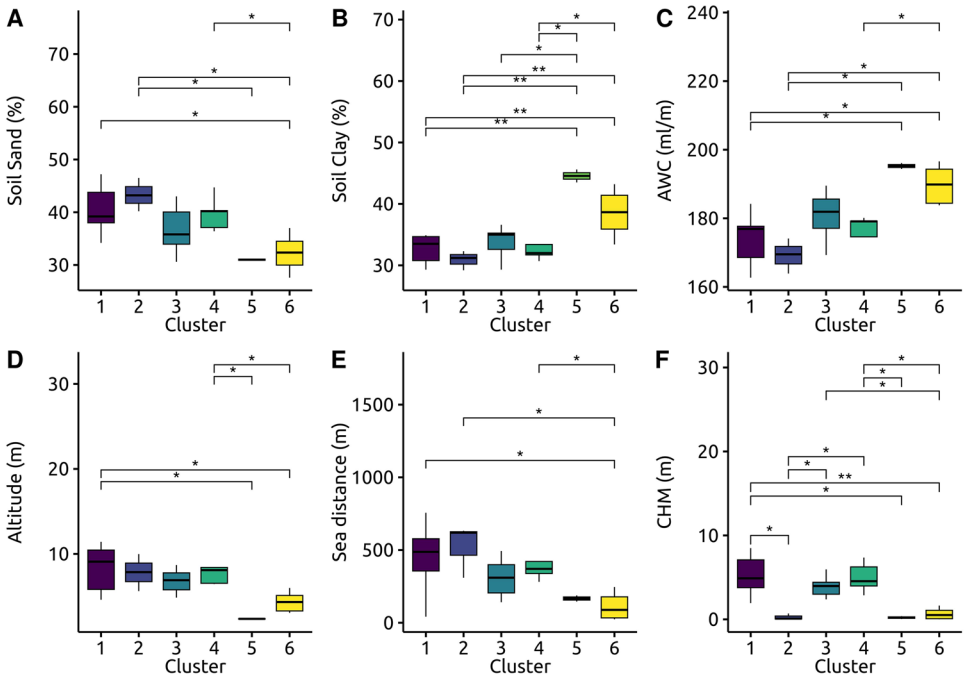


Fig. 5 Boxplots showing the main significative differences between the six cluster based on the environmental variables: **A** Soil sand percentage; **B** Soil clay percentage; **C** Available Water Content (AWC); **D** Altitude; **E** Sea distance; **F** Canopy Height Model (CHM)

2008; Touhami et al., 2020). Temperature increasing in tandem with an overall tendency for decreasing precipitation is expected to significantly impact the vitality, structure, composition, and functions of oak forest ecosystems, causing further cases of forest die-off.

Although the area in Palo Laziale is relatively small and geologically homogeneous, the floristic analysis highlights a significant environmental heterogeneity, common in many Mediterranean environments (Testi et al., 2010). Disentangling such complexity to intercept key components and their interrelations is paramount in habitat conservation, especially for those ecosystems needing restoration attention. Approaching this domain with a purely structure examination or with a restricted focus on the dominant woody species or overlooking the species from the herbaceous layer would not match otherwise with such a high degree of heterogeneity. Besides, all species can inform on the patterns, processes, and influence of ecological proxies in an ecosystem through the use of indicators from the Ellenberg system (Bartelheimer et al. 2016; Hellegers et al., 2020). In fact, our approach is based on the concept of plants as environmental indicators. Since plant species have a well-defined realised niche, it is possible to infer environmental conditions based on this. This requires extensive experience, although it is facilitated by Ellenberg indicators, which provide the realised niche for each species, and by extensive literature that indicates the indicator species for each syntaxon (Biondi et al., 2014; Rivas-Martínez et al., 2002).

The grid squares of 100 m revealed six distinct groups that differ ecologically by variations in the sampled environmental parameters (granulometry, pH, and proximity to the sea). The six groups can be sorted into two main groups divided into forest-dominated (1, 3 and 4) and grassland-dominated groups (2, 5 and 6) as highlighted from the NMDS. Within the forest main group, it was possible to identify three different types: (1) Group 1 with mesophilic forest species; (2) Group 3 with damp woodland species; (3) Group 4 with thermophilous woodland species.

The six groups are not scattered randomly in the study area but show a clear pattern. The grassland main group is present mainly in the southern part of the SAC along the coast, in formerly cultivated areas, and in the proximity of urban areas in the north, more susceptible to anthropogenic disturbance, whereas the forest main group occupies predominantly the site's core.

Interestingly, only the vegetation belonging to group 3 was mainly affected by dieback (Fig. 6). The concurrence of damped soil characteristics (clay and high AWC) with water-tolerant species (highlighted by the F indicator) suggests an interaction between 2 factors in the dynamics of dieback, i.e., edaphic moisture and low rainfall. An explanation could be the higher extent of water scarcity in the soil column due to a prolonged period of aridity in areas where AWC demand is critical. In fact in the other forest groups, there are different soil properties leading to different forest types (mesophilous and thermophilous species assemblages).

Shifting focus onto grasslands, it is noteworthy that the absence of forest cover and the higher clay content in the soil leads to the presence of species of significant conservation value, not only for the species themselves but for the potential communities they can

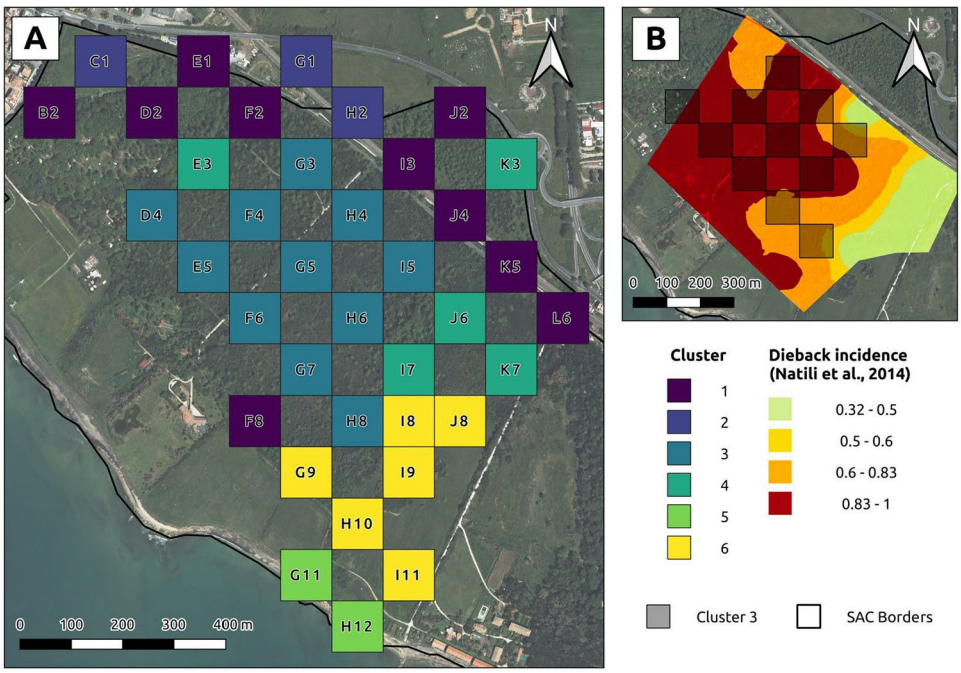


Fig. 6 **A** Representation the identified groups on the grid square used for sampling. **B** Cluster 3 plots overlapped on the dieback incidence map from Natili et al. (2014)

form. In our case, the presence of species such as *Isoëtes histrix*, *Serapias lingua*, *Mentha pulegium* is associated with clayey soils that allow for greater water retention during rainy periods. The conservation challenge stems from both the significant probability of encountering 'Mediterranean temporary ponds' (habitat 3170*), and the considerable anthropogenic disturbance, evident from the hemeroby index, and discernible due to the proximity to urban areas.

Notwithstanding its small size, Palo Laziale is a complex biotope, with heterogeneity related mainly to the fine variation of soil parameters (altitude, sand and clay percentage, AWC, Fig. 5). Sandy soils and higher areas are on average drier, whereas clayey soils and lower altitudes are on average wetter, differentiating ecological units more or less on drought tolerance. This heterogeneity drives the high diversity of the area. Details on the ecology of the six groups can be found in the appendix S2.

The study area was notably subjected to typical limiting environmental factors and human-induced pressures of the region that hamper the field investigation and the related analysis (prolonged aridity, extreme heat waves, unbalanced rainfall regimes, ineffective forest management practices, forest stands over-competition, shrub encroachment, tree mortality). The vegetation structure is nowadays hugely fragmented and uneven due to the forest dieback and the fungal infection. Other parts of the study area have been interested in a massive shrub encroachment due to the abandonment of appropriate forest management practices. Therefore, it was extremely challenging to carry out a homogenous phytosociological study of the entire area of interest.

The method of squares allowed identifying ecological types according to species presence, even when the disturbance has been so strong as to remix the vegetation completely. The approach based on the square surveys was therefore particularly suitable to identify the site's ecological units and the influence of environmental drivers. Although a complete understanding of such interrelation requires prolonged studies over time, the method demonstrated to be promising in addressing similar degraded ecosystems over the Mediterranean region. Particularly, in the case of Palo Laziale, it unconcealed several habitats and related links with site-specific factors of decline (i.e., soil water scarcity) that have not been highlighted in previous analyses. This confirms the site of Palo Laziale as an area of great conservation interest with high vulnerability.

Conclusions

Boosted by the need for restoration and conservation urged by the project LIFE PRIMED, Palo Laziale is among one of the most deeply studied Natura 2000 sites over the Mediterranean biogeographical region. A great diversity of experts from several disciplines (botanists, ecologists, zoologists foresters, naturalistic engineers, phytopatologist, etc.) have taken action and cooperated to define an Adaptative Restoration Plan. This study describes the methodologies employed to achieve the vegetation ecology studies included in the plan, reinforcing the evidence that adopting plant diversity analysis and ecological indicators is fundamental in hypothetical-deductive ecological restoration practices.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42974-024-00194-6.

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