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**HISTORY, DISTRIBUTION AND ECOLOGICAL CHARACTERIZATION  
OF OLD GROWTH FORESTS IN SARDINIA**

Scientific Disciplinary Sector

*BIO/03 Environmental and Applied Botany*

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“Le cose sono unite da legami invisibili,  
non puoi cogliere un fiore senza turbare una stella”

Galileo Galilei, 1630

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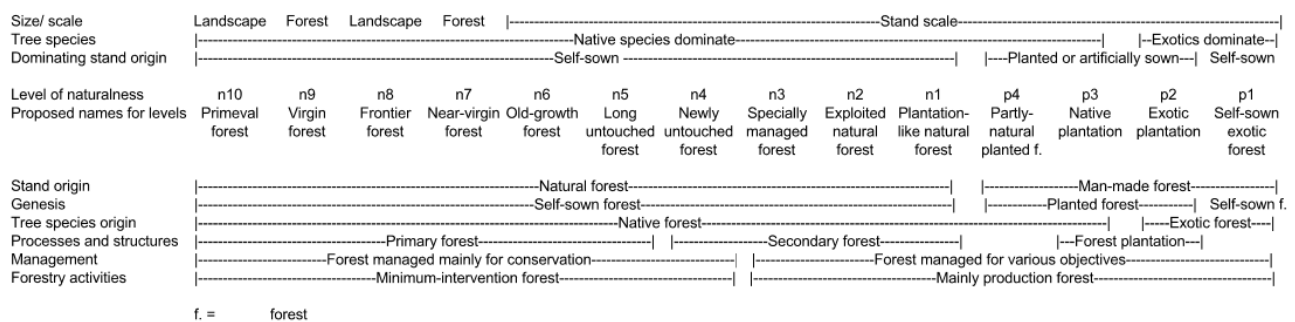
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# GENERAL INTRODUCTION

## 1.1 Preface: Definitions, structure and biodiversity of Old-growth forests

About 300 to 350 million people are living within or adjacent to dense forests and are depending on them for their subsistence and income (FAO & UNEP 2020). The culture of indigenous people, their ecological relationships with plants and animals, as well as the livelihoods, are inextricably linked to the forests. However, there are still “old-growth forests” where the human footprint is not perceptible. The definitions of what can be considered an “old-growth forest” are many and often ambiguous. Forests, whose composition and structure widely reflect natural processes, are called with various analogous terms including “primary”, “frontier”, “virgin”, “persistent” forests (Fig. 1).

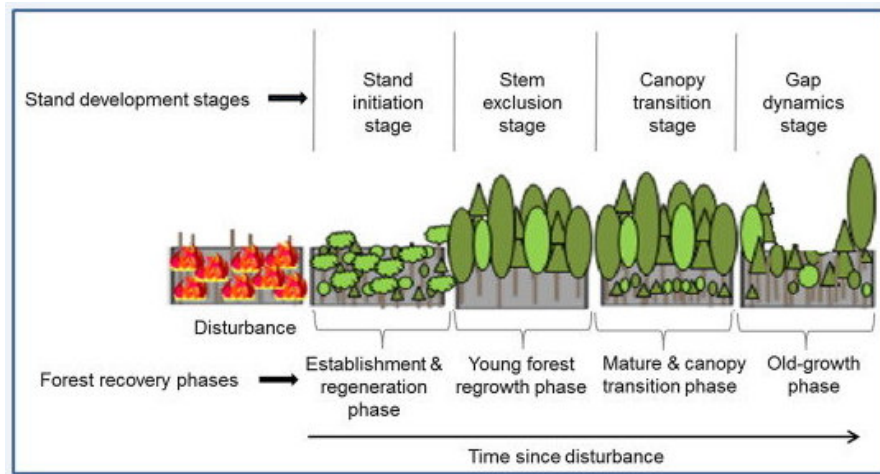


**Figure 1.** Levels of naturalness (Buchwald 2005).

The most widely used definition of primary forest is reported by the United Nations Food and Agriculture Organization (FAO 2015): naturally regenerated forest of native species, where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed. According to FAO (2015), primary forests have the following unique characteristics: “Natural forest dynamics, such as natural tree species composition, occurrence of dead wood, natural age structure, and natural regeneration processes; sufficient geographic extent to maintain natural characteristics; and in-existent significant human intervention - or the last significant human intervention was long enough ago to have allowed the natural species composition and processes to have become re-established”.

Regardless of the definitions, it is interesting to describe old-growth or primary forest in terms of intactness of structural, biological and bio-cultural characteristics (Kormos et al. 2018):

**Structurally**, on large spatial scales, the forest landscape of an old-growth forest is characterised by high complexity and heterogeneity of spatial distribution, both vertical and horizontal. The height and stratification of the canopy layer, canopy cover, presence of old trees and gaps are the consequences of forest aging and natural disturbances such as wildfires, parasites, and droughts (Chazdon et al. 2010). Old forests can be considered a mosaic where every forest successional stage is represented (Fig.2), as a consequence of chronic disturbances that allow the forest to renew itself over time (Franklin & Van Pelt 2004).



**Figure 2.** Stages of early to mature forest stand development following major disturbances (Bartels et al. 2016) adopted from Oliver and Larson (1996).

Degraded or managed forests are generally dominated by younger and smaller trees, in fragmented areas where change of land use has recently occurred;

**Biologically and ecologically**, the ecosystem of old-growth forests at different scales is very complex, generally richer in biodiversity and is made up of numerous ecological interactions (ranging from lichens to small mammals). For this reason, they are thought to have a greater degree of resilience to disturbing events compared to the felled and degraded forests (Levin 1992, Kormos et al. 2018). Native species that have evolved in these ecosystems perform fundamental processes of population regulation such as seed dispersal or predation. The exploitation and degradation of the habitat can cause the disappearance of these important species (especially those that require interior forest conditions).

Besides, recent researches have highlighted that old-growth forests, especially in the Mediterranean (Torrás & Saura 2008; Badalamenti et al. 2017), are characterised by the presence of high number of species of conservation concern for several taxonomic groups, such as bryophytes, lichens, beetles and vascular plants, which can be exclusive to such forest typologies (e.g., Jansen et al. 2009, Vicol 2016, Lelli et al. 2019); Finally, old-growth forests have an anthropological interest related to the intactness of the **"bio-cultural landscape"** where indigenous populations are part of the habitat and the dynamics of ecosystems in which they live. Under these conditions, people used to better recognise and preserve such relatively intact territories that are historically and culturally interconnected with the neighboring human settlements.

## **1.2 The importance of old-growth forest conservation**

Old-growth forests are globally declining. Their total area reported for 234 countries decreased by 31 million hectares from 1990, with a decline rate ranging from 2.5% to 1% per decade (Morales-Hidalgo et al. 2015). Around 70% of the world's forests are now within 1 km of a forest edge and are therefore subject to the degrading effects of fragmentation, which reduces biodiversity by 13 to 75% and impairs key ecosystem functions (Haddad et al. 2015). Industrial logging and road building are the principal initial causes of primary forest degradation and fragmentation (Laurance et al. 2009). Industrial agriculture, conversion of forests for food production, mining, oil and gas extraction, harvesting woody biomass for energy are increasing in all forest biomes (Ferarnside 2005).

Old-growth forests are the most biodiverse terrestrial ecosystems on the planet (Kormos et al. 2018). Huge centuries-old trees, the presence of dead trees standing and on the ground, shady places covered by mosses and mushrooms are, in our imagination a typical landscape of an old-growth forest. Preserving biodiversity linked to old-growth forest environments also means not losing parts of ecosystem functions (e.g. saproxylic insects for the wood detritus chain). Moreover, there are other important reasons why it is essential to preserve these landscapes. Forests in the later stages of the succession (> 200 years) and old-growth forests up to 800 years, are considered to be carbon sinks and their capacity to mitigate CO<sub>2</sub> emissions is crucial (Luyssaert et al. 2008, Pan et al. 2011). Most of the terrestrial carbon is stored in forests and, in particular, old-growth forests contain between 30% and 70% more carbon than degraded forests (Mackey et al. 2014). Estimated emissions from deforestation represents at least one tenth of annual greenhouse gas emissions, i.e. > 1 billion tons of carbon (or 3.67 billion tons of CO<sub>2</sub>) each year (Le Quéré et al. 2015). The European Commission released a new "Biodiversity Strategy for 2030", which has among its objectives to legally protect at least 30% of the land area of the EU, including all the primary and ancient forests still existing, highlighting the importance of defining, mapping, monitoring and strictly protecting them (European Commission, 2020).

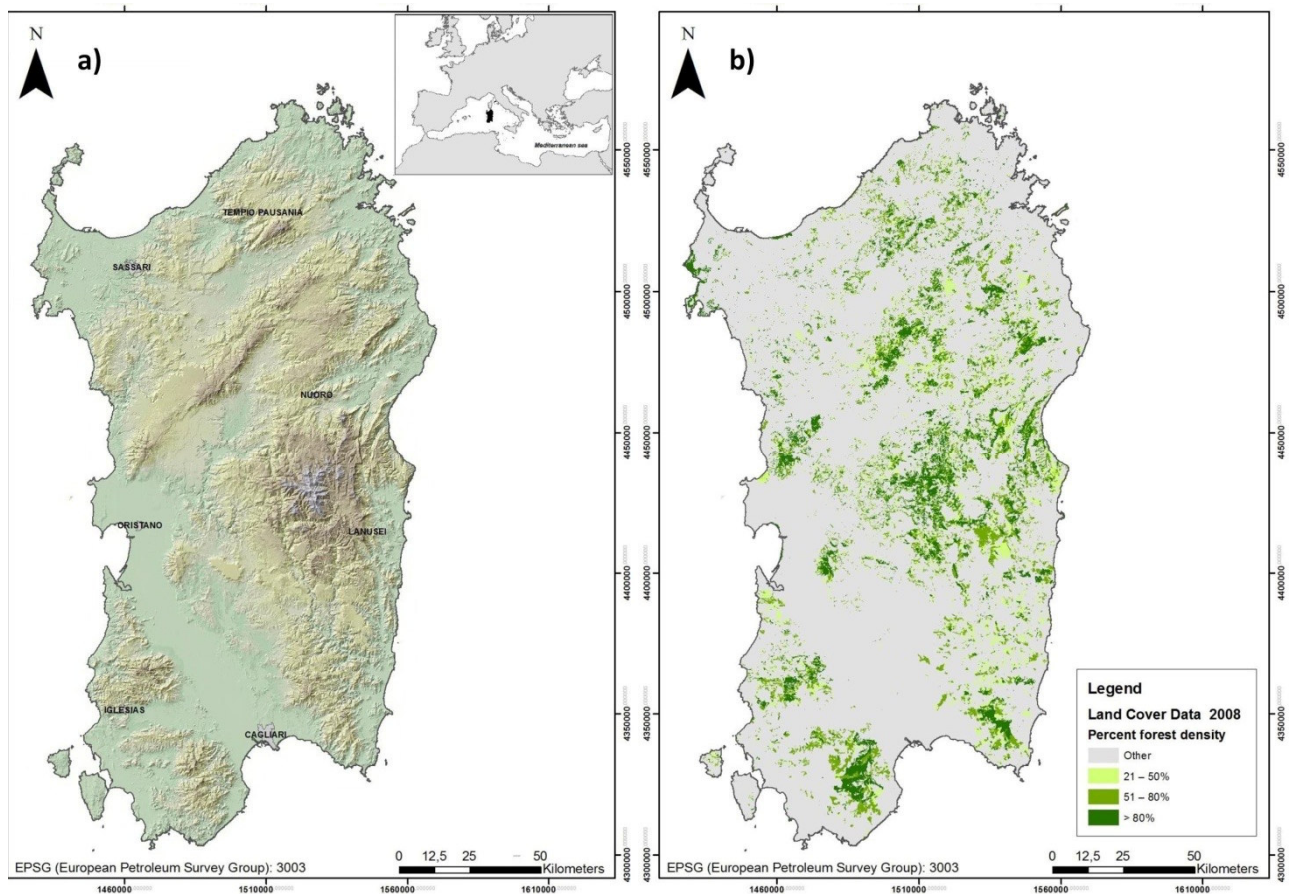
## **1.3. Study area: Sardinia**

Italy ranks sixth in the ranking of European countries with the largest forest area with a coverage of 5% of the total European forests and 34% of the total national area (Pupo D'Andrea & Romano 2014). Historically, Italian forests have always been subject to the influence of anthropic activities, but since the early 1800s the strong demand for materials and energy from the rising industries has caused the intensive exploitation of forests. Only forest communities that have been left to natural evolution could reach the maximum stage of development, structural heterogeneity and age.

The reference area of this study is the island of Sardinia, Italy (Fig.3a). Sardinia is located in the central-western part of the Mediterranean Basin and, together with Corsica and the Tuscan Archipelago, it constitutes an independent biogeographical province (Fenu et al. 2014). Its climate is typically



Mediterranean, with dry and hot summers and relatively rainy and mild winters. For the high concentration, even equal to 50%, of endemic species (especially vascular plants and insects), it is part of the biodiversity hotspot of global (Tyrrhenian islands) and regional (Sardinia) importance, namely “macro” and “meso” hotspots (Medail & Quezel 1997, Bacchetta et al. 2012, Cañadas et al. 2014). Forests in Sardinia mainly consists of holm oak (*Quercus ilex* L.) and cork oak (*Quercus suber* L.) evergreen forests and forests of deciduous oak woods (*Quercus* sp.pl.), with a wide ecological range and a widespread distribution throughout the island, from coastal areas up to 1750 m above sea level (Bacchetta et al. 2004a, Bacchetta et al. 2004b, Bacchetta et al. 2009). Furthermore, particular soil-climatic conditions support the instauration of mesophilic and edafoxerophilous woods (e.g. *Taxus baccata* L., *Ilex aquifolium* L., *Ostrya carpinifolia*, Scop. *Juniperus* sp. pl.) which make the island very diverse in this aspect.



**Figure 3.** (a) Study area of Sardinia and (b) percent forest density

The landscapes and woods of the island of Sardinia have historically been a valuable resource of goods exploited by the populations and colonisers that succeed over the centuries. Starting from the Phoenicians (9<sup>th</sup> century BC), the Carthaginians, and the Romans exploited the island for agriculture, firewood (charcoal) and timber harvesting. The increasing demand for charcoal during the industrial revolution of the 19<sup>th</sup> century resulted in the massive exploitation of the island and its deforestation. The subsequent introduction

of sheep monoculture and the consequent use of fire to create pastures have definitively changed the landscape of the island (Pungetti 1995, Caterini 2013).

Sardinia reflects the significant increase in the forest area (Fig.3b) that has been going on in all Italian regions during recent decades. Particularly in the period from 2005 to 2015 the forest areas estimated from national forest inventories increased by around 28,000 ha (Gasparini & Marchetti 2019). Nevertheless, only a small percentage of the original forest heritage was saved from the last deforestation that began in the early nineteenth century and continued until more than half of the twentieth century. It has been estimated that the forests of Sardinia have decreased by at least 4/5 during the nineteenth century, dramatically changing the landscapes of the entire island both from a naturalistic and anthropological point of view (Caterini 2013). The image that the ancient travelers of a fertile, thriving island, rich in forests and waterways gave us contrasts sharply with the description provided by the geographers of the early decades of the 1900s, who describe Sardinia as an arid, poor, dry and woodless island (Le Lanneau 1941). Nowadays, the island retains fragmented stands of old-growth forests. From historical information, it is clear that the limited areas of old-growth forests persisted in morphologically impervious and sparsely inhabited places. Such places are far from the main communication routes, so clearing the wood, and raising or producing coal was difficult and economically disadvantageous. Moreover, it was difficult for fires to reach them. In the present time, few stands within the boundaries of the former Gennargentu National Park and the Gutturu Mannu Regional Park have already been recognised as sites with old-growth features (Burrascano et al. 2009, Marchetti & Blasi 2010) and, more recently, defined and mapped as long untouched forests (Sabatini et al. 2018). Based on current knowledge, old-growth forests in Sardinia were highlighted as areas where restoration is needed and feasible (Sabatini et al. 2020). However, a complete knowledge of the consistency, distribution, structure and types of ancient forests is still not available in Sardinia. Furthermore, there is no comprehensive information on their conservation status and any threat that might affect them.

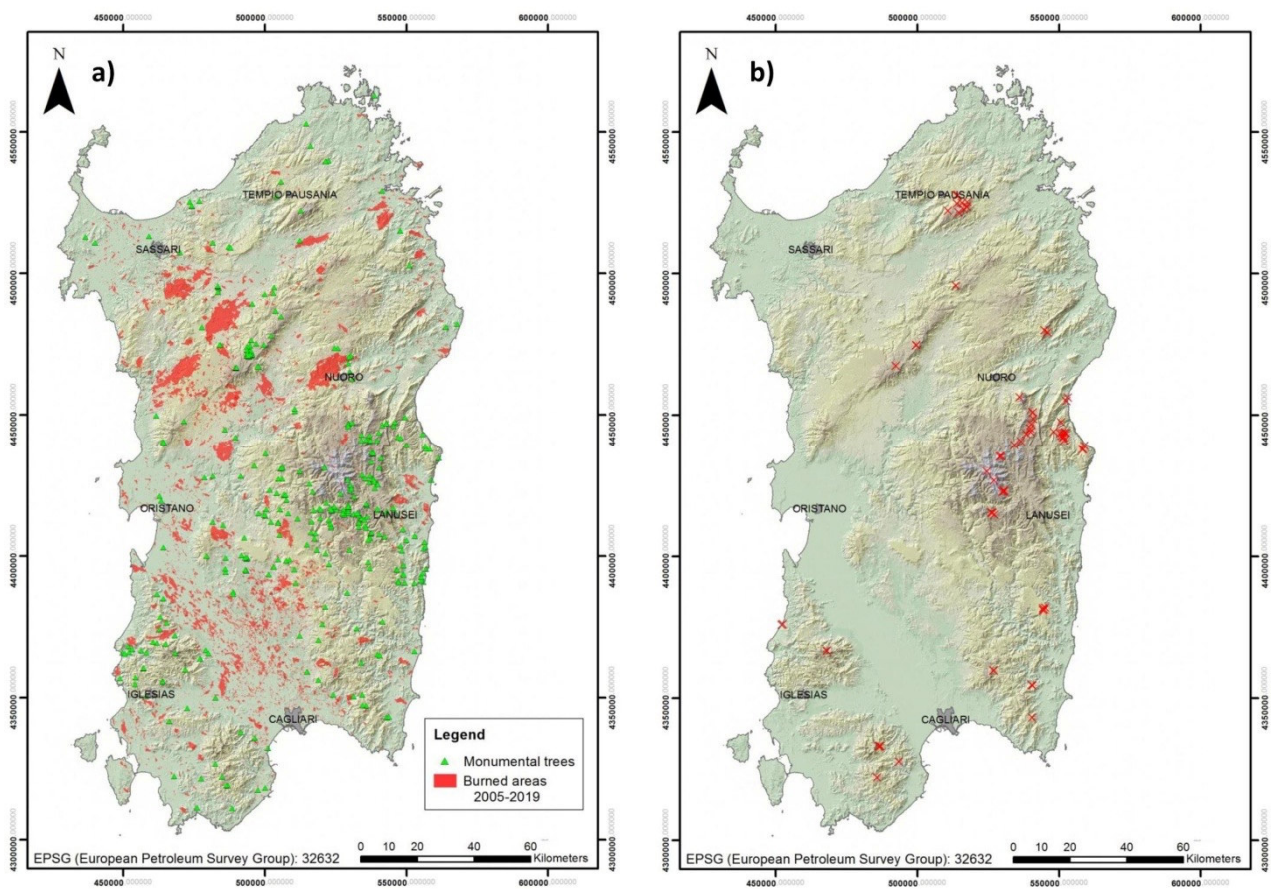
#### **1.4 Research objectives and structure of this thesis**

The objectives of the thesis were to:

1. improve the knowledge of the distribution and structural characteristics of old-growth forests in Sardinia;
2. quantify their structural heterogeneity and evaluate its variation across biological, environmental or human-related factors;
3. establish their degree of protection from wildfire hazard;

During the first months of the study, the work was focused both on the literature search on existing knowledge about the geographical distribution of Sardinian old-growth forests. This was possible through a GIS cartographic study which, through the photo interpretation and analysis of geographical information made available by the public administration of Sardinia ([www.sardegnaeoportale.it](http://www.sardegnaeoportale.it)), like burned areas or

presence of monumental trees (Fig.4a), provided a first indication of the potential presence/absence of old forests. Furthermore, in the first year of the study, expert knowledge of old-growth forests in Sardinia was collected through a reporting questionnaire that was submitted to about 50 managers of Sardinian forests and researchers. A following survey campaign was carried out in spring-summer of 2019 in order to verify all the gathered information. A first screening in the field allowed to verify the presence of dead wood, large trees, and negligible signs of recent human presence of each stand indicated in the questionnaires. Finally, 68 plots of 530 m<sup>2</sup>, distributed over the whole island, were sampled. Plots were often located in the most difficult and inaccessible areas of Sardinia (Fig.4b). The collected data was thus processed and used for the development of the entire thesis.



**Figure 4.** (a) Monumental trees and burned areas and (b) location of surveyed plots

**In chapter 1**, a structural index was developed in order to quantify the heterogeneity of forest stands in an objective way, to statistically evaluate the relationship of the index with biological, environmental or human-related factors (Fig.5a, 5b).



**Figure 5.** (a) Dead wood and (b) measurement of trees' circumference

**In chapter 2**, the relationship between the presence of great longhorn beetles (parasitic and saproxylic beetles that play an important role as ecosystem engineers, Fig. 6) and biologically related structural parameters of old-growth holm oak forests, were investigated.



**Figure 6.** (a) and (b) The Great Capricorn beetle, *Cerambyx cerdo*

**In chapter 3**, analyses based on GIS environment were performed. These allowed the researcher to identify which old-growth stands are included in the regional protection network. In addition, a visibility analysis of the network of fire lookouts (Fig.8) was used to complement the fire risk-status level of old-growth forests.



**Figure 7.** Fire lookout “Montiferru” Cardedu (NU). Author: Giovanni Lotto, image downloaded from [www.sardegnaforeste.it](http://www.sardegnaforeste.it)

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## **CHAPTER I - Structural heterogeneity and old-growthness: A first regional-scale assessment in Sardinia**

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## **Abstract**

Mediterranean forests have been altered by several human activities. Consequently, relatively intact forests that have been unmodified by humans for a relatively long time (i.e., old-growth forests) are often reduced to isolated and fragmented stands. However, despite their high conservation value, little is known about their features and even presence several Mediterranean areas. First steps of their investigation are based on the identification of old-growth features such as amount of large size and old trees, tree species composition, canopy heterogeneity, occurrence and amount of deadwood. The Structural Heterogeneity Index (SHI) is commonly used to summarise features of old-growthness in one single value. Here, the SHI was derived for 68 plots included in 45 forest stands within the 4,297 km<sup>2</sup> of territory that is covered by forests in Sardinia. SHI values were affected by variables that are likely to be related to forest age and structural complexity, such as presence of cerambycids, canopy cover, forest layers, location and three old-growthness classes. Results confirm a high structural variability, ranging from 25.6% to 76.6%, among forests with old-growth features, determined by the presence, or lack, of given living and deadwood features. Our findings identified, for the first time, most of the forest stands that need special protection in Sardinia for the presence of old-growth features. In this sense, the SHI was confirmed useful for improving their management and conservation, although more specific and deeper studies are necessary for better understanding their species composition and dynamics.

**Keywords:** old-growth forests, forest structure, forest naturalness, forest conservation, Mediterranean basin, Structural Heterogeneity Index.

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## 1. Introduction

Forest ecosystems have been subject to human exploitation for millennia, since the establishment of the first agricultural societies in the mid-Holocene, mainly for fuel wood production, food, cropland, pasture, and construction materials (Parviainen 2005, Kaplan et al. 2009). The impact is more pronounced where the stable presence of humans is historically documented, like in Europe and especially in the Mediterranean Basin (Grove & Rackham 2001). Despite being one of the most threatened by current changes (Gauquelin et al. 2018), plant diversity in the Mediterranean Basin is still high, primarily as a result of habitat diversity (Fois et al. 2017). Among them, thermophilous deciduous, broadleaved evergreen and coniferous forests and woodlands represent a wide range of habitats of conservation concern in the Mediterranean (Gauquelin et al. 2018). In this context, human disturbance has, among others, caused simplification of forest structure, changes in plant composition, abundance and distribution (Blasi et al. 2010, Abadie et al. 2018). Moreover, forest conversions into managed systems have been proven to decrease the capacity of storing carbon below ground due to simplification of foliage and root litter inputs (Błonska et al. 2020).

A long-lasting history of land use has reduced forests without visible human interventions to cover in Europe about 0.25% of land (Sabatini et al. 2018). This is particular evident in the southern shore of the Mediterranean Basin, where forest degradation, mainly as a result of intensive wood collection and livestock grazing, is still intense and leads to their fragmentation or disappearance (Gauquelin et al. 2018) or in countries, like Italy, where forest structure since Roman times has been greatly influenced by man (Chiavetta et al. 2012). Exotic trees species such as *Pinus* spp., *Eucalyptus* spp. and *Acacia* spp. have been largely used to restore degraded Mediterranean ecosystems, which are now modifying the natural structure and composition of plant cover and the vegetation successions (Gauquelin et al. 2018). This situation is even exacerbated in the southern Mediterranean by global warming, which is expected to result in increased frequency, intensity and duration of drought, heat stress and wildfires (Cardil et al. 2014, Gauquelin et al. 2018, Arar et al. 2020).

Naturally regenerated forests of native species, where there are no clearly visible signs of human activities and ecological processes are not significantly disturbed, are generally called primary forests (FAO 2015). These often isolated primary forest stands recover compositional, structural and functional features and can be also defined old-growth forests or long untouched forests (Buchwald 2005, Chirici & Nocentini 2013). As a forest ages, peculiar structural features develop, for instance through the accumulation of high quantities of large trees and deadwood, which determines an increase in general complexity (=heterogeneity) of the forest structure (Burrascano et al. 2018). Besides being extremely complex in structure (Motta et al. 2015), recent researches has highlighted that old-growth forests, especially in the Mediterranean, are characterised by hosting an especially high number of species of conservation concern for several taxonomic groups such as invertebrates, bryophytes, lichens, and vascular plants (Janssen et al. 2009, Brunialti et al. 2010, Vicol 2016). However, the response of biodiversity to the cessation of management remains in many aspects unclear, due to the interdisciplinary and time-consuming efforts required, joined to site-specific socio-ecological features that differently drive forest dynamics in different contexts (Paillet et al. 2010, Burrascano et al. 2018).

Due to the low knowledge level about such old-growth forests and woodlands in several Mediterranean landscapes, first steps towards their understanding focus on indices or proxies of “old-growthness”. Structural components of forests are often used for the relative simplicity in measuring, calculating and interpreting their variability (McElhinny et al. 2006, Sabatini et al. 2015). Among forest features that have been used to rank the old-growthness of forests and stands, the most common are: occurrence and amount of large size and old trees, tree species composition, canopy heterogeneity, occurrence and amount of deadwood, lack of human disturbance, and gap dynamics (Burrascano 2010, Ziaco et al. 2011). Because no one single proxy indicator is able to be a measure of old-growthness alone, various indices have been elaborated in order to summarise various forest characteristics in one single value (Storch et al. 2018). Ideally, this would allow a quantification and comparison of old-growthness of different stands and provide an indication of their potential contribution to biodiversity (Parkes et al. 2003). Measures of structural complexity were elaborated in several contexts (e.g., McElhinny et al. 2006, Sabatini et al. 2015); these were based on a core of attributes collected from standardised plots arranged within each stand. Each attribute is quantified proportionally to the observed level and combined with others through an additive index. The rationale of this approach is that forest ecosystems containing stands with a variety of structural components are considered likely to have a variety of resources and species that utilise these resources. In fact, there is often a positive correlation between elements of biodiversity and measures of the variety and/or complexity of structural components within forest ecosystems (McElhinny et al. 2006, Parisiet al. 2016).

In the Mediterranean Basin, Amici et al. (2013) showed that light-demanding species richness decreased with increasing successional age of forest. Plant species in old-growth forests are often specialists, with short distance dispersal mechanisms and no persistent soil seed bank, which makes them more vulnerable to forest habitat loss (Burrascano et al. 2009, Campetella et al. 2016, Abadie et al. 2018). Saprobic fungi diversity is often particularly high in temperate and boreal old-growth forests (Ohlson et al. 1997), even though this was not confirmed in drier conditions, like in Corsica, where ectomycorrhizal fungi were dominant (Richard et al. 2004). Also, some lichens, such as *Lobaria pulmonaria* (L.) Hoffm., *Antitrichia curtispindula* Bridel-Brederi, and *Homalothecium sericeum* (Hedw.) Schimp. (Brunialti et al. 2010), and invertebrates, like *Cerambyx cerdo* L. (Casula 2017), are found as indicators of old-growth features in Mediterranean forests. Despite such a kind of promising results, compared to temperate contexts, old-growth forests have been much less explored in the Mediterranean (Abadie et al. 2018). Patched and uncomplete information is present at this scale, and exhaustive literature on old-growth dynamics and features is available for only few Mediterranean territories, such as the Cilento, central Italy or eastern Pyrenees (e.g., Marchetti et al. 2010, Lombardi et al. 2015, Fortuny et al. 2020).

Such first-step research work, towards a knowledge improvement about old-growth forests, is therefore needed in Sardinia, the second largest island of the Mediterranean Basin. Although a recent increase in forest cover occurred mainly due to the spontaneous colonisation of marginal agricultural areas, following the abandonment of crops (INFC, 2015), the extension of old-growth forests in Sardinia was estimated to be considerably reduced during the nineteenth century, mainly due to deforestation, subsequent livestock,

coupled with fire to maintain pastures (Pungetti 1995, Caterini 2013). Nonetheless, several small and scattered stands remained untouched in remote mountainous areas of the Island. Despite their high conservation value, there is not much knowledge about the distribution, composition, structure and function of the residual fragmented stands of old-growth forests in Sardinia (hereafter forest stands). In this study, our goals were thus to: i) identify forest stands with old-growth features in Sardinia and evaluate their degree of structural heterogeneity; ii) investigate how the structural heterogeneity index varies across biological, environmental or human-related factors; iii) identify strengths and limitations of the structural heterogeneity index as an informative tool for the conservation and management of Mediterranean old-growth forest.

## 2. Materials and methods

### 2.1 Study area

The reference area of this study is the island of Sardinia (Fig. 1), the second Mediterranean island after Sicily by extension, with a surface area of about 24,090 km<sup>2</sup>. Sardinia is located in the central-western part of the Mediterranean Sea and, together with Corsica and the Tuscan Archipelago, it constitutes an independent biogeographical province (Fenu et al. 2014). The island is under populated compared to other Italian and European regions: it has a population density of 68 inhabitants per km<sup>2</sup>, compared to the average of 200 people per km<sup>2</sup> for Italy (ISTAT 2019). Around 40% of Sardinians live in urbanised areas in the North of the island (Sassari) and in the South (Cagliari).

The mountainous inland areas of Sardinia are still relatively isolated and sparsely populated where the island preserves many natural environments with difficult access, partly wild and relatively well preserved (Fois et al. 2019). For the high concentration of endemic species (especially plants and invertebrates), it has been identified as a biodiversity hotspot of global and regional importance (Biondi et al. 2013, Fois et al. 2018).

Forests in Sardinia have been estimated to cover a surface of 4,297 km<sup>2</sup> (Puddu et al. 2012), which mainly consists of holm oak (*Quercus ilex* L.) and cork oak (*Quercus suber* L.) evergreen forests and forests of deciduous oak woods (*Quercus congesta* C. Presl and *Q. ichnusae* Mossa, Bacch. & Brullo), with a wide ecological range and a widespread distribution throughout the island, from coastal areas up to 1400 m above sea level. These formations constitute a wide range of potential climax forests, some of them endemic to the island, such as the *Glechomo sardoae-Quercetum congestae* or the *Prasio majoris-Quercetum ilicis quercetosum virgilianae* (Bacchetta et al. 2004a,b, 2009). Furthermore, particular soil-climatic conditions support the instauration of several formation types, which make the island very diverse in this aspect. One of the most interesting examples are relic yew (*Taxus baccata* L.) forests, which can be found mainly in the central-northern sectors of Sardinia, often limited to gorges or high slopes, in soils often rich in skeleton (Farris et al. 2012). Other potential natural forests are summarised in Bacchetta et al. (2009) and are represented, in peculiar soil-climatic conditions, by formations of hop hornbeam (e.g., *Cyclamino repandi-Ostryetum carpinifoliae*), junipers (e.g., *Chamaeropo humilis-Juniperetum turbinatae*), phillyreas (e.g., *Prasiomajoris-Quercetum phillyretosum latifoliae*) and olive trees (e.g., *Asparagoalbi-Oleetum sylvestris*).

Riparian forests are mainly constituted by black alders (*Alnus glutinosa* (L.) Gaertn.), willows and poplars (*Salix* spp. and *Populus* spp.), tamarisks (*Tamarix* spp.) and oleanders (*Nerium oleander* L.). Planitial woods of silver poplars (*Populus alba* L.), raywoods (*Fraxinus oxycarpa* Willd.) and field elms (*Ulmus minor* Mill.) are also present in few and small alluvial planes.

## **2.2 Selection of study forest stands**

The investigated forest stands were identified through a questionnaire sent to local experts from research institutes universities and public forestry agencies. Forest stands were reported by indicating the location and describing main forest characteristics, including the presence of large old trees, dead wood, and presence human disturbance. The full questionnaire is available on supplementary material (Appendix, supplementary Fig.1). Each stand was considered to be inventoried or not, after a first screening in the field of the following features: presence of dead wood, large trees, and negligible signs of recent human presence. In other words, the forest stands reported in the questionnaires that showed clear signs of management, like pure coppices, were not inventoried.

## **2.3 Variables selection and collection**

The selected forest stands were sampled following methods described in the National Inventory of Forests and forest Carbon reserve INFC 2015 (Gasparini et al. 2016). Within each surveyed stand, circular plots of 13 m radius (approx. 530 m<sup>2</sup>) were positioned. Such plot surface was considered as enough for providing a reliable inventory in old-growth forest conditions (Lombardi et al. 2015).

The sampling effort (i.e., number of plots per stand) was determined by the need to survey the most representative as possible number of stands reported by the questionnaires on a regional scale. Random plots within each old-growth stand were positioned as following: hiking tracks were walked and, once inside the old-growth stand, a random direction was selected and a constant distance of about 100 m walked to reach the centre of the plot. In very small stands, this distance was reduced to 50 m to avoid old-growth forest edges. In any case, plots were positioned at least 100 m from edges. At least one plot per each reported forest stand was surveyed and, where forest stand was suitable and topography allowed it (i.e.time to reach localities, accessibility, forest stand extension), up to 10 plots per stand and four plots per day were investigated.

In each plot, the following parameters were considered: heights of all live trees, with a minimum diameter of 9.5 cm at breast height (DBH), were measured with a Blume-Leissipsometer for an as much as possible number of individuals and at least for 10% of the total number. These were used as standard comparison for measuring the remaining trees. Length and diameters (minimum, maximum and average) of the three different kinds of deadwood (deadwood debris, stumps and standing dead trees) were recorded, as well as their decay level according to the 1-5 scale proposed by Hunter (1990). Deadwood debris on the ground was measured with a minimum diameter  $\geq 9.5$  cm. The volume was calculated according to Huber's formula (Fridman&Walheim2000):

$$V(m^3) = S_{0.5} \times h$$

where  $S_{0.5}$  is the median sectional area,  $h$  = length. We considered as stumps the truncated stems at a height of less than 1.30 m from the ground, whose diameter on the cutting plane is equal or greater than 9.5 cm. The volume of stumps was computed by equation:

$$V(m^3) = \pi \times h/3 \times [(D/2)^2 + (d/2)^2 + (D/2) \times (d/2)]$$

where  $V$  is the volume;  $h$  is the height;  $D$  is the maximum diameter, and  $d$  is the minimum diameter (Lombardi et al. 2013).

Since no volume tables are available, the estimate of the volume of live trees was performed using the model tree method, applying the general equation of standing trees for each plant:

$$V(m^3) = D^2 \pi / 4 \times H \times F = G \times H \times F$$

In which  $D$  is the diameter with bark measured at 1.30 m from the ground,  $G$  is the basal area and corresponds to the surface of the cross section at 1.30 m,  $H$  is the estimated height of the plant and  $F$  is the reduction coefficient. The reduction coefficient ( $0 < F < 1$ ) can be calculated exactly only on felled plants which are the model trees. As this is not foreseen in our study, it was estimated based on a representative sampling of the average shape of one or more plants of the stand (Berneti & La Marca 1983).

Data collected in the field and derived in the laboratory (26 structural variables) were used for the elaboration of an index of structural heterogeneity (Table 1). These variables comprise those commonly found in national forest inventories and reported in the literature of old-growth forests and forest structural complexity (McElhinny et al. 2005, Sabatini et al. 2015).

Other indicators of old-growthness, such as number of hollow trees (Lindenmayer et al. 2000, McElhinny et al. 2006, Rozas 2006), the type of layering of the canopy (single, double, multi) (Franklin & Van Pelt 2004), the percentage of canopy (Jennings et al. 1999, Franklin & Van Pelt 2004) and lichen-muscinal covers (Lesica et al. 1991, Ódor & Standovár 2001) were also recorded. Furthermore, the presence of the large longhorn beetles (*Cerambyx cerdo*, *Aegosoma scabricorne* (Scopoli) and *Prinobius myardi* Mulsant), generally associated with mature trees and aging forests (Parisi et al. 2016, Casula 2017), was also recorded. This was established by searching for exit holes of longhorn beetle adults (larger diameter of about 20 mm) in the lower part of the trunks. The presence of livestock grazing was evaluated by the searching for faecal material, presence of grazing signs and by interviewing local people. Finally, forest types were defined based on the relative dominance (basal area) of the recorded tree species. Mixed forest stands were those without a species representing more than 75% of the total basal area. Such mixed stands were defined by species representing at least 25% of the total basal area (Gauthier et al. 1996).

**Table 1.** Variables identified measured (M) and estimated (E) in the field or derived (D)

n	Code	Variable description	Data typology
1	BA	Basal area (m <sup>2</sup> /ha)	D
2	BASnagST	Basal area of standing dead trees and stumps (m <sup>2</sup> /ha)	D
3	CC	Canopy cover (%)	E
4	CWD	Coarse woody debris volume (m <sup>3</sup> )	D
5	DensNLiv	Living trees density (per ha)	D
6	DensStuDW	Standing dead trees including stumps density (per ha)	D
7	Dw/Liv	Deadwood/living wood volume ratio	D
8	Dwtot	Total deadwood volume (m <sup>3</sup> )	D
9	GSDBH	DBH diversity (calculated using the Gini-Simpson index)	D
10	QMDDBH	Quadratic mean DBH	D
11	HM	Maximum height (m)	E/D
12	Hm	Average height (m)	D
13	Hsd	Height standard deviation	E
14	Lam	Lichens and mosses layer (%)	E
15	LenghtCWD	Total length of coarse woody debris (m)	M
16	Liv	Living trees volume (m <sup>3</sup> )	E
17	NDBH	Number of diameters classes	M
18	NDC	Number of decay classes occurring in the plot	M
19	NHt	Number of hollow trees	M
20	NstuStDW	Number of standing dead trees including stumps	M
21	RDBH	Range of diameters distribution	D
22	STDw	Standing dead trees volume (m <sup>3</sup> )	D
23	STUMPS	Stumps volume (m <sup>3</sup> )	D
24	STUStDw	Standing dead trees including stumps volume (m <sup>3</sup> )	D
25	T>40	Number of living trees with dbh> 40 cm	M
26	TreeRich	Tree species richness	M

#### ***2.4 Elaborating and evaluating the Structural Heterogeneity Index (SHI)***

A simplified structural index was elaborated according the methodology developed by McElhinny et al. (2005) and Sabatini et al. (2015). The number of variables was reduced from 26 to eight, identifying a single attribute that best represented each of the eight categories of complexity recognised for the old-growth forests in Italy (Sabatini et al. 2015): (1) vertical heterogeneity (VH); (2) compositional diversity (CH); (3) uneven agedness (UA); (4) density of large living trees (LLT); (5) growing stock (GS); (6) total deadwood volume (DW-TOT); (7) deadwood decay classes (DW-DC); (8) standing deadwood, dead trees and stumps (DW-ST).

Each of the eight variables was selected according to the following criteria: (1) to have a kurtosis < 2, in order to avoid attributes with a non-normal distribution and a low discrimination ability: for those attributes that showed a high Kurtosis value (> 2), their distribution was corrected through the logarithmic or the

square root transformation; (2) to be not correlated with other attributes: strengths of correlation were estimated by Spearman correlation coefficients. Accordingly, the number of attributes was reduced by choosing only one among those having a correlation coefficient  $< 0.50$ ; (3) to have the highest as possible contribution of variations retained by two principal components PC1 and PC2. Principal component analysis (PCA) was made in R (ver.R-3.6.1) using R PackageFactoMineR version 1.34 (Le et al. 2008). Total contribution of each variable on explaining the variations retained by the two principal components was calculated by using R package factoextraversion 1.0.5 (Kassambara et al. 2017). Among the correlated variables with a Kurtosis values  $< 2$ , the variable showing the higher contribution of variation was retained; (4) to have good field sampling efficiency: following the example of Sabatini et al. (2015), each attribute was classified in three sampling efficiency classes, 1 (low), 2 (medium) and 3 (high). Attributes with higher values were preferred. Kurtosis values were calculated in Microsoft Excel 2013, while the rest analyses were carried out in R environment Version 3.5.2 (R Core Team 2018).

A score ranging from 0 to 10 was assigned to each one of the eight retained variables. We first set a score of 2.5, 5, 7.5 and 10 to the quartile midpoints (corresponding to the 12.5, 37.5, 62.5 and 87.5 percentiles, respectively) of the raw attribute distribution. Then, a linear regression through quartile values was fitted to ensure that the attribute scores were evenly distributed between 0 and 10. This regression equation was used to associate a score with each observation (Table 2). Finally, a Structural Heterogeneity Index (SHI) was obtained by summing the scores in the range 0-10 assigned to each variable in the core set, and then expressed as a percentage.

**Table 2.** Regression equations used to assign a score to attributes on a scale of 0-10.

Structural indicator	Regression equation	R <sup>2</sup>
Hsd: Height standard deviation	$y = 1.010x + 1.720$	R <sup>2</sup> = 0.838
TreeRich: Tree species richness	$y = 1.446x + 1.821$	R <sup>2</sup> = 0.939
DensNLiv: Stem density, LOG+1	$y = 7.789x - 15.23$	R <sup>2</sup> = 0.937
T>40: Number of living trees with DBH>40cm	$y = 0.535x + 0.892$	R <sup>2</sup> = 0.900
BA: Basal area, LOG	$y = 9.368x - 12.30$	R <sup>2</sup> = 0.896
Dw/liv: Deadwood/living wood volume ratio, RAD	$y = 9.281x + 2.316$	R <sup>2</sup> = 0.886
LenghtCWD: sum of lengths of every coarse woody debris piece, LOG+1	$y = 4.436x + 2.014$	R <sup>2</sup> = 0.930
DensStuDW: Density of standing deadwood, LOG+1	$y = 2.790x + 2.106$	R <sup>2</sup> = 0.945

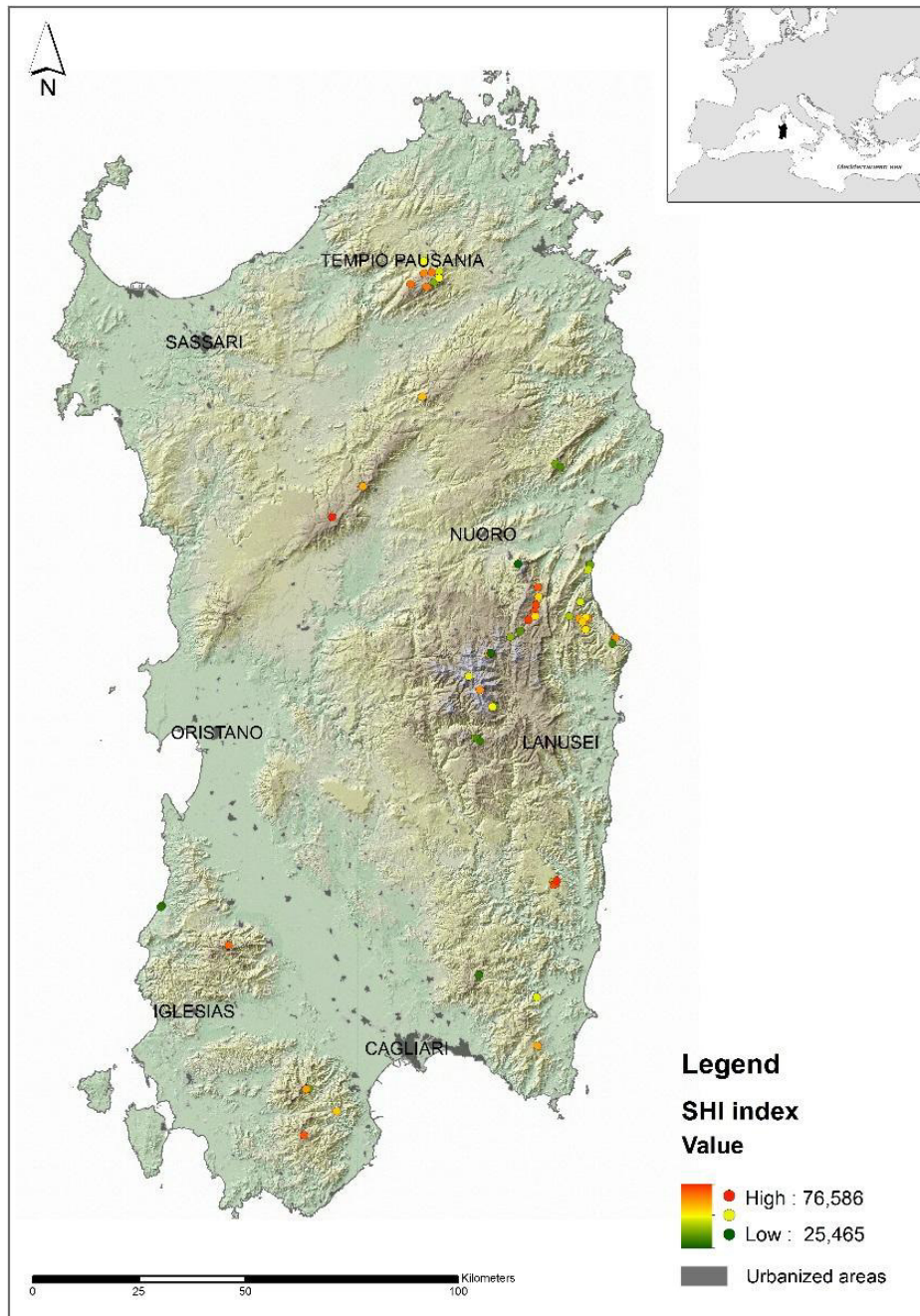
To evaluate the descriptive capacity of the SHI, it has been related to variables that are likely to be related with forest age and structural complexity, such as presence of cerambycids (higher presence associated with mature forest), canopy cover (higher canopy cover in older forests), forest layers (higher complexity of layers in mature forests), grazing (lower structural heterogeneity in forest with regeneration strongly affected by grazing) and location (easy coastal access favours the economic exploitation of the wood and the drier climate slows down its growth). Moreover, each site was classified according to the three old-growthness classes proposed for different types of Sicilian forests (Badalamentiet al. 2018). Such classification was



based on field measurements of four internationally recognised indicators of old-growthness: deadwood, tree size, structural characteristics and tree species richness. In particular, for the proxy indicator “deadwood” was assigned a score ranging from 0 to 2 based on the total volume of dead tree values (DW) and the number of decay classes (DC): 0 for  $DW \leq 0.09$ , 1 for  $0.09 < DW \leq 0.5$ , and 2 for  $DW > 0.5$ , attributing one class higher if  $DC \geq 4$ . For “structural characteristics”, was assigned a suitability (1/0) based on the type of coverage (single, double or multi), on the value of the standard deviation and on the range of diameters. Also, for “tree size” and for the “tree species richness” was assigned only the suitability (1/0), based on the presence of trees with  $DBH > 40$  cm and on the number of species detected, respectively. On the basis of these 0-5 scores, each site was classified into three classes of old-growthness, as high (H, with scores  $\geq 4$ ) medium (M, with scores = 3) and low (L, with scores  $< 3$ ). Differences among all the above-described characteristic parameters were graphically represented by box plots and tested using Kruskal-Wallis rank sum tests for pairwise comparisons and Dunn’s test for multiple comparisons.

### **3. Results**

After field surveys, eight areas reported by questionnaires were excluded, as they showed clear signs of forest management. Accordingly, a total of 68 plots included in about 45 forest stands were selected for this study. Most of these plots (67.7%) were in central-northern Sardinia (Fig.1), while five plots each were sampled in the South-East and South-West side of Sardinia.



**Figure 1.** Plots distribution map and SHI values.

Two different forest types were mostly represented in this study: pure or mixed forests with *Quercus ilex* (42) and pure or mixed forests with *Taxus baccata* (15). Eleven plots were representative of persistent formations dominated by *Juniperus* sp.pl. (n= 5), *Phillyrea latifolia* L. and *Arbutus unedo* L. (n=2, each), and *Quercus congesta* and *Alnus glutinosa* (n=1, each). See supporting information (Appendix, supplementary Tab. 1) for further details.

Eight structural indicators were identified (Table 3). The basimetric area (BA) and the density of standing deadwood (DensStuDW) were the most contributing variables. The reliability of these variables was confirmed by their high sampling efficiency.

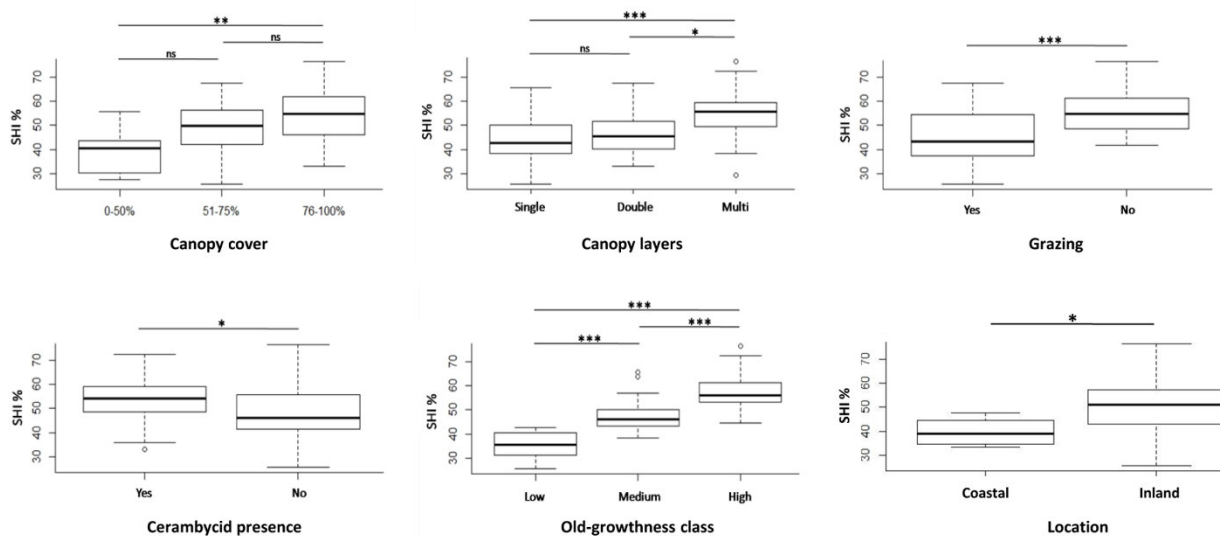
**Table 3.** List of categories of structural complexity and the corresponding identified structural indicators with selection criteria. (BA): Basal area; (RDBH): range of diameter distribution; (Liv): growing stock; (NDBH): number of dbh classes; (DensNLiv): living trees density; (TreeRich): tree species richness. (CWD): Coarse woody debris volume; (STDw): standing dead trees volume; (STUStDw): volume of standing dead trees (including stumps); (NstuStDW): number of standing dead trees (including snags); (BASnagSt): basal area of standing and stumps); (Dwtot): total deadwood volume; (Dw/liv): deadwood/livingwood volume ratio; (LenghtCWD): total length of coarse woody debris; (HM): maximum height; (NDC): number of decay classes occurring in the plot; (NDBH): number of dbh classes; (DensStuDW): density of standing dead trees including stumps; (NHt): number of trees with cavities > 20cm; (GSDBH): Gini-Simpson index; (T > 40) number of living trees with dbh > 40cm. Sampling efficiency: 1- poor, 2- medium, 3 - high.

Structural indicators	Sources of structural complexity	Function as a surrogate (significant $\rho \leq 0,5$ )	Contribution of variations by first two principal components	Value of Kurtosis	Sampling efficiency
Hsd: Height standard deviation	Vertical heterogeneity (VH)	HM (0,689).	1.670	1.807	2
Treerich: Tree species richness	Compositional diversity (CH)	-	0.782	-0.615	3
DensNLiv: Stem density, LOG+1	Uneven-agedness (UA)	NDBH (0.632); NstuStDW (0.510); DensStuStDw (0.510).	4.561	-0.037	3
T>40: Number of living trees with DBH>40cm	Density of large living trees (LLT)	NHt (0.522).	3.563	0.283	3
BA: Basal area, LOG	Growing stock (GS)	RDBH (0.698); Liv (0.868).	6.483	1.287	3
Dw/liv: Deadwood/living wood volume ratio, RAD	Total deadwood volume (DW-TOT)	StDw (0.529); StuStDw (0.565); BasnagSt (0.543); CWD (0.661); Dwtot (0.786).	4.338	0.607	1
LenghtCWD: sum of lengths of every coarse woody debris piece, LOG+1	Deadwood decay classes (DW-DC)	CWD (0.843); NDC (0.633); Dwtot (0.719).	4.542	0.317	3
DensStuDW: Density of standing deadwood, LOG+1	Standing deadwood, dead trees and snags (DW-ST)	BasnagST (0.781); STDw (0.814); StuStDw (0.814); Dwtot (0.517); DensNLiv (0.510); GSDBH (0.531).	5.611	-1.287	3

The SHI showed a normal distribution (Appendix, supplementary Fig.2), ranging from 25.6% to 76.6% (median = 50.31). Results showed that the plots with the highest SHI values are those located in mountainous areas. All specific values related to each site, with ADSXX codes and toponyms, are reported in Appendix supplementary Table 1. Three sites located within the Gennargentu massif of central Sardinia (ADS29, ADS31, ADS32) accounted for high SHIs (65.5%, 67.4%, 67.60%, respectively). Another massif where several sites with high SHI were recorded is the Limbara in northern Sardinia. Here, SHIs range from 58.3% (ADS58) to 61.5% (ADS41). In the south-eastern Sardinian mountains of Sarrabus, plots with high SHIs were found in the locality of Buddidorgia (ADS06, ADS08, ADS09), with values of 61.7%, 65.3%, 72.5%, respectively. In general, the 20 plots with the highest SHI values were often characterised by a high number of large trees (mean=10.15), high density of live trees (mean=517.89) and standing deadwood (mean=78.15),

and high tree species richness (mean=3.10). Coastal plots in the south-west (ADS38, ADS39) and in the centre (ADS11, ADS12) had lower SHI values (33.3%, 36.2%,41.8%,47.5% respectively) and were characterised by a low amount of large trees (mean=1.75), tree species richness (mean=2.00) and coarse woody debris (mean=0.24 m).

No significant difference ( $p > 0.05$ ) was found by relating forest type with SHI. On the other hand, SHI significantly increased with higher percentages of canopy cover and with the number of canopy layers. SHIs were higher in absence of livestock grazing and when large longhorn beetles were present. Inland stands showed significantly higher SHIs than coastal. A significant correspondence among old-growthness classes and SHIs was found (Fig.2).



**Figure. 2** Boxplot of SHI across grazing, canopy cover, canopy layers (single, double, multi-layered), cerambycid presence, old-growthness class location plots. Ns=  $P > 0.05$ ; \* =  $P \leq 0.05$ ; \*\* =  $P \leq 0.01$ ; \*\*\* =  $P \leq 0.001$ . Differences were tested using Kruskal-Wallis rank sum tests (pairwise) or Dunn’s test (multiple comparisons; R-package “dunn.test”; Dinno 2016) using rank sums with Bonferroni correction.

## 4. Discussion

### 4.1 Factors affecting forest heterogeneity in Sardinia

Proxies related to growing stock and standing deadwood, namely BA and LenghtCWD, were the most contributing variables in discriminating the examined plots. This confirmed again that the structural complexity of a forest stand is roughly equally defined by the co-presence of different characteristics related to both living and deadwood. For instance, plots with lower SHI values are characterised by a low number of large trees ( $T > 40$ ) and coarse woody debris (LenghtCWD). Under these conditions, the presence of few and majestic old trees, although they are quite important for the maintenance of saproxylic entomofauna, was unable to determine high structural heterogeneity. Low SHI values associated with low LenghtCWD are mainly explained by the removal and exploitation of dead wood by the local populations. In this sense, morphology and socio-economic factors are likely to be crucial drivers in inhibiting or favour the use of the land and consequently the permanence of old-growth forest stands. In particular, steep and mountainous

morphologies have generally favoured the conservation of most of mature forest areas in the mountainous areas of Limbara and Gennargentu of central-northern Sardinia.

As regards the distribution of SHI values among plots, our results confirmed that the SHI is influenced by variables that are likely to be related with structural complexity, which was, in this case, measured by means of number of canopy layers. Although their management is debated, evidences that live-tree structural complexity is generally higher in old-growth than in mature and early transitional stands are ample. Among others, including also geomorphological aspects, big old trees have a crucial role in shaping a high structural complexity by determining a lower tree density and increased tree size heterogeneity (Zenner 2004). Moreover, coastal plots appear with lower SHI values than inland ones, probably as a consequence of higher human accessibility, economic interest and, possibly, to slower forest growth associated with dry climatic conditions and general low forest resilience of Mediterranean coastal areas (Mayor et al. 2007). As already reported for different European countries, livestock grazing (Bergmeier et al. 2010) and human activities (Motta 2002), appear to be crucial factors for shaping the structural variability of the forests in Sardinia and consequently old-growthness. Furthermore, our results showed significant differences of the SHI among the three levels of canopy cover, as well as among the number of canopy layers, confirming that such structural characteristics are discriminant characters for old-growthness definitions. Indeed, old growth forests have generally multiple or continuous canopy layers and are "bottom loaded" in foliage mass, in contrast to the top loaded canopies of young stands (Franklin & Van Pelt 2004). The presence of large longhorn beetles was also weakly associated with higher structural complexity of forests, generally associated with mature trees and aging forests (Buse et al. 2008, Casula 2017).

#### ***4.2 The SHI as a proxy forest of old-growthness and conservation value***

Although a large part of the Sardinian forests preserves traces of ancient human activities, such as paths and small plateaus for the coal production, and woodlands are currently still used for livestock grazing and firewood production, most of the investigated plots showed at least some characteristic or even a high level of old-growthness, which make them priority areas for conservation. In some cases, mature forests were maintained by the local communities who preserved them from cuts, recognising their cultural value, besides their productive function (Heatherington 2001) or, such as the plots with a high SHI value in "Buddidorgia" (ADS09, SHI up to 72.5%), forest stands are interdicted under military jurisdiction since 1956.

However, signs of human impact, such as livestock grazing, were significantly influencing the SHI (i.e. a lower SHI in grazed stands). Even though grazing may in some cases favour forest development by, for instance, reducing litter and flammable biomass (Diaci et al. 2010), this is one of the main threats to the conservation of old-growth forests in Sardinia (Farris et al. 2012) and in other several Mediterranean areas (e.g., Bergmeier et al. 2010, Motta et al. 2015). The excessive trampling and/or herbivory of seedlings does not allow replacement of dead trees in the long term. An illustrative case is the secular *Taxus baccata* forest of "Sos Nibberos", where the presence of several large old trees is associated with the lack of renewal due to overgrazing. Moreover, the historical presence of human modifications was still visible in several

investigated plots. For instance, small plateaus built by the charcoal burners are still visible, even if such practices were generally abandoned (Scotti & Cadoni 2007). Following the definitions of Buchwald (2005), who developed an array of levels of naturalness of natural forests, we could classify part of the forests found in Sardinia as "relatively intact forest (stand level) that has been essentially unmodified by human activity for the past sixty to eighty years or for an unknown, but relatively long time", as in the case of high SHI values measured for ADS09 (SHI 72.5%) or ADS32 (SHI 67.6%). This was supported by the significant differences of SHIs among forest stands classified under three classes of old-growthness. Even though the SHI is not conceived for classifying old-growth forests, like the one proposed by Badalamenti et al. (2018), it can be used as a preliminary conservation priority-ranking measure of old-growth forests and persistent woodlands in Sardinia and other poorly investigated territories. Forests with high SHI stands should be prioritised for conservation and investigations aimed at understanding local processes underlying forest structural complexity and dynamics.

#### **4.3 Potential and limitations of the SHI**

One of the main advantages of the application of this methodology is that it comes from the sum of scores for each structural attribute, omitting the subjectivity due to a human evaluation. In this study, it was chosen to include in the SHI only those structural variables that can be easily measured in a plot of approx. 530m<sup>2</sup>, which are proxies of other attributes very difficult and expensive to measure, such as biodiversity, the fraction of the gaps, or the interactions among biotic and/or abiotic components. The structural attributes considered are a compromise between the relevance of information to include in the index and its cost, due to the large extent of the study area and the low available resources and information. Surprisingly, no significant differences were identified among the investigated forest and persistent woodlands types. On one side, this confirms that the SHI is unusable for comparisons among forest types. On the other side, the rarity of some forests such as the ones dominated by *Phillyrea latifolia* and *Arbutus unedo*, which does not allow achieving statistical significance in comparisons, suggests more specific and deeper studies on the structure dynamics of such uncommon typologies.

Although the SHI does not discriminate the process (anthropogenic or natural) that has determined the accumulation of a certain structural heterogeneity in a stand, human-related processes, such as livestock grazing, were confirmed to lower SHI values. Moreover, the index showed that, in some cases, plots with a different structure might have similar SHI values. An example can be the comparison of ADS18 (SHI 63.7%), characterised by a high number of live trees and low values of tree species diversity, with ADS08 (SHI 65.3%), characterised by a smaller number of live trees, but a high diversity of tree species. Despite these differences, both plots showed roughly the same SHI value (Appendix, supplementary Table 1). This suggests that old-growthness and maturity does not necessarily take into account the arboreal layer diversity, in accordance with McElhinny et al. (2005), which stated that structural complexity is a relative concept rather than absolute. Similarly, remarkable SHI values can be obtained in forest areas modified by silvicultural practices such as coppice with standards and retention forestry (Fedrowitz et al. 2014). An

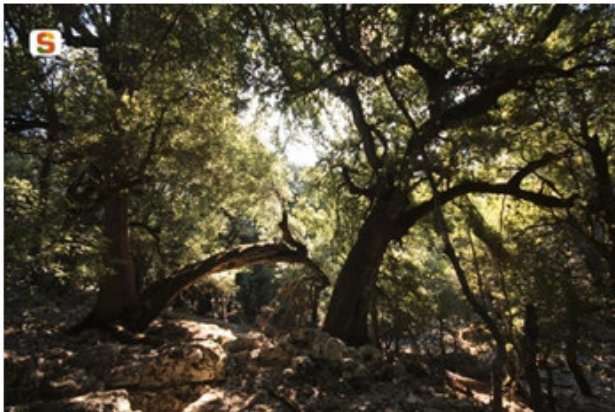
example is ADS45 (SHI 53.1%), a typically biplane forest where a limited number of tall and large *Quercus ilex* trees dominate the lower layer of *Phillyrea* coppice.

## 5. Conclusion

The structural heterogeneity, in terms of SHI, of a representative sample of natural forests in Sardinia was for the first time elaborated. Specifically, a total of 68 plots included in 45 forest stands were here studied. Pure or mixed forests with *Quercus ilex* and pure or mixed forests with *Taxus baccata* were the most represented types. Similarly to other studies (e.g., Storch et al. 2018), the SHI was applied for analyses at a relative large spatial scale and for different types of forests, in an attempt to obtain an adequate assessment of the structural diversity of several forest types that co-occur in Sardinia. The SHI was mostly defined by the co-presence of both living and deadwood characteristics, namely basal area and density of standing deadwood, respectively. SHI increased with the number of canopy layers and canopy cover and it was likely to be disfavoured by overgrazing and by the soil-climatic and human accessibility conditions of coastal areas. Although a large part of the Sardinian forests preserves traces of ancient human activities, such as paths and small plateaus for the coal production, and woodlands are currently still used for livestock grazing and firewood production, most of the investigated plots showed at least some characteristic or even a high level of old-growthness, which make them priority areas for conservation.

This work produced a first characterisation of the ancient residual forests of Sardinia, which could be followed by more in-depth studies. On a small spatial scale, it would be interesting investigating which species respond as a maturity qualitative indicator. Among them, the presence of specific nemoral herbs/geophytes, such as *Viola* sp.pl., *Glechoma sardoa* (Bég.) Bég. or several ferns like *Polystichum setiferum* (Forssk.) Woynt. and *Dryopteris oreades* Fomin (Bacchetta et al. 2004a,b, Farris et al. 2012), moss-lichen assemblages with, for instance, *Lobaria pulmonaria* (Brunialti et al. 2010), fungi such as *Fomes fomentarius* (L.) Fr. (Bernicchia et al. 2008) and bats like *Myotis mystacinus* (Kuhl) and *Plecotus sardus* Mucedda, Kiefer, Pidancedda and Vieth (Mucedda et al. 2002, Kaňuch et al. 2008) are just few of the rich array of species that might be investigated in this sense. On a large scale, the use of remote sensing techniques as the object oriented classification (Johansen et al. 2007), might allow an automated mapping and monitoring of their evolution through the identification of spatial structures typical of old growth forests, such as gaps or dead branches in the forest canopy. Furthermore, finding out which and how environmental and anthropogenic factors affect SHI might provide useful insights for forest conservation and management. Even if it represents just a first step toward old-growth forests identification, considering the very sparse knowledge in the Mediterranean Basin, we believe that this method can be replicated in order to preliminarily assess the distribution and structure of old-growth forests and persistent woodlands at Mediterranean scale.

## 6. Appendix



Compiler _____ _____
Institution belonging to the compiler _____ _____
Date _____

The old-growth forest is a particular habitat where trees of considerable size and of different ages coexist, where it is possible to find dead trees standing and dry trunks on the ground. This forest is not managed by man and even where it was in the distant past, the effect of its presence is completely negligible. The old-growth forest is the habitat of many plant species, fungi and animals. Unfortunately the ancient forests in Sardinia are rare and unknown and also thanks to the compilation of this questionnaire we will try to identify and characterize them

- **LOCATION OF OLD GROWTH FOREST**

Province \_\_\_\_\_ Municipality \_\_\_\_\_

Location \_\_\_\_\_ Coordinate system \_\_\_\_\_

Coordinates \_\_\_\_\_ ; \_\_\_\_\_

Area dimensions in ha (approximately) \_\_\_\_\_

Is it easily accessible?  yes  no

Access routes (roads, paths) and journey times from the nearest car park or known location

\_\_\_\_\_  
\_\_\_\_\_

Type of cartography attached with identification of the area: \_\_\_\_\_



- **WHICH OF THE FOLLOWING CRITERIA MADE YOU CONSIDER THE REPORT OF THE FOREST APPROPRIATE?**
  - Absence of wooded cuts or other forms of disturbance for a long time, absence of grazing from domestic cattle, absence of roads and recent artefacts, etc. (absent or very limited anthropic disorder)
  - Presence of trees of different ages and sizes
  - Presence of large trees (patriarchs)
  - Presence of dead wood (dead trees standing, branches and trees fallen to the ground)
  - Presence of trees with cavities
- Other \_\_\_\_\_

- **PRESENCE OF DEAD WOOD**

- Wood is collect on the ground?  Yes  No
- Presence of dead wood  Yes, sporadic  Yes, frequent  No
- Components of dead wood  Standing dead trees  On the ground dead trees
- Coarse woody debris on the ground  Dead branches on living individuals

Altro \_\_\_\_\_

- **MANAGEMENT**

- Forest currently managed  Yes  No
- Year (or period) of the last cut if known \_\_\_\_\_
- Traces of fires / charcoals / sheepfolds  Yes  No

- **WOODLAND TYPE**

Most common trees (insert common name of the species):

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

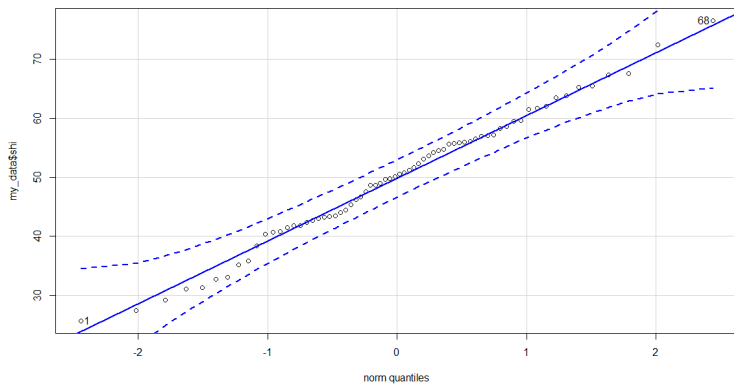
Most common shrubs (insert common name of the species):

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

**Figure 1.** Questionnaire used for the survey among experts in forest management and conservation.



**Figure 2.** Quantile-comparison (qq-) plot of the SHI calculated on a set of 68 sites. Functions QQnorm, QQline, QQplot. R-Package: ‘car’ version 3.03

**Table 1.** Site name and ID (ADS\_XX) of each 531 m<sup>2</sup> plot; forest typology (J: *Juniperus* sp.pl.; T: *Taxus baccata*; Q: *Quercus ilex*; Ar: *Arbutus unedo*; Ph: *Phillyrea latifolia*; QP: *Quercus gr. Pubescens*; A: *Alnus glutinosa*); location of each site (coastal/inland); presence/absence of grazing and cerambycids; estimated % of canopy cover; structure of canopy layers; number of: trees with DBH > 40cm (T > 40); tree species richness; number and density of living trees (DensNLiv); density of standing dead trees including stumps (DensStuDW); sum of lengths of every coarse woody debris (CWD) piece; Old-growthness class estimated according to Badalamenti et al. (2018); SHI value.

Name	ID site	Forest Typology	Location	Grazing	Cerambycid presence	Canopy cover	Canopy layers	T>40	DensStuDW	DensNLiv (N/ha)	Tree Rich	Number of living trees	CWD (m)	Old-growthness class	SHI value
Arala	ADS_01	Q	Inland	No	Yes	76-100%	Double	6	37,66	583,80	4	31	10.0	Medium	48.720
Aranzos	ADS_02	T	Inland	Yes	No	51-75%	Single	16	18,83	338,98	1	18	51.0	Medium	57.064
Baccu Addas_1	ADS_03	Q_mix	Inland	No	Yes	51-75%	Multi	5	75,33	357,82	1	19	45.0	High	49.785
Baccu Addas_2	ADS_04	T_mix	Inland	Yes	No	51-75%	Multi	8	56,50	376,65	3	20	24.0	High	56.485
BacusaFigu	ADS_05	Q_mix	Inland	No	Yes	51-75%	Multi	3	131,83	395,48	4	21	25.0	High	56.111
Buddidorgia_1	ADS_06	Q	Inland	No	No	76-100%	Multi	11	0,00	508,47	4	27	75.5	High	61.672
Buddidorgia_2	ADS_07	Q	Inland	No	No	76-100%	Multi	11	0,00	451,98	2	24	8.0	Medium	46.236
Buddidorgia_3	ADS_08	Q	Inland	No	Yes	76-100%	Multi	13	131,83	602,64	5	32	20.0	High	65.300
Buddidorgia_4	ADS_09	Q_mix	Inland	No	Yes	76-100%	Multi	13	207,16	696,80	5	37	117.0	High	72.491
Carracana	ADS_10	Q	Inland	No	Yes	51-75%	Single	9	18,83	225,99	1	12	18.1	Medium	43.081
CalaFuili	ADS_11	J	Coastal	No	No	51-75%	Multi	2	56,50	659,13	2	35	8.0	Low	41.798
PuntaliMannu	ADS_12	J_mix	Coastal	No	No	51-75%	Multi	4	18,83	866,29	3	46	10.0	High	47.534
Dortesi	ADS_13	Q	Inland	Yes	Yes	51-75%	Single	7	37,66	131,83	1	7	9.0	Medium	40.819
Goloritzè_1	ADS_14	Q_mix	Inland	Yes	No	51-75%	Multi	5	0,00	131,83	3	7	12.0	Medium	38.367
Goloritzè_2	ADS_15	Q	Inland	Yes	No	51-75%	Single	3	0,00	56,50	1	3	4.0	Low	25.645
Gorropeddu	ADS_16	T	Inland	Yes	No	51-75%	Single	9	0,00	301,32	3	16	18.7	High	44.493
Is Arridelaxius	ADS_17	Q	Inland	No	No	51-75%	Multi	8	18,83	376,65	3	20	34.0	High	49.025

Is Cannoneris	ADS_18	Q	Inland	No	No	76-100%	Single	10	508,47	1996,23	2	106	25.0	Medium	63.792
Is Cioffus	ADS_19	Ph	Inland	No	Yes	51-75%	Multi	6	18,83	828,63	5	44	15.5	High	54.787
Janne 'e Cori	ADS_20	Q	Inland	Yes	Yes	76-100%	Multi	10	225,99	470,81	1	25	11.2	High	54.248
La Signora	ADS_21	Q	Inland	Yes	Yes	51-75%	Multi	7	94,16	659,13	2	35	59.6	High	59.656
Li Femmini	ADS_22	Q	Inland	No	Yes	51-75%	Multi	4	56,50	753,30	2	40	15.1	Medium	48.638
Lispedda	ADS_23	Q_mix	Inland	Yes	Yes	51-75%	Multi	5	37,66	640,30	3	34	29.0	High	52.299
Canali mau_1	ADS_24	T_mix	Inland	No	No	76-100%	Multi	7	0,00	338,98	4	18	7.5	Medium	43.312
Canali mau_2	ADS_25	T	Inland	No	No	76-100%	Multi	10	75,33	244,82	3	13	59.5	High	62.046
MandraBrujata	ADS_26	Q	Inland	Yes	Yes	51-75%	Double	5	0,00	414,31	5	22	3.0	Low	40.381
Marmurata	ADS_27	T_mix	Inland	Yes	No	51-75%	Single	4	0,00	320,15	3	17	14.5	Medium	42.331
Barbudu	ADS_28	Q	Inland	No	No	51-75%	Multi	5	18,83	414,31	2	22	53.0	High	53.663
Donnianigoro_1	ADS_29	Q	Inland	Yes	Yes	76-100%	Single	18	94,16	433,15	1	23	71.0	Medium	65.525
Fumai	ADS_30	Q	Inland	Yes	No	51-75%	Single	9	18,83	188,32	1	10	4.8	Medium	43.251
Mereu	ADS_31	Q	Inland	Yes	Yes	51-75%	Multi	15	75,33	583,80	2	31	100.0	High	67.413
Tureddu	ADS_32	Q	Inland	No	Yes	51-75%	Double	8	56,50	451,98	3	24	241.0	High	67.597
Monti di Deu_1	ADS_33	Q	Inland	No	No	76-100%	Double	12	18,83	301,32	1	16	11.0	Medium	45.364
Monti di Deu_2	ADS_34	Q	Inland	No	Yes	51-75%	Multi	7	56,50	338,98	1	18	51.4	Medium	50.061
MularzaNoa	ADS_35	T_mix	Inland	No	No	76-100%	Multi	11	94,16	659,13	6	35	60.0	High	76.586
Nieddoni	ADS_36	Q	Inland	Yes	Yes	76-100%	Single	11	37,66	621,47	1	33	18.5	Medium	50.568
Oruddulè	ADS_37	Q	Inland	Yes	Yes	51-75%	Single	9	18,83	244,82	4	13	31.0	High	54.587
Piscinas_1	ADS_38	J	Coastal	Yes	No	51-75%	Single	1	94,16	244,82	1	13	3.5	Low	33.318
Piscinas_2	ADS_39	J_mix	Coastal	Yes	No	51-75%	Single	0	37,66	414,31	2	22	2.0	Low	36.249
Rio Aratu	ADS_40	T_mix	Inland	Yes	No	51-75%	Single	4	94,16	207,16	2	11	2.0	Medium	49.629
Rio Columbano	ADS_41	Q_mix	Inland	No	Yes	51-75%	Multi	5	94,16	1167,61	3	62	49.2	High	61.461
Correboi_1	ADS_42	T_mix	Inland	Yes	No	0-50%	Multi	9	37,66	188,32	5	10	11.5	High	55.850
Correboi_2	ADS_43	QP	Inland	Yes	No	0-50%	Single	5	0,00	112,99	2	6	0.0	Low	31.285
Rodè	ADS_44	T_mix	Inland	No	Yes	76-100%	Multi	7	37,66	564,97	4	30	10.2	High	55.620
Salatore Logu	ADS_45	Q_mix	Inland	No	No	76-100%	Double	5	56,50	772,13	4	41	17.0	High	53.116
Punta Salinas	ADS_46	Q	Inland	Yes	Yes	51-75%	Multi	7	18,83	357,82	5	19	14.0	High	57.220
Sambuco Giuntura	ADS_47	Q_mix	Inland	No	No	76-100%	Multi	6	37,66	451,98	2	24	50.7	High	55.789
Sambuco Nord	ADS_48	Q	Inland	Yes	Yes	0-50%	Double	8	0,00	188,32	2	10	16.7	Medium	44.000
Trattalas_1	ADS_49	Q	Inland	Yes	Yes	0-50%	Multi	9	18,83	225,99	1	12	7.5	Medium	43.442
Trattalas_2	ADS_50	Q	Inland	Yes	No	0-50%	Single	10	0,00	188,32	1	10	11.0	Low	40.675
Trattalas_3	ADS_51	Q	Inland	Yes	Yes	51-75%	Double	4	0,00	131,83	1	7	4.5	Low	35.890
Sos Nibberos	ADS_52	T	Inland	Yes	No	76-100%	Single	12	0,00	527,31	2	28	0.0	Low	42.736

Sos Nibberos_2	ADS_53	T	Inland	Yes	No	76-100%	Single	14	56,50	451,98	2	24	10.0	Medium	55.973
Su Irove	ADS_54	Q_mix	Inland	No	Yes	51-75%	Multi	7	112,99	772,13	4	41	13.0	High	58.664
Su prappare	ADS_55	Q	Inland	No	Yes	76-100%	Multi	11	37,66	433,15	1	23	46.8	High	59.511
Su Suercone Ilex	ADS_56	Q	Inland	No	Yes	51-75%	Double	5	0,00	131,83	2	7	67.3	High	51.707
Su Suercone Taxus	ADS_57	T	Inland	No	No	76-100%	Multi	10	301,32	414,31	1	22	63.9	High	63.460
Suliana	ADS_58	Q	Inland	No	Yes	51-75%	Multi	8	94,16	583,80	3	31	25.2	High	58.259
Tedderieddu_1	ADS_59	T	Inland	Yes	No	51-75%	Multi	6	18,83	131,83	4	7	10.8	High	51.187
Tedderieddu_2	ADS_60	J	Inland	Yes	No	0-50%	Multi	6	0,00	131,83	1	7	0.0	Low	29.252
Tedderieddu_3	ADS_61	A	Inland	Yes	No	76-100%	Single	9	0,00	169,49	2	9	4.0	Low	41.500
Tuones	ADS_62	Q	Inland	Yes	No	0-50%	Single	3	0,00	94,16	2	5	0.0	Low	27.486
Tuviois_1	ADS_63	Ph	Inland	Yes	No	51-75%	Single	5	18,83	112,99	1	6	14.2	Low	35.176
Tuviois_2	ADS_64	Q	Inland	Yes	Yes	76-100%	Double	8	0,00	150,66	2	8	0.0	Low	33.028
Arcosu_Su Corteddu	ADS_65	Q	Inland	Yes	No	76-100%	Single	5	0,00	451,98	1	24	8.0	Medium	41.782
Arcosu_Monte Lattias	ADS_66	Ar_mix	Inland	No	No	76-100%	Multi	5	56,50	1544,26	4	82	16.0	High	56.974
Arcosu Longufresu_1	ADS_67	Ar_mix	Inland	No	Yes	76-100%	Multi	4	0,00	772,13	2	41	46.5	High	50.827
Arcosu Longufresu_2	ADS_68	T_mix	Inland	No	No	76-100%	Single	11	0,00	414,31	3	22	12.0	Medium	46.677

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## **CHAPTER 2: Positive interactions between great longhorn beetles and forest structure**

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**Abstract:**

Great longhorn beetles (GLBs) may affect forest structure, because their larvae colonize trees and create networks of cavities further exploited by other species, resulting in dead or broken branches and tree mortality. At the same time, tree size, condition and location are known to affect the likelihood of tree colonization by GLBs. Here, we study the relationship between GLBs and the structure of old-growth holm oak Mediterranean forests in Sardinia, Italy. Generalized linear models were used to relate presence of GLBs with structural parameters that can be affected by or can affect these ecosystem engineers. We found a strong positive relationship (Effect size=20.5%; P=0.009) between GLBs and the number of trees with cavities, while the relationships between GLBs and the number of dead wood decaying classes, amount of coarse woody debris, stand basal area, forest canopy layer complexity were positive but weak. Overall, our results suggest that larval activity of GLBs could be responsible for increased tree cavity and dead wood formation, enhancing forest structure. On the other hand, forests with larger and older trees could be more likely to be colonized by GLBs. While it is not possible with observational studies to disentangle to what extent GLBs affect forest structure or vice versa, it seems likely that reciprocal interactions may enhance the structure of holm oak forests. Therefore, parasitism from native GLBs should be seen and understood more as a key ecological process that enhances the structure of Mediterranean holm oak forest habitats.

**Keywords:** dead wood, ecosystem engineering, forest management, old-growth, *Quercus ilex*, parasitism.

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## 1. Introduction

Forest structure, the spatial arrangements of the various components of the forest ecosystem, is related to habitat heterogeneity, biodiversity and ecosystem functioning (Casula et al. 2017, McComb 2008, McElhinny et al. 2005). Definitions and measurements of forest structure can vary considerably depending on perspectives, but generally consider several aspects of arrangements of living plants, as well as dead wood components (McElhinny et al. 2005) and tree related microhabitats (Larrieu et al. 2018). The importance of dead wood and tree related microhabitats for forest ecosystem structure and functioning is generally explained in terms of carbon sequestration, nutrient cycling and provision of niche space such as refuges, conditions and resources for living species (Grove 2002, McComb 2008, Parisi et al. 2020, 2019). Therefore, conservation or enhancement of these components of forest structure is generally thought to enhance biodiversity, ecosystem functioning and services (Brockerhoff et al. 2017).

Longhorn beetles (Cerambycidae) are known among forest managers for the impact of feeding larvae on trees. Many species of great longhorn beetles (GLBs), such as *Cerambyx* spp. and *Prinobius myardi* Mulsant in the Mediterranean area, can cause relevant damages to forest productions by colonizing living trees and boring into wood (e.g. Martín et al. 2005, Torres-Vila et al. 2017), and have been even hypothesized to contribute to the decline of protected oak habitats under climate change scenarios (Duque-Lazo & Navarro-Cerrillo 2017). Fundamentally for the same impact on trees, GLBs such as *Cerambyx cerdo* L. and *Aegosoma scabricorne* Scopoli have been seen also as ecologically important ecosystem engineers, playing a major role in the decomposition of wood, nutrient cycling, refuge and resource provision for biodiversity conservation (Buse et al. 2008, Ettwein et al. 2020, Foit et al. 2016, Gottfried et al. 2019). GLBs are able to visibly affect forest structure, as they create networks of trunk cavities further exploited by other species, resulting also in dead or broken branches and, finally, tree mortality (López-Pantoja et al. 2011; Torres-Vila et al. 2017). Therefore, their conservation may result in increased forest structure and functioning, with particular reference to tree related microhabitats and dead wood components.

The relation between modifiers keystone species, habitat structure, and ecosystem functioning is widely recognized in conservation (Mills et al. 1993). That is perhaps why the European Habitats Directive (92/43/EEC) protect both habitat “structure and function” and ecosystem engineers such as *Cerambyx cerdo* (Buse et al. 2008, Casula 2017). Albeit the European normative framework clearly refers to dead wood components among the structures to be protected in forest habitats (Ellwanger et al. 2018), management options to achieve conservation and enhancement of forest structure and function focusing on ecological processes such as parasitism (Bennett et al. 2009) are often overlooked (Kovac et al. 2020) or difficult to establish due to political conflicts (Müller, 2011). In fact, conservation of forest habitats and endangered wood borers such as *C. cerdo* have been presented as contrasting alternatives, with proposed wood borer control actions to protect habitats (Duque-Lazo and Navarro-Cerrillo 2017). While wood borer control could be justified in productive or urban landscapes, controversial aspects emerge in natural forests, where ecosystem processes should be the focus of conservation (Bennett et al. 2009, Hudson et al. 2006). Evaluating to what extent wood borers affect forest structure may help showing that conservation of parasites

and their hosts can be different facets of the same coin: conservation of forest ecosystems based on maintaining or restoring important ecological processes, such as parasitism (Bennett et al. 2009, Müller et al. 2008).

Here, by means of generalized linear modeling, we studied the relationship between presence of emergence holes of GLBs and the structure of old-growth holm oak forests, across the whole Mediterranean island of Sardinia. Specifically, we investigated forest structural variables that can be linked to the biology of the great longhorn beetles present in Sardinia (*C. cerdo*, *P. myardi* and *A. scabricorne*), according to the following hypotheses:

- a) Given the effect on trees of their larval activity, GLBs could be positively related to amounts of dead wood and tree related microhabitats such as cavities and injuries.
- b) Forests with higher canopy layer complexity provide better conditions for GLB colonization or, vice versa, parasitism from GLBs increases tree and branches mortality, reduces tree canopy cover and enhances layer complexity: GLBs could be positively related to canopy layer complexity.
- c) GLBs are generally associated with mature trees (Buse et al. 2007, Foit et al. 2016) and could be positively associated with forest structural parameters related to tree size.
- d) GLBs seem to be associated with sun exposed parts of trunks (Albert et al. 2013, Buse et al. 2007) and could be negatively associated with tree density and canopy closure.

## 2. Materials and Methods

### 2.1 Study species and sites

Three GLB species are present in Sardinia (Sama & Rapuzzi 2011): *Cerambyx cerdo*, *Prinobius myardi*, both known in the Mediterranean as holm oak (*Quercus ilex* L.) and cork oak (*Quercus suber* L.) pests and ecologically important forest ecosystem engineers (Buse et al. 2008, Casula 2017, Torres-Vila et al. 2017), and *Aegosoma scabricorne*, preferentially associated with soft-wooded trees such as *Alnus glutinosa* Scop., *Ulmus* spp., *Fraxinus* spp., *Populus* spp. or *Salix* spp. (Foit et al. 2016), but that could also colonize *Quercus* spp. (Baviera et al. 2017). The species *C. cerdo* is listed in the European Red List of Saproxylic Beetles (Calix et al. 2018) as near threatened and is protected under the Habitats Directive (Annex II e IV), while *P. myardi* and *A. scabricorne* are listed as least concern (Calix et al. 2018) and are not generally protected under the European Union. However, the three species have similar ecological function and importance. Indeed, they have similar size and biology, preferentially colonizing trees with reduced vitality and creating cavities that can be exploited by other species, such as fungi (Torres-Vila et al. 2017), plant pathogens (Martín et al. 2005), saproxylic beetles (Buse et al. 2008), woodpeckers (Ettwein et al. 2020) and tree-dwelling bats (Gottfried et al. 2019), finally resulting in increased dead branches and tree mortality.

The study focuses on holm oak forests, the most widespread and representative forest type present in Sardinia (Bacchetta et al. 2009, 2004, Camarda et al. 2015), listed in Annex I of the Habitats Directive (*Q. ilex* and *Q. rotundifolia* forests). In the Mediterranean Basin and in Sardinia, holm oak forests are also

traditionally managed for firewood production, resulting in the rarity of old-growth forest remnants and simplification of forest structure (Casula et al. 2017, Fantini et al. 2020, Puddu et al. 2012). The study was carried out in 10 main holm oak forest areas scattered all over Sardinia, where the presence of relic old-growth holm oak forests was known (Figure 1).



**Figure 1.** Distribution of study plots (white triangles, with code) and forest areas (dark grey)

Within these areas, depending on forest extension and actual presence of old-growth forest remnants, from one to 11 circular plots of 13 m radius were randomly selected (Fantini et al. 2020) for a total of 47 plots. The few plots sampled in the large areas of southern Sardinia result from the rarity of old-growth forest

remnants still present, after centuries of extensive coppicing (Bacchetta 2006, Puddu et al. 2012). Other areas present a higher density of old-growth forest remnants and have thus a higher density of plots. To reach old-growth forests and to select plots for sampling, hiking tracks were walked; once well inside the old-growth forest, a random direction was selected and a constant distance of approximately 100 m walked to reach the centre of the plot. In very small old-growth forest remnants this distance was reduced to 50 m to avoid forest edges. In any case, plot centers were distant at least 100 m from edges. Presence of GLBs and forest structural variables were assessed during spring-summer 2019.

## **2.2 Presence of GLB**

Presence of GLBs was assessed by direct observation of insect adults or adult emergence holes. Within circular plots, adults and emergence holes were searched in the visible parts of all living and dead tree trunks (lower parts of standing trees and exposed parts of logs). GLBs are difficult to detect as the larval stages bore into wood and adults are cryptic, sedentary and have mainly nocturnal or crepuscular activity (Foit et al. 2016, Redolfi De Zan et al. 2017). Therefore, trees colonized by the three species present in Sardinia can be best identified via the typical oval emergence holes that can reach up to 20 mm in the longer diameter (Albert et al. 2013, Buse et al. 2007, Foit et al. 2016, Torres-Vila et al. 2017). In our study, most of gathered observations were presence of emergence holes in living or dead trees, from which the exact GLB species cannot be distinguished. Therefore, the study refers to past presence of this small functional group, even if *P. myardi* and *C. cerdo* should be the most likely species colonizing holm oak trees. Additionally, emergence holes can persist for decades in living, senescent and dead trees: the presence of GLBs assessed in this way should be seen as cumulative information about occurred colonization of forest stands.

## **2.3 Variables related to GLBs**

Seven structural variables, thought to be linked to the biology of the GLB species investigated, were measured within the circular plots described above. Observed values are shown in Supplementary material (SM1 Data).

a) **Dead wood and tree related microhabitats.** Dead wood amount was measured as coarse woody debris (*CWDI*: the total length of trunks and branches with diameter higher than 10 cm found on the ground, expressed in meters), number of snags (*nSnag*: number of standing dead trees), total volume of dead wood present at the stand level (*TotDW*: volume of standing dead trees and CWD calculated using measured length/height and diameters) and number of dead wood decaying classes (*nDC*: up to five decaying classes identified). Total amount of tree related microhabitats that can be linked to GLBs biology was measured as the number of trees with cavities (*nTCav*: measured as the number of trees that have cavities bigger than emergence holes of GLB, among which also longitudinal trunk cracks have been considered).

b) **Canopy layer complexity** was measured as three levels, where *Layer = 1* indicates old-growth holm oak forests with tree canopies that are approximately at the same height, without relevant shrub layer; *Layer = 2*

means that the tree layer is clearly separated from the shrub layer; *Layer = 3* means that tree and shrub layers are present but heights are heterogeneous and layers cannot be distinguished (maximum level of complexity).

c) **Tree size.** Stand basal area (*BA*, the sum of the basal area of live trees with diameter higher than 10 cm, measured at breast height), average tree diameter at breast height (*DBH*; measured on all trees with diameter higher than 10 cm) and number of trees with a minimum diameter of 40 cm (*nTD40*), were used to describe tree size at the plot level.

d) **Tree density and canopy closure.** Stand density (*nLT*; the number of living trees with diameter higher than 10 cm) and canopy closure (*Cclos*; % ground covered by vertical crown projections) could capture stand features that reduces the exposition of trunks to sun.

Additionally, three more variables have been considered in the analysis, as described below.

e) **Forest type** (*Ftype*: pure vs. mixed stands). Available data were taken from pure and mixed stands of holm oak forests. Mixed stands were considered where basal area of holm oak trees represented less than 75% of total plot basal area. The remaining basal area was composed mainly of arboreal forms of *Phillyrea latifolia* L. (six plots) and *Arbutus unedo* L. (four plots), or *Taxus baccata* L. (four plots). Given that variations in forest composition could affect GLB presence patterns, this factor was considered in the analysis.

f) **Tree height** (*H*), measured as average tree height at the plot level. This variable was considered to address possible problems of detectability of emergence holes. Emergence holes of GLBs are often associated with lower parts of trunks and should be thus easily detected from ground surveys (Albert et al. 2013). However, *C. cerdo* populations were also found to be associated with the uppermost part of trees, being thus undetectable from ground (Redolfi De Zan et al. 2017). In this case, higher tree height could negatively affect observations of GLBs.

g) **Forest area** (*Area*). Given the sampling design, with plot scattered over different forest areas, this factor was considered in the analysis.

## 2.4 Statistical analysis

The state variable of interest is binary (GLB presence/absence): correlation with structural variables has been investigated using Generalized Linear Models (GLMs), family binomial, using software R version 3.5.0 (R Core Team, 2016). Generalized linear mixed models implemented in the R package *lme4* (Bates et al. 2015) were used to evaluate the effect of forest area as a random factor. However, as we found variance of the random factor equal to zero, mixed models were not used and *Area* effect was evaluated as a fixed factor with GLMs.

Considering the relatively small sample size ( $n=47$ ), a univariate GLM analysis was first performed, where each effect was evaluated at a time (see Supplementary material, SM2 R Script), according to the following model (R script):

*Effect = glm(formula = GLB ~ 1 + Effect, family = binomial).*

A null model,  $m_0 = \text{glm}(\text{formula} = \text{GLB} \sim 1, \text{family} = \text{binomial})$ , with 1 intercept and no effect hypothesized, was used for confrontation. Univariate models were compared with  $m_0$  by means of AICc (Burnham & Anderson, 2002) and Likelihood Ratio Test (*LRT*). Models that had  $\Delta\text{AICc}$  higher than 2 or that differed significantly from  $m_0$  according to the *LRT* were considered for multivariate analysis.

Using the R package *glmulti* (Calcagno & de Mazancourt, 2010), effects supported by the univariate model selection were combined and evaluated with automated multivariate model selection. Considering univariate results presented in Table 1, the following analysis was run:

```
multivariate = glmulti("GLB", c("nTCav", "nDC", "BA", "Layers", "CWDI"), data = data, level = 1, intercept=TRUE, crit = aicc, family = binomial),
```

where  $level = 1$  means that interactions among variables were not allowed to avoid an excessive number of models automatically run on a small data set. With this setting, a total of 32 multivariate models were evaluated on the data set. Pearson correlation coefficient showed that selected variables were not collinear (see Supplementary material SM2 R Script for details).

Multivariate results showed several weak and uncertain effects (*nDC*, *AB*, *Layers*, *CWDI*). Such effects could be additive, i.e. their cumulative effect could provide an overall better explanation of the data. The possibility that weak effects could be additive was evaluated by creating a cumulative variable that summed up *nDC*, *AB*, *Layers* and *CWDI* (*WADD*: weak additive). To do that, each variable was scaled to values ranging from 0 to 1 and the a posteriori model  $\text{GLB} = 1 + nTCav + WADD$  was confronted with the best model *nTCav* (see Supplementary material SM2 R Script).

Calculation of effect size was based on model deviance:  $[(\text{Null deviance} - \text{Residual deviance})/\text{Null deviance}] * 100$ . Model selection tables based on AICc were developed using the R package *AICcmodavg* (Mazerolle, 2019), while for LRTs we used the R package *lmtest* (Zeileis & Hothorn 2002).

### 3. Results

Univariate model selection provided support for five structural variables (Table 1). The first five models have AICc lower than the null model ( $m_0$ , 6th,  $\Delta\text{AICc} = 10.42$ ) and are also significantly different from it, providing support for the effect of the number of trees with cavities (LRT *nTCav*vs.  $m_0$ ,  $p = 0.0004$ ), number of dead wood decaying classes (*nDC*,  $p = 0.0495$ ), stand basal area (*AB*,  $p = 0.0559$ ), level of canopy layer complexity (*Layers*,  $p = 0.0607$ ) and the amount of coarse woody debris (*CWDI*,  $p = 0.0712$ ). However, only the effect of *nTCav* is strongly supported, having high AICc distance from  $m_0$  and effect size of 20.5%. Models ranked 2nd – 5th are closer to  $m_0$  and have small effect size (weak effects). Slope parameter values are systematically positive, i.e. variables are positively correlated with GLB presence (Table 1). Univariate models ranked from 7th to 14th do not provide any support for hypothesized effects. Forest area (14th), tree height (13th) and forest type (9th) do not appear to affect results and will be not discussed in the next section.



**Table 1.** Univariate analysis supports positive associations between the number of trees with cavities, and great longhorn beetle presence. The effect of the number of dead wood decaying classes, basal area, canopy layer complexity and total length of coarse woody debris (CWDI) are weakly supported.

Rank	Model: Effect	K <sup>a</sup>	AICc	ΔAICc	Deviance	Effect size <sup>b</sup>	Slope	SE	P
1	mnTCav: N. tree with cavities	2	53.180	0.000	48.907	20.5%	0.3103	0.1188	0.009
2	mnDC: N. decaying classes	2	61.926	8.746	57.654	6.3%	0.4765	0.2554	0.062
3	mBA: basal area	2	62.132	8.952	57.859	5.9%	0.0216	0.0136	0.111
4	mLayer: Canopy layer complexity	2	62.267	9.087	57.994	5.7%	0.6644	0.3610	0.066
5	mCWDI: lenght of CWD	2	62.531	9.351	58.259	5.3%	0.0205	0.0140	0.142
<b>6</b>	<b>m0: no effect</b>	<b>1</b>	<b>63.602</b>	<b>10.422</b>	<b>61.513</b>	-	-	-	-
7	mTotDW: total dead wood	2	64.241	11.061	59.968				
8	mnSnag: n. of snags	2	65.077	11.896	60.804				
9	mFtype: forest type	2	65.404	12.224	61.131				
10	mCclos: canopy closure	2	65.406	12.226	61.134				
11	mnTD40: n. trees D>40 cm	2	65.441	12.261	61.168				
12	mLTn: n. living trees	2	65.681	12.501	61.408				
13	mH: average tree height	2	65.729	12.548	61.456				
14	mArea: forest area	10	78.723	25.542	52.611				

<sup>a</sup> Number of parameters; <sup>b</sup> Based on model deviance.

Multivariate automated model selection showed that combined variables do not explain data much better than nTCav (Table 2). Indeed, model selection shows similar AICc values for the first 10 models, where several combinations of variables appear to equally explain the data. The best model selected (nTCav + Canopy layer complexity) has AICc similar to that of the 2nd (nTCav) and it is not significantly different from it (LRT  $p = 0.1207$ ; Effect size = 24.4%): the most parsimonious univariate nTCav should be selected. Relative importance of each effect, estimated with the automated model selection (Table 3), is high only for the variable nTCav (Importance = 0.9772). Therefore, weak and uncertain support was found for the remaining effects emerged with the univariate analysis.

**Table 2.** Multivariate analysis supports the positive association between the n. of trees with cavities (nTCav) and presence of great longhorn beetles.

Rank	Effects	AICc	w <sub>i</sub> <sup>a</sup>
1	nTCav + Canopy layer complexity	53.0576	0.1264
2	nTCav	53.1801	0.1189
3	nTCav + Coarse woody debris	53.3896	0.1070
4	nTCav + Basal area + Canopy layer complexity	53.6181	0.0955
5	nTCav + n. of decaying classes	53.8758	0.0839
6	nTCav + Canopy layer complexity + Coarse woody debris	54.2768	0.0687
7	nTCav + Basal area	54.3048	0.0677
8	nTCav + Basal area + Coarse woody debris	54.9814	0.0483
9	nTCav + n. of decaying classes + Canopy layer complexity	54.9883	0.0481
10	nTCav + n. of decaying classes + Coarse woody debris	55.0913	0.0457

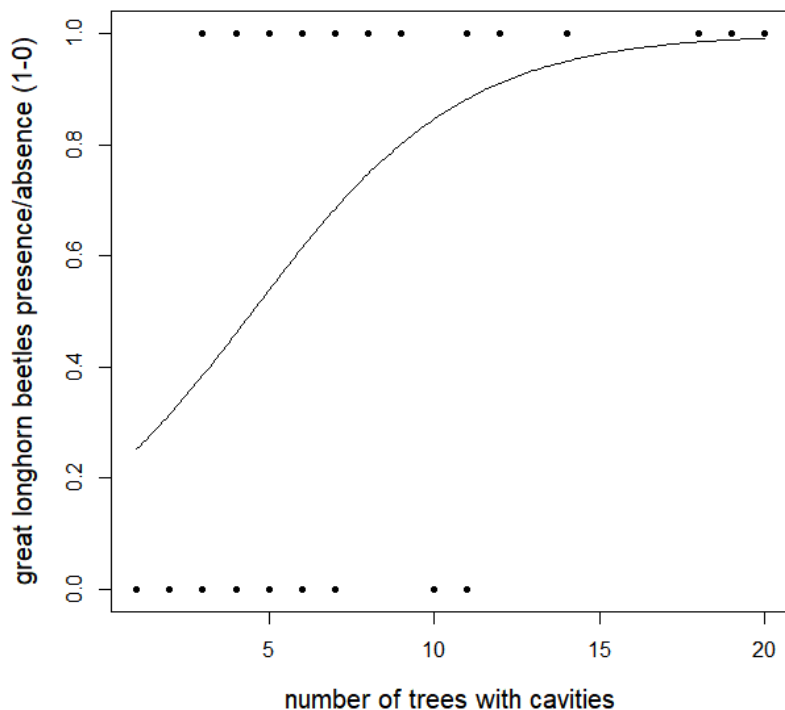
Notes: <sup>a</sup> Akaike's weight.

**Table 3.** Relative importance of effects and model averaging of parameter estimates.

Effect	Estimate	Unconditional variance	Importance
n. of decaying classes	0.0796	0.0262	0.3138
Basal area	0.0061	0.0001	0.3717
Coarse woody debris	0.0046	0.0001	0.3718
Canopy layer complexity	0.2925	0.1774	0.4569
n. of trees with cavities	0.2851	0.0161	0.9772

However, slope parameter estimates obtained with the multivariate analysis are consistent with univariate estimates (all positive). Additionally, the *a posteriori* model  $GLB = 1 + nTCav + WADD$  has  $AICc = 51.22$ , which is lower than 1.96 if compared with  $nTCav$ , and is also significantly different from it ( $LRT p = 0.0394$ ; Effect size = 27.4%). Therefore, there is some support for a cumulative effect of weak variables. The positive association of each variable with GLB presence (Table 3) could perhaps be discussed, considering the hypotheses put forward in the introduction.

Finally, Fig. 2 shows how the probability of GLB presence was correlated with the number of trees with cavities. The figure suggests that at a certain threshold (above 15 trees with cavities per plot) occurred colonization by GLBs is very likely ( $p = 1$ ).



**Figure 2.** Probability of presence of great longhorn beetles in forest stands increases with the number of trees with cavities (dots = observed values; line = predicted values).

#### 4. Discussion

This study provides strong support for a relationship between presence of GLBs, which has to be interpreted as past occurrence, and the number of trees with cavities found within old-growth holm oak forests in Sardinia. As the number of trees with cavities increased, past occurrence became very likely ( $p \approx 1$ ). That is, GLBs were found to be widespread in well-structured holm oak forests with a high number of trees with cavities. Considering that these insects are well known to affect trees, with larval activity creating trunk cavities that can be exploited and enlarged by other species (Buse et al. 2008, Ettwein et al. 2020, Foit et al. 2016, Gottfried et al. 2019, Regnery et al. 2013), it seems likely that GLBs occurred in the past positively affected holm oak forest structure at the stand level. On the other hand, GLB females preferentially lay eggs in tree bark crevices and damaged parts of trunks (Redolfi De Zan et al. 2017, Torres-Vila et al. 2017). Previous tree injuries could therefore increase the likelihood of GLB colonization (Buse et al. 2008) and a correlative study cannot distinguish to what extent GLBs affected trees to enhance cavity formation and tree injuries or, vice versa, cavity formation and tree injuries enhanced GLB colonization. Nevertheless, effects could be reciprocal, and it seems likely that interactions between GLBs and trees can be beneficial to improve forest structure.

We also found some evidence about a positive correlation between GLB past occurrence and basal area, forest layer complexity, number of dead wood decaying classes and the amount of coarse woody debris. Such effects were weakly supported by the univariate and multivariate analyses. However, when summed up to form the WADD variable, the effect was well supported. We cautiously interpret this result as evidence of an additive effect of several weak variables that, overall, describe enhanced forest structure and senescence. Similarly to other forest systems, larval activity of GLBs could in the long term result in increased numbers of dead branches and trees that fall to the ground (Buse et al. 2008, Torres-Vila et al. 2017), contributing to the enhancement of coarse woody debris and wood decaying classes. Larval activity of GLBs could also result in more heterogeneous tree heights, given its possible contribution to gap formation in forest canopies. On the other hand, forests with larger and senescent trees could just provide better conditions for GLB colonization. Again, it is not possible to distinguish with correlative studies to what extent GLBs affect forest structure or vice versa, and effects could be reciprocal.

It is also important to note that the investigated old-growth holm oak forests persisted despite widespread colonization by GLBs, possibly suggesting that population control of GLBs can be provided by natural enemies (e.g. Ceia & Ramos 2016). Until proven otherwise, GLBs should not be considered pests in protected forests (Duque-Lazo & Navarro-Cerrillo 2017), where productive interests are of lower concern and higher diversity of natural enemies reduces the likelihood of pest outbreaks (Brockhoff et al. 2017, Casula et al. 2006). Additionally, once mature holm oak trees are colonized by GLBs, they generally survive for long time, thus providing relatively stable habitats for other species, promoting ecological heterogeneity and species diversity (Buse et al. 2008, Regnery et al. 2013, Sirami et al. 2008). Albeit GLBs may damage productive trees, it does not seem they can jeopardize persistence of natural holm oak forest ecosystems.

No effects of canopy closure and tree density were found. We have no evidence to confirm that GLBs in Sardinian holm oak forests prefer sun exposed trees, as shown in several studies (Albert et al. 2013, Buse et al. 2007, Foit et al. 2016, Torres-Vila et al. 2017). The association of *C. cerdo* with sun exposed parts of trees has been suggested in the colder central European countries, to support traditional forest management strategies such as coppicing and woodland pastures (Albert et al. 2013, Buse et al. 2007). On the other hand, it has been shown that habitat requirements of *C. cerdo* may greatly vary among locations (Platek et al. 2019) and little is known about its habitat requirements in Mediterranean landscapes (Casula 2017). Similarly to other studies on *C. cerdo* (Redolfi De Zan et al. 2017), emergence holes of GLBs were here associated with old-growth natural forests, possibly suggesting that these species could be well preserved also in unmanaged forests, where natural processes dominates (Schnitzler 2014). It could be that conservation of GLBs is fundamentally a matter of host tree aging and weakening (Platek et al. 2019), which can be achieved in different forest or landscape management scenarios. Possibly, retention forestry at different spatial scales (Grove 2002), i.e. from single trees in landscapes (Sirami et al. 2008), to set-aside forest islands (Lassauce et al. 2013) up to extensive unmanaged forests (Schnitzler 2014), could have beneficial effects on GLB populations and their habitats.

In conclusion, our study shows that colonization by great longhorn beetles appears to be important to enhancing holm oak forest structure, with particular reference to the creation of tree related microhabitats. To achieve conservation of these species and holm oak forest habitats in the Mediterranean Basin and European Union it is important to acknowledge and more deeply investigate their ecological role and interactions with forest structure, as we attempted to do here. Given that disease and mortality are fundamental ecological processes that create niche space and allow ecosystems to persist and evolve through time (Odling-Smee et al. 2013), native parasites that have coexisted with forests for a long time could be seen more as strategic allies than enemies (Bennett et al. 2009, Hudson et al. 2006, Müller et al. 2008). Very often forest habitats are protected to preserve native species, among which parasites might be eventually tolerated. Here, we suggest that native parasites of forests, among which great longhorn beetles are an ecologically and economically relevant study case, are worthy of protection as they contribute to enhancing forest structure.

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## **CHAPTER 3: Incorporating the visibility analysis of fire lookouts for old-growth woods fire risk reduction in the Mediterranean island of Sardinia**

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## **Abstract**

The island of Sardinia, like most of Mediterranean territories, is subject to many fire events every year. In this study, we performed a visibility analysis of old-growth woods from the entire network of fire lookouts. This article describes an approach to estimate wildfire risks through the incorporation of the visibility of fires from lookouts and the level of old-growthness of woods to the common information of wildfire hazard maps, such as flammability, slope, road network and inhabited areas. The results of this study show that old-growth woods in Sardinia are unevenly protected from fires and that, compared with the wildfire hazard map, a vulnerability map obtained through the proposed approach led to different outputs in terms of fire protection prioritisation. These outputs allow a better risk evaluation for territory protection and improve the preventive planning of territorial control operations. The integration of other parameters to wildfire hazard maps, in our case the visibility and the characteristics of old-growth woods, is an easily replicable focus-oriented approach. Testing the effectiveness of its application with other parameters and in other contexts is recommendable.

**Keywords:** forest fires, fire management, geographic information system, parametric method, visibility analysis.

## 1. Introduction

In Sardinia, fires are one of main problems for both environmental and social security. Data collected by the Regional Administration of Sardinia (RAS; <http://www.sardegnaoportale.it>) shows that from 2004 to 2016 the extension of the forest fires (with areas greater than 1 ha) covered an average area of 17,400 ha per year. The Sardinian fire fighting system consists of a network of lookouts, teams of men, fire fighting cars, a fleet of helicopters and planes (RAS, Regione Autonoma della Sardegna 2019). In Sardinia, fires are facilitated by the typically Mediterranean climate, characterised by mild wet winters and warm to hot, dry summers (often prolonged during late spring and early autumn) and by very frequent winds, mainly from West and North West (Chessa & Delitala 2020). The fire mapping carried out by the RAS in the last 13 years (<http://www.sardegnaoportale.it>), shows that the phenomenon affects a large percentage of the regional territory and that forest fires often start near roads, which lead to suppose a frequent anthropogenic origin (Lovreglio et al. 2010).

In this context, fire lookouts, positioned in strategic positions, are proved to be effective tools for early detection of fires and to facilitate the efforts to prevent their spread (Rego & Catry 2006, Kucuk et al. 2017, Hognogi et al. 2020). The current fire detection system in Sardinia consists of 217 lookouts, 49 of which with night hours integrated by the itinerant sighting (RAS, Regione Autonoma della Sardegna 2019). Due to limited resources, not all lookouts operate 24 hours a day. For this reason, it is necessary to locate lookouts in a cost-effective way, in order to increase the percentage of covered territory and guarantee an immediate intervention by air and ground teams. With this aim, RAS created a fire hazard map in which, considering the main factors that contribute to the occurrence of fires, the most exposed areas of Sardinia were mapped (RAS 2017).

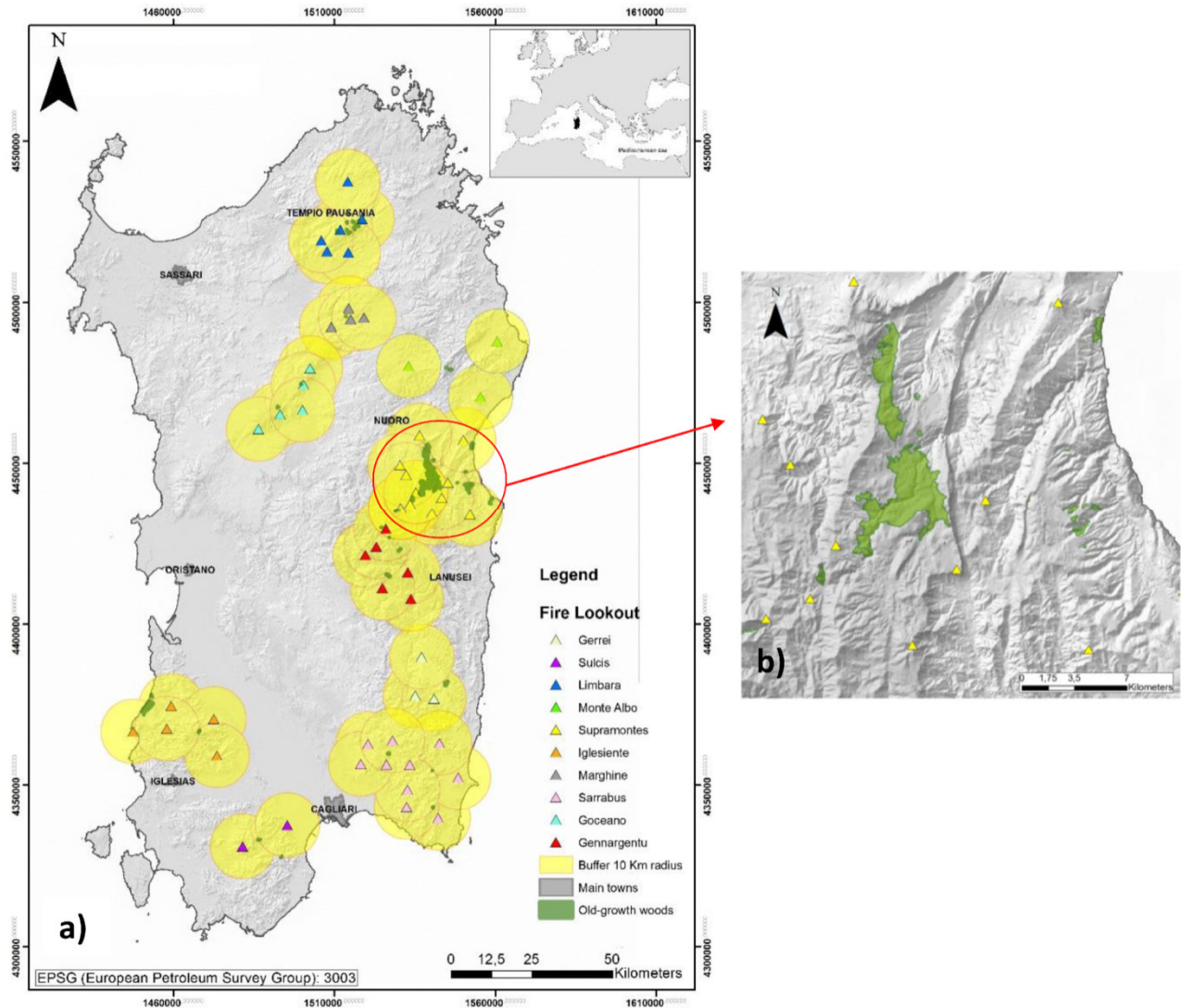
However, such hazard map was not linked with forest conservation value. For instance, despite its usefulness, fire hazard maps were not designed to evaluate and display the presence and vulnerability of old-growth woods. Old-growth woods stands are the Mediterranean equivalent of primary or secondary forests that have developed the structures and species normally associated with old primary forest (FAO 2020). They have a high and irreplaceable conservation value because they ensure a rich array of particular niches for several taxonomic groups, such as invertebrates (Siitonen 2001), lichens, mosses, fungi (Norden et al. 2007) and vascular plants (Aude & Lawesson 1998), which are not present in managed forests and woods (Lindenmayer & McCarthy 2002, Pezzi et al. 2020). The global disappearance of primary, natural or unmanaged forests and woods is of great concern and, in fact, these are rare in Europe, due to their historical exploitation (Parviainen 2005, Marchetti & Blasi 2010). Also in the island of Sardinia, the extension of such unmanaged woods was estimated to be considerably reduced during the nineteenth century, mainly due to deforestation, subsequent livestock of sheep and goats, coupled with fires to maintain pastures (Pungetti 1995). In this paper, the spatial information of fire lookouts was overlapped in a geographic information system (GIS) environment with relevant information about old-growth woods. The aims were (i) to evaluate the visibility of old-growth woods from the Sardinian fire lookouts network and (ii) to assess their vulnerability with a parametric method through an implementation of RAS wildfire hazard map with the

values of old-growthness classes (of old-growth woods) and visibility (of lookouts) in the case study of “Supramontes”. Such results, coupled with the coverage of old-growth woods within protected areas, provide new useful information for more effectively planning the protection of woods from fires. The same parametric approach might be applied in other contexts and with different specific biotic and abiotic parameters.

## **2. Material and methods**

### **2.1 Study area**

The reference area of this study is the island of Sardinia (Figure 1a), the second Mediterranean island after Sicily by extension, with a surface area of about 24,090 km<sup>2</sup>. Sardinia is in the central-western part of the Mediterranean Basin. Several landscapes are present here: few plains, basaltic plateaus, coastal dunes, mainly large coastal and several temporary inland wetlands, coastal and inland cliffs, and several long and pocket beaches (Fois et al. 2017). Forests in Sardinia have been estimated to cover a surface of 4,297 km<sup>2</sup> (Puddu et al. 2012), which mainly consists of evergreen holm oak (*Quercus ilex*) and cork oak (*Quercus suber*) woods and deciduous oak woods (*Quercus* sp.pl.), with a wide ecological range and a widespread distribution throughout the island, occurring from coastal areas up to 1750 m above sea level (Bacchetta et al. 2009). Furthermore, particular soil-climatic conditions support the instauration of mesophilic and edafoxerophilous woods (e.g. *Taxus baccata*, *Ilex aquifolium*, *Ostrya carpinifolia*, *Juniperus* sp. pl.) which make the island very diverse in this aspect. The test site for the parametric method was the Supramontes, on central-eastern Sardinia (Figure 1b). Supramontes is an area of great naturalistic interest, where one of the oldest holm oak woodlands of the Mediterranean area is present. Here, the woods, which find its climatic optimum in the carbonate and limestone-dolomitic substrates of the biogeographic ‘Supramontano’ sector (Fenu et al. 2014), are dominated by *Quercus ilex* with other sclerophylls such as *Phillyrea latifolia*, but also by relic populations of *Taxus baccata*, *Ilex aquifolium*, deciduous trees of *Acer monspessulanum*, *Quercus virgiliana* and geophytes such as *Paeonia corsica*, *Cephalanthera damasonium* and *Epipactis microphylla* (Susmel et al. 1976, Bacchetta et al. 2009). This area is rich of individuals of large diameter (on average 40-60 cm, up to 150 cm) very developed in height (dominant plane that touches 30 meters) with expanded and globose crowns, both single and in small groups, interspersed with smaller diameter trees (30-40 cm). However, these woods suffered a vast fire of 1931, which reduced its former extent to smaller and scattered stands (Susmel et al. 1976).



**Figure 1.** (a) study area, old-growth stands, fire lookouts and scanning radius. Colors differ according to the macro areas where each of fire lookout falls in; (b) territorial framework of Supramontes, fire lookouts and old-growth stands.

## 2.2 Mapping old-growth stands in Sardinia

The study was carried out during spring-summer 2019. The selected 68 woods with old-growth features were identified according to peer opinion, considering the knowledge acquired during about twenty years of field investigation, and by consulting the most relevant literature concerning Sardinian forest vegetation (e.g. Bacchetta et al. 2004, 2009, Marchetti & Blasi 2010, Farris et al. 2012, Puddu et al. 2012). Within these areas, depending on forest extension, from 1 to 11 circular plots of 13 m radius were randomly positioned and surveyed (Lombardi et al. 2015). Each site was classified according to the three old-growthness classes proposed by Badalamenti et al. (2018): high (H), medium (M) and low (L). Such classification was based on an overlay of four internationally recognised indicators of old-growthness: deadwood, tree size, structural characteristics and tree species richness. For the proxy indicator “deadwood” was assigned a score ranging from 0 to 2 based on the total volume of dead tree values and the number of decay classes. For “structural characteristics”, was assigned a suitability (Y/N) based on the type of coverage (single, double or multi), on the value of the standard deviation and on the range of diameters. Also for “tree size” and for the “tree

species richness” was assigned only the suitability (Y/N), based respectively on the presence of trees with DBH > 40 cm and on the number of species detected. The evaluation of the presence-absence of these seven variables determined the classification of each site in three classes of old-growthness. Finally, the surface of each old-growth wood was polygonised in ArcGIS 10.2 software (ESRI, Redlands, CA, USA) through the photo interpretation of digital aerial images (pixel resolution of 0.2m).

### ***2.3 Quantifying the protection degree and study of the visibility of old-growth woods***

To facilitate data processing, the old-growth woods were grouped into 10 geographical macroareas (Figure 1a), defined and named according to the historical and morphological regions of Sardinia (Bacchetta et al. 2009). As a first step, all old-growth woods in each macroarea were overlapped in ArcGIS 10.2 with the public and private protected areas of the entire island, in order to establish which surfaces are without any legal protection. As a second step, the visibility map of the fire-fighting lookouts was created for all the old-growth stands. The visibility analysis was carried out in ArcGIS 10.2 with the Spatial Analyst Viewshed module to determine the coverage of the territory that is visible from fire lookouts. This analysis considers the morphological constraints that might enhance or limit visibility. For this scope, all lookouts managed by the Forestas Agency were positioned over the Digital Terrain Model (DTM) at 20 m resolution. The observation point was set at a height of 3 m for each location. This choice is due to the fact that lookouts can be positioned both on the ground and on a structure and it therefore constitutes an average value (OFFSET A). The observation of fires refers not only to the visibility of flames but also to the visibility of columns of smoke. The visible height was set in the software at 100m (OFFSET B), the horizontal scan angle (Azimut 1, 2) was set from 0 ° to 359 ° and the vertical scan angles at 90° in BVert1 and -90° in BVert. The visibility analysis was carried out for each lookout over an area with a radius of 10 km, an ascertained distance to view the smoke and its origins for observations made with the naked eye or with binoculars in optimal visibility conditions (Kucuk et al. 2017, Hognogi et al. 2020). The visibility parameter was classified in the visible/not visible binary form.

### ***2.4 Parametric method applied in Montes old-growth stands for fire vulnerability value***

Using the old-growth woods of Supramontes as a test site, a parametric method was applied through the Spatial Analyst of the ArcGIS functions which, with the "Raster Calculator" module, allowed to relate the grids to the following parameters: (i) Increasing old-growthness classes (1, 2, 3); (ii) Increasing fire hazard (1, 2, 3, 4); (iii) Visibility (0= visible, 1= not visible). The sum of these parameters ranges from 2 to 8 and a six-class vulnerability map was therefore obtained. This map was subsequently compared with the RAS wildfire hazard map of Sardinia (RAS 2007). The RAS wildfire hazard map was defined by the association of the following parameters: flammability, slope, exposure, altitude, road network and inhabited areas. The representative values of this map vary on a scale from 1 to 4, where the minimum value indicates a lower hazard and the value 4 indicates the higher level of danger. To compare the two maps, the classes of vulnerability map were reduced to 4, through the reclassification of the original values. This resulted in a

scale between 1 and 4, where 1 represents the value indicating a minimum vulnerability to fire and 4 a maximum vulnerability.

### **3. Results**

#### ***3.1 Visibility and environmental protection analysis***

Our results show that 78% of old-growth woods in Sardinia are visible from the fire lookout network (Figure 2) and 99.2% fall into the network of public or private protected areas by law. Particular attention should be paid to the Sulcis macroarea, where 60% of old-growth woods are not visible and 54% of these areas are unprotected. Differently, the entire macroarea of Gerrei is not visible nor protected but it falls entirely within a military zone, whose access and any activity is in any case controlled. Finally, the two macroareas of Sarrabus and Monte Albo are almost completely uncovered by the lookout network, even though they entirely fall within the network of protected areas (Table 1).

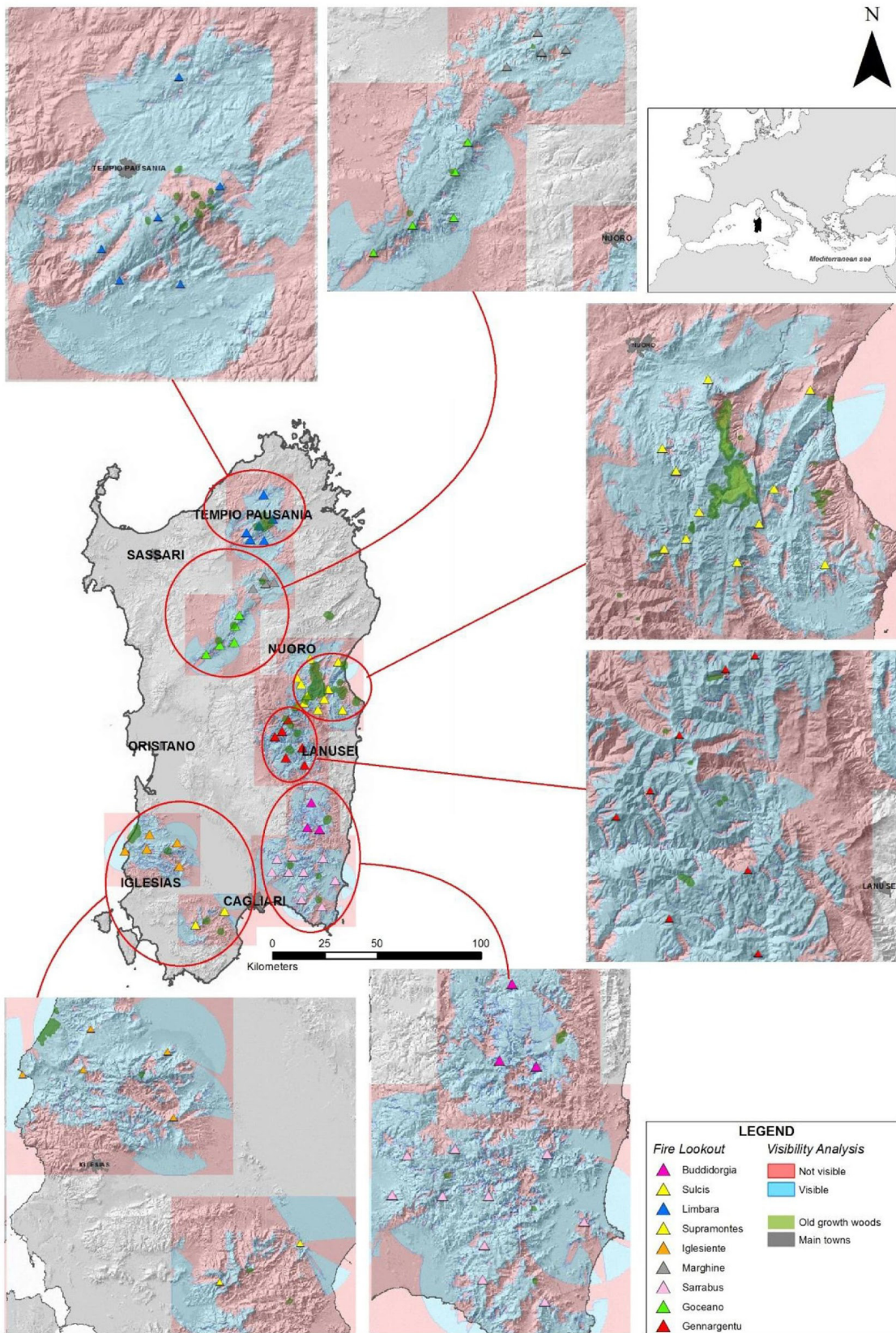


Figure 2. Visibility map of old-growth woods in Sardinia.

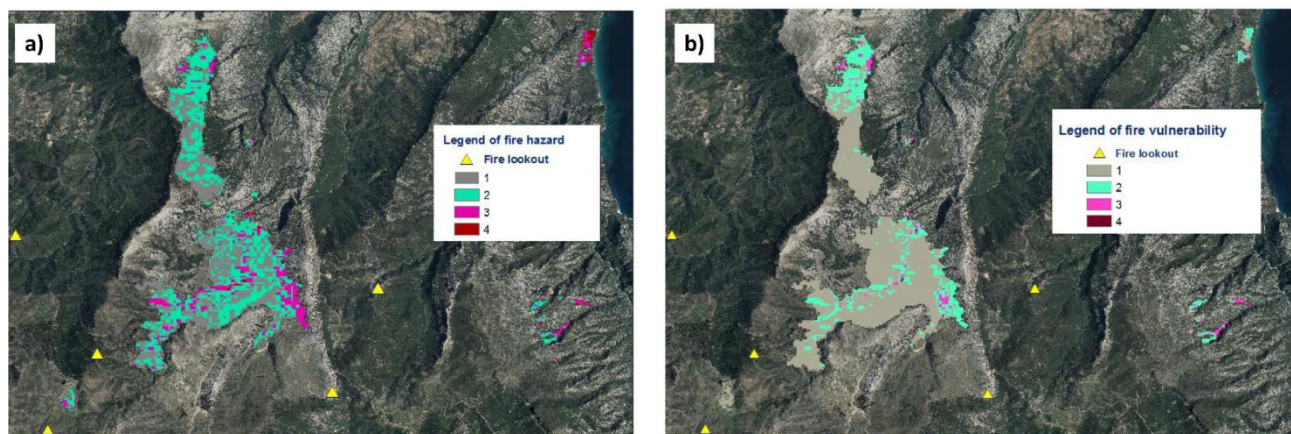


**Table 1.** Coverage and percentage of visibility from fire lookouts and protection of old-growth woods in each macro area of Sardinia

	Area (m <sup>2</sup> )	Visibility (m <sup>2</sup> )	Visibility (%)	Protected (m <sup>2</sup> )	Protected (%)
Sulcis	65,995	26,120	39.6	30,363	46.0
Gerrei	234,858	9	0.0	0	0.0
Limbara	437,935	235,064	53.7	437,935	100.0
Supramontes	27,978,980	21,800,302	77.9	27,978,980	100.0
Gennargentu	400,817	308,031	76.9	400,817	100.0
Goceano	135,159	37,808	28.0	135,159	100.0
Iglesiente	2,737,735	2,737,735	100.0	2,737,735	100.0
Marghine	3,309	3,309	100.0	2,358	71.3
Sarrabus	125,409	1,963	1.6	125,409	100.0
Monte Albo	132,376	0	0.0	132,376	100.0
<b>TOT</b>	<b>32,252,573</b>	<b>25,150,341</b>		<b>31,981,132</b>	

### 3.2 Parametric method applied in Supramontes old-growth woods for fire vulnerability value

Starting from the values of the RAS wildfire hazard map (Figure 3a) a vulnerability map was obtained by taking into account the old-growthness of the woods and the visibility from the lookouts. Our result allows a different assessment of the areas most at risk (vulnerability map, Figure 3b). In the map, the areas that have the greatest vulnerability to fire are those classified with parameters 3 and 4, which in our test site represent very small portions of territory compared to the studied area.



**Figure 3.** Levels from low (1) to high (4) of (a) wildfire hazard and (b) vulnerability of old-growth woods in Supramontes

## 4. Discussion

The results obtained in this research have shown that the risk of fires in the woods with old-growth features in Sardinia could be minimised by the fact that the stands are mostly visible from the lookout network and are almost entirely included in protected areas. However, a careful and well-designed planning of lookout locations for the conservation of Sardinian forests is needed. The fact that most of old-growth forest stands

fall within protected area might be controversially interpreted. On one side, protected areas are usually better managed and controlled and thus less prone to intentional and unintentional fires; on the other side, the declaration of protected areas may raise conflicts with local communities that might represent the cause and motivation of intentional fires (Rodrigues et al. 2018). Accordingly, the forest conservation might be ensured by both actions simultaneously.

Through the application of the parametric method for the assessment of the vulnerability to fire in the study area, it was possible to identify the most vulnerable areas through a focus-oriented approach that also considers the parameters of visibility and of wood old-growthness. The analyses showed that most of the study sites are not very vulnerable. Through a comparison between the two maps (wildfire hazard map and vulnerability map, respectively Figure 3a and 3b), most of the high hazard zones were reclassified to a lower level according to the visibility parameter, which was not considered in the wildfire hazard map, where only the intrinsic danger, related to the elements on the ground and the type of fuel, were included. The assessment showed in the vulnerability map was revealed as more detailed, allowing a different and more cost-effective assessment at civil protection planning level, leading to greater precision in planning and greater savings in human and economic resources. For instance, the vulnerability map highlighted less and more specific places where fires might be especially monitored. Such cost reduction, in terms of humans and structures, was obtained by avoiding redundantly visible areas and by focusing on places, such as old-growth woods, which are especially worth of protection. Moreover, our approach is in line with other researches that highlighted fire risk reduction and biodiversity conservation as compatible objectives (Syphardet et al. 2016). In this sense, several studies demonstrated the negative effect of fires on the conservation of several endangered species groups and the interactions among them, including plants (e.g. Vilà et al. 2001, Fois et al. 2018), macrofauna (e.g. Slavchev et al. 2014, Bosso et al. 2018), fungi and microbial communities (e.g. D'Ascoli et al. 2005, Buscardo et al. 2010).

This paper provides an easily replicable method that could also be applied in other environmental conservation contexts. For instance, other biotic aspects, such as endemic species richness or priority habitats (sensu Habitats Directive 92/43/CEE) might be added or used instead of old-growth woods. Such valuable information for conservation should be integrated into a single system comprising fire lookouts and protected areas networks as well as other pre-existing hazard maps with intrinsic risk parameters in order to provide useful information for a more correct assessment of a system and a rational use of the available resources.

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# SUMMARY

## 1.1 General conclusions

This PhD thesis was conceived to improve the knowledge of old-growth forests in Sardinia, an inestimable but scarcely known heritage. The main findings of this thesis are:

Chapter 1: The knowledge about stands with old-growth characteristics reported by experts has been improved. Most of the plots (67.7%) were located in Central-Northern Sardinia, in mountainous areas. Two different types of forests were mostly represented in this study: pure or mixed forests with *Quercus ilex* and pure or mixed forests with *Taxus baccata*. The Structural Heterogeneity Index (SHI) was elaborated according to several old-growth features such as the amount of large size and old trees, tree species composition, canopy heterogeneity, occurrence and amount of deadwood. The index was shown to be an objective proxy of old-growthness. This work produced a first characterisation of the residual old-growth forests of Sardinia. In particular, our results confirmed that steep and mountainous morphologies are generally associated with structured and mature forest areas in mountains, while human activities and livestock grazing appeared to be crucial factors that affected their conservation.

Chapter 2: The relationship between the presence of large longhorn beetles (saproxylic beetles that play an important role as ecosystem engineers) and the structure of the old holm oak wood, the most widespread and representative type of forest present in Sardinia, were investigated. We discussed how great longhorn and old-growth forest structure may beneficially affect each other, emphasizing the role of these parasites in creating conditions and resources for other species.

Chapter 3: The degree of protection of old-growth forests from the risk of fires was investigated. Results showed that 78.0% of old-growth stands in Sardinia are visible from the fire lookout network and 99.2% of them are within protected areas. This work also showed how, in the context of GIS analysis, the integrated approach of fire risk with the conservation value is economical, effective, and desirable.

## 1.2 Final considerations

The structural heterogeneity of a representative sample of natural forests was measured for the first time in Sardinia by means of SHI. However, this project represents only a step towards a more comprehensive characterisation of the remnant forests that, in ancient times, were covering most of Sardinia. We are also aware that, considering the large surface investigated, not all forests may have been identified. The evolution of technology today allows for many types of multi-scale investigations (e.g. high definition satellite images, multi-spectral, the use of drones, LIDAR). More accurate studies on a smaller scale are also needed. Indeed, the link between forest structure and biodiversity, addressed here for a very restricted group of modifier species (great longhorn beetles), needs very focused sampling and detailed investigations. From a practical

conservation standpoint, the fact that the old-growth woods and forests are largely visible from the lookouts and legally protected is positive, but this does not automatically determine their persistence. The places where the local populations maintained a strong connection with forests, especially for the cultural ecosystem services they provide, will be more likely preserved. Therefore, promoting cultural services provided by unmanaged forests in wilderness areas and natural parks (Schnitzler 2014) could be a sustainable strategy for old-growth forests conservation. On the other hand, retention forestry (Fedrowitz et al 2014) in managed forests could allow to maintain or restore old-growth structural attributes, enhancing forest biodiversity, functioning and resilience and cultural values as well. In general, more welcoming attitudes towards tree elders in forests would perhaps be a useful societal progress to preserve this almost lost piece of natural heritage and identity, old-growthness of forests.

### **1.3 References of summary**

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