LIFE SySTEMiC

Guidelines for Sustainable Forest Management of Oaks

(*Quercus robur* L., *Quercus pubescens* Willd, *Quercus ilex* L.)

Guidelines for Sustainable Forest Management of Oaks (*Q. robur* L., *Q. pubescens* Willd., *Q. ilex* L.)

Deliverable: Section of the guidelines on management activities in forest conservation areas in climate change for each of the 4 species/genera complexes targeted

LIFE SySTEMiC PROJECT DESCRIPTION

The LIFE Programme is the European Union's instrument to finance projects for the conservation of the environment, biodiversity and the fight against climate change.

The LIFE Programme is the European Union's instrument to finance projects for the conservation of the environment, biodiversity and the fight against climate change.
The aim of LIFE SySTEMiC Project (Close-to-nature Forest Sustainable Management under Climate Changes) is to use the "modelling tool" based on genetic diversity to determine best silviculture practices in order to protect our forests in times of climate change. The basic idea is simple: the greater the genetic diversity of trees in a forest, the more likely it is that some trees have genetic characteristics that make them more adaptable to climate change, increasing the resistance and resilience of the forest system.

Based on these premises, the main project objectives are to:

- Investigate the relationships between forest management and genetic diversity for eight forest tree species in three European countries (Croatia, Italy, Slovenia) in order to identify the silvicultural systems that maintain high levels of genetic diversity.
- Develop an innovative Genetic Biodiversity and Silvicultural model (GenBioSilvi) based on the combination of advanced landscape genomics, applied genetics and silvicultural models to support Sustainable Forest Management.
- Spread the knowledge of the method across Europe and transfer its use in forestry practice by involving different types of stakeholders.

The Web page of LIFE SySTEMiC project, including project deliverables: https://www.lifesystemic.eu/

1. Introduction

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Quercus spp.

Oaks are a genus of trees and shrubs in the Fagaceae family. Ecologically, oaks are key species found in areas ranging from the continental parts of the Northern Hemisphere, through Mediterranean semi-deserts, to subtropical rainforests. There are over 600 different species of oaks. Oaks are monoecious and can be either deciduous or evergreen. The oak symbolizes sturdiness, strength, and resilience and is often referred to as the "king of the forest". They are frequently characterized by their large size and slow growth. Oaks produce a nut called an acorn, which is encased in a cup-shaped cap, matures in the same year, and contains tannic acids that protect it from certain fungi and insects.

Quercus robur L. - Biology and area distribution

The pedunculate oak (*Quercus robur* L.) is one of the most widespread and valuable tree species in Europe, having historically played a significant economic, social, and ecological role (Morić *et al.*, 2018). According to Klepac (1996), the ecological impact of pedunculate oak forests is estimated to be several times greater than their economic impact, with particular emphasis on their anti-erosion and hydrological regulatory functions.

Figure 1.1. Pedunculate oak distribution range (EUFORGEN 2009, www.euforgen.org).

The pedunculate oak grows throughout nearly all of Europe, from Norway and Sweden in the north to the Iberian, Apennine, and Balkan Peninsulas, and Turkey in the south (Pasta *et al.*, 2016), even reaching northern Scotland. It also extends to the Caucasus and Asia Minor, covering areas north and east of the range of the sessile oak (Figure 1.1). The soils on which the pedunculate oak thrives are predominantly fertile clayey or sandy soils, typically moist with high groundwater levels. The pedunculate oak often grows in communities with hornbeam and field ash (Franjić and Škvorc, 2010). The pedunculate oak tolerates winter well, although late spring frosts can cause significant damage to young leaves, ultimately impacting growth. Additionally, because nutrients from the root system are used for the development of new leaves, a year with frost is expected to result in a significantly lower acorn yield.

Additionally, in its habitat, the pedunculate oak prevents waterlogging of the terrain and positively influences the soil water system by maintaining the balance of water status through the process of transpiration.

Figure 1.2. Pubescent oak distribution range (EUFORGEN 2009, www.euforgen.org).

Quercus ilex L. - Biology and area distribution

Quercus ilex L., the holm oak or evergreen oak, is a broad-leaved evergreen tree or shrub native to the Mediterranean basin, where it represents the dominating species in woodlands and maquis vegetation.

The natural distribution of holm oak occurs in the Mediterranean Basin (Figure 1.3). Across its distribution, two subspecies are identified primarily by variations in leaf morphology: *Quercus ilex* subsp.

rotundifolia (sometimes referred as *Quercus ilex* subsp. *ballota* or as separate species *Quercus rotundifolia*) has more lanceolate leaves with 6-8 veins and is found in Portugal, southern and south-eastern Spain, and Morocco; while *Quercus ilex* subsp. *ilex* has more ovate leaves with 8-9 veins and occurs in the remaining areas (Schwarz, 1993; Praciak *et al.*, 2013). In western regions (the Iberian Peninsula, the Atlantic and Mediterranean coasts of France, the Italian peninsula, the main Mediterranean islands), holm oak forming large pure stands, while in eastern regions (Balkan coasts, Greece, Crete, Black Sea and northern Lebanon) it is more commonly found in mixed stands (Schirone *et al.*, 2019). The altitudinal range is variable, growing from 100–140 m above sea level in the Black Sea area, up to 400-600 m in the Mediterranean, while in Morocco, it grows up to altitudes of 2000–2600 m (Schirone *et al.*, 2019).

The holm oak is a tree able to grow on various soil types and in diverse Mediterranean climates, ranging from semi-arid to very humid conditions with respect to precipitation, and from warm to very cold temperatures at high altitudes, provided the precipitation remains low (Barbero *et al.*, 1992). However, despite its ability to thrive in diverse environments, pure stands of holm oak forests are becoming increasingly rare due to human activities such as deforestation, urbanization, and agricultural expansion over centuries. Table 1.1. reports the list of the sites for *Quercus* spp. of the LIFE SySTEMiC project

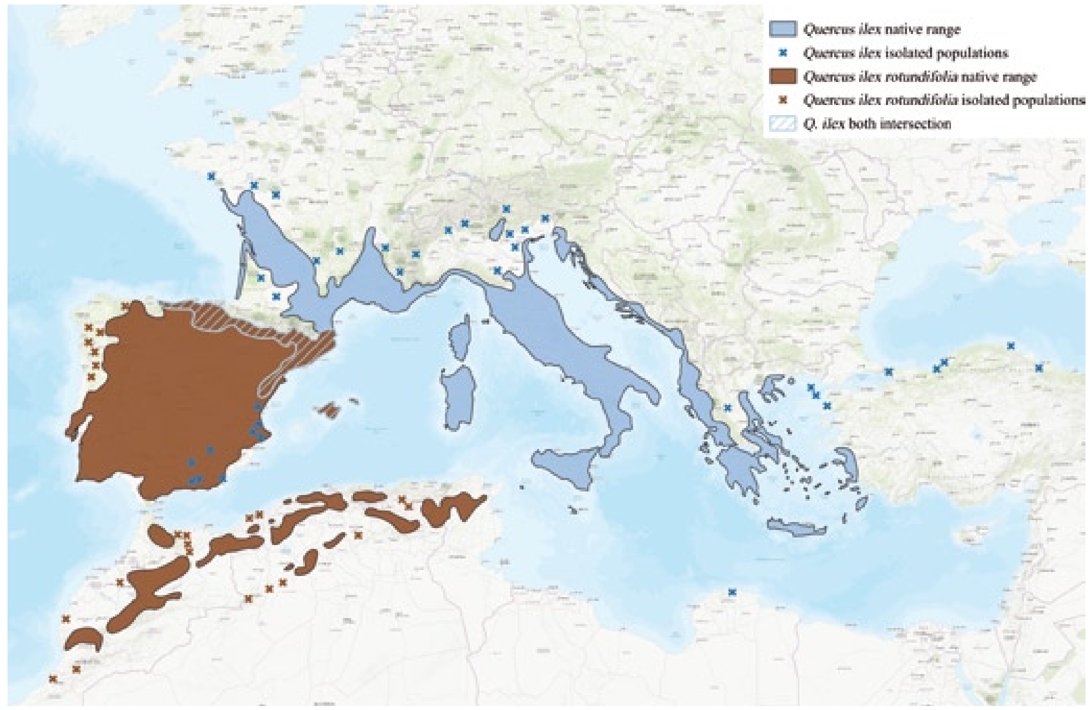

Figure 1.3. Holm oak distribution range (EUFORGEN 2009, www.euforgen.org).

Among the 13 European white oak species, pedunculate (*Quercus robur* L.) and sessile (*Quercus petraea* (Matt.) Liebl.) oaks are the most important, economically and ecologically, deciduous forest tree species in Europe (Diaci, 2006), while other oak species such as downy oak (*Quercus pubescens* Willd.) and holm oak (*Quercus ilex* L.) which have been also studied within LIFE SySTEMiC project are gaining their importance due to their resistance to climate change (Table 1.1).

Table 1.1. List of sites for *Q. robur* L., *Q. pubescens* Willd., and *Q. ilex* L.) of the LIFE SySTEMiC project.

Id	Site name	Country	Species	EFT*	Structure	Silvicultural system
10	Culatta	Italy	*Q. robur*	5.1	Uneven-aged/Un-managed	Unmanaged
13	Nova Gradiška	Croatia	*Q. robur*	5.1	Even-aged	Uniform shelterwood
20	Pula	Croatia	*Q. ilex*	9.1	Even-aged	Uniform shelterwood
21	Črni kal	Slovenia	*Q. pubescens*	8.1	Even-aged	Irregular shelterwood
28A	Krakovo (Managed)	Slovenia	*Q. robur*	5.1	Even-aged	Uniform shelterwood
28B	Krakovo (Reserve)	Slovenia	*Q. robur*	5.1	Uneven-aged/Un-managed	Unmanaged

* EFT = European Forest Type: 5.1 Pedunculate oak-hornbeam forest; 8.1 Downy oak forest; 9.1 Mediterranean evergreen oak forest.

2. General guidelines on Sustainable Forest Management and on Adaptation of forest to climate change

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Oaks are widely distributed in Europe. Also, they are closely related, they can mix, compete, and naturally hybridize with one another. Oaks are therefore among the most diverse species of forest trees. High levels of diversity are most likely due to the maintenance of large population sizes, overlapping of ecological niches, long-distance gene flow, and their interfertility (Ducousso and Bordacs, 2004). Studied oak stands within LIFE SySTEMiC have been mostly even-aged, unmanaged or managed as irregular or uniform shelterwood systems. Silvicultural system that is most suitable for pedunculate oak forests is irregular shelterwood with larger openings between 0.5 and 2 ha or uniform shelterwood system, which covers oak demand for light. Silvicultural systems that are rarely used in the area are the intensive management of even-aged forests, while the coppice system is common in Italy, especially in downy oak and holm oak forests (Ciancio and Nocentini, 2004). Additionally, an abandonment of any forest management of Mediterranean oak stands on steep-slope forests with limited accessibility can also be the case.

Oak site characteristics can change in short distances. If we want to preserve these characteristics and benefit from their specifics to the maximum extent, suitable mixed tree and forest stand structures should be used. Directed development of oak stands adapted to individual site and stand conditions, demands great flexibility in the selection of a proper system of forest management and careful planning of measures. Oak species differ morphologically and in terms of their site conditions requirements (Diaci, 2006).

All oaks are light-demanding species, at a young age they grow quickly in height. On better sites with no influence of overstorey trees, they reach a culmination of increment already between 30 and 45 years of age. Thereafter, the volume increment decreases but not rapidly so that the average volume increment of 200-year-old stands is still almost the highest (Diaci, 2006). Especially in young phases oaks respond perfectly to silvicultural measures which have an important effect on tree form and stand structure.

With the increase of average annual temperatures, oak sites will gradually become drier which will lead to the reduction of suitable areas (ZGS, 2021). Due to the complex action of biotic (diseases, pests) and abiotic factors (drought), the proportion of growing stock in older development stages is also partly at risk. With increased aridity, the fire risk of oak forests will also increase. Admixture of conifers with a high proportion of forest decline (red and black pine) also alter the vulnerability of those forests. *Q. robur* stands, due to degradation, changes in tree species composition and changes in the temperature and water regime, face a lack of suitable stands for seeding or with the absence of full crops (ZGS, 2021). The big threat to genetic diversity of the oaks is the introduction of exotic genotypes through plantations. White oaks have very large ecological niches and sometimes occupy extreme habitats (rocky slopes in mountains, dunes, saline soils, peat bog, garigues). These populations are at high risk of disappearing because the number of individuals is low, habitats are unstable and human impact is often considerable (Bajc *et al.*, 2020). Pests and pathogens represent a serious threat. Oak mildew (*Microsphera alphitoides*) is reported to be of the most common oaks pathogen. Mediterranean oaks are facing additional threat in overharvesting and overgrazing and climate change, indiscriminate cutting, improper silvicultural management (coppices or clear cuttings over large areas, where regeneration cannot succeed) and intensive ungulate browsing.

Natural regeneration can also be a problem for oaks. Due to the unbalanced ratio of development phases, over-abundance of game or changes in the groundwater regime natural regeneration is limited (ZGS, 2021).

Regeneration of preserved pedunculate oak stands should be done after the oak seed year. Stands are restored primarily naturally and where necessary also by planting and sowing. When introducing an oak stands for restoration (Figure 2.1), the understory tree layer must not be completely removed, due to the favorable effect on the microclimate, the protection of the saplings and the prevention of the intensive growth of weeds and shrubs (ZGS, 2021). Restoration is then followed by a series of two or three felling: preparatory felling with 30% strength, seeding felling with 50% and final felling. Felling have to be done quite quickly with an interval of 3 to 5 years. The understory tree layer should be completely removed within two to three years after seeding.

Figure 2.1. Introduction of oak stands into regeneration is done after seed year.

Restoration with planting or sowing is necessary in cases where seed trees are partially or completely missing or are of insufficient quality, when the competing vegetation has a very pronounced tendency to develop, in forest stands, damaged due to natural disasters or in cases of the transformation of altered forests, and when in terms of structure, structure and other properties of the stand (micro-climate), natural regeneration is not successful. The planting density should be between 3.000 and 5.000 seedlings/ha. In addition to planting also sowing can be used. The optimal number of acorns for sowing should be between 400 and 800 kg/ha depending on the method of sowing (scattering of seeds, planting seeds). Most suitable tending as defined on the basis of SFM guidelines in Slovenia (ZGS, 2021) and LIFE SySTEMiC results include primarily intensive tending of young trees, which is necessary to ensure the proper stand structure of the future forest. In natural young growth priority to balancing the mixture of tree species is needed. In the initial phase, the biggest problem is the fast-growing understory layer, so it must be removed annually (Figure 2.2) until the oak is no longer threatened. In the case of artificially regenerated oak, regular and timely tending is necessary, twice a year, depending on the conditions on the ground. If the loss is more than 30%, we carry out additional planting with oak and noble deciduous trees (mountain maple, wild cherry) (ZGS, 2021). In the young growth phase oak mildew's negative effect must be controlled since it represents one of the limiting factors of natural regeneration.

Genetic resources of oaks are endangered not only by the loss of natural ecosystems and limitation of seed sources but also by the impact of air pollution for several decades and by long-term climate changes (Bajc *et al.*, 2020). The forest restoration system in oak stands needs to be adapted to the increasingly frequent natural disasters and to determine the priorities for action after natural disasters and methods of restoration of damaged forests. The size of the areas for restoration must be smaller, as this ensures the mosaic structure of future stands and increases their resilience. Nevertheless, we must not ignore the light/growth requirements of individual tree species and narrow down the species diversity of the future young growth.

Figure 2.2. Regular tending of young growth is needed due to the competition of herbaceous and shrub vegetation.

The relationship between natural regeneration and regeneration through planting must follow other strategies, especially in terms of ensuring the constant coverage of forest areas and ensuring the genetic diversity of the young forest. Where possible, natural regeneration is used, as this way the evolutionary process remains less disturbed. The problem arises when the environment changes faster than the trees can adapt. This can lead to reduced vitality and even to a critical point where the population can no longer regenerate itself. The main orientation remains rejuvenation under the canopy and indirect care with the help of the mature stand. Rejuvenation periods need to be critically re-evaluated and shortened wherever possible, or extended in certain forest stands.

With appropriate, sufficiently frequent, and sufficiently intensive tending of oak stands, we can influence on the improvement of the structure of stands and thus reduce susceptibility to natural disturbances and also reduce the impact of negative biotic and abiotic factors. It is also necessary to adjust (mainly reduce) the density of forest stands to ensure greater heterogeneity of stand structure (more vertical layers) and to maintain a diverse vertical, horizontal, and age structure of forest stands (Breznikar, 2021). Classic selective thinning in suitable stand conditions is replaced by situational thinning, which is a significantly less risky way of caring for growing stands. With the increase in the frequency and severity of injuries, the risk of damage to stands also increases, and thus the devaluation of the high investment in tending measures (ZGS, 2021).

3. Landscape genomics

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We used Landscape Genomics approaches to analyse the neutral and adaptive components of genetic diversity to highlight possible patterns of local adaptation in the populations. To study possible patterns of adaptation to the local environment, we used neutral and adaptive molecular markers in combination with spatial data and bioclimatic indicators. Nuclear microsatellite markers (nSSR) were analysed as a measure of neutral genetic variation and structure of the studied populations. Single Nucleotide Polymorphism (SNPs) were genotyped using a target Re-sequencing approach of candidate genomic regions and were analysed as a measure of adaptive genetic variation of the studied population. As a result of *Quercus robur* L. target re-sequencing, about 1600 SNPs were observed in 27 genomic regions relevant for response to one or more abiotic stresses (results reported in deliverable Action B1: SNP road-map of each study site). Through the spatial distribution of SNPs (results reported in deliverable Action B3: Handbook for Sustainable Forest Management), it was possible to observe a high number of site-specific SNPs in all the oak sites analysed. This could be perceived as an early signature of adaptation to the local environment. The presence of a specific set of national SNPs in the sites located in Slovenia is also interesting. This prevalence of SNPs could be interpreted as a sign of adaptation to a Central Europe/continental bio-climatic regime that characterizes the Slovenian region and sets it apart from the more Mediterranean climate found in Italy. To identify local adaptation signatures in oak stands, we conducted GEA analyses. The results of the analysis showed the existence of four different genotypes present in Italy, Croatia and Slovenia. Additionally, an even more interesting finding is the presence of an association between 42 allelic variants and the mean values of the 12 environmental variables considered for these analyses. The presence of these associations could be interpreted as the basal adaptation genotype of oak spread in the Central European range. Of particular interest was finding some site-specific allelic variants associated with a particular country (Italy or Slovenia/Croatia) and individual sites. The presence of allelic variants associated with individual sites could be correlated with the local rather than regional pattern of adaptation. In the environmental association analysis (EAA) it is important to account for neutral genetic structure (Rellstab *et al*. 2015), as neutral genetic structure can produce patterns similar to those expected under non-neutral processes (Excoffier & Ray 2008; Excoffier *et al*. 2009; Sillanpää 2011). Furthermore, the genetic structure of populations was analyzed using STRUCTURE (Pritchard *et al*., 2000) and GENELAND software (Guillot, 2008). Observing each site separately, we found the highest number of allelic variant (21 SNPs) in unmanaged sites (Site 10 – Culatta; Figure 3.1). The presence of a high number of SNPs associated with adaptation to environmental variables at these sites could be correlated with the neutral genetic structure observed for these sites (Aravanopoulos, 2018; Paffetti *et al*., 2012; Stiers *et al*., 2018).

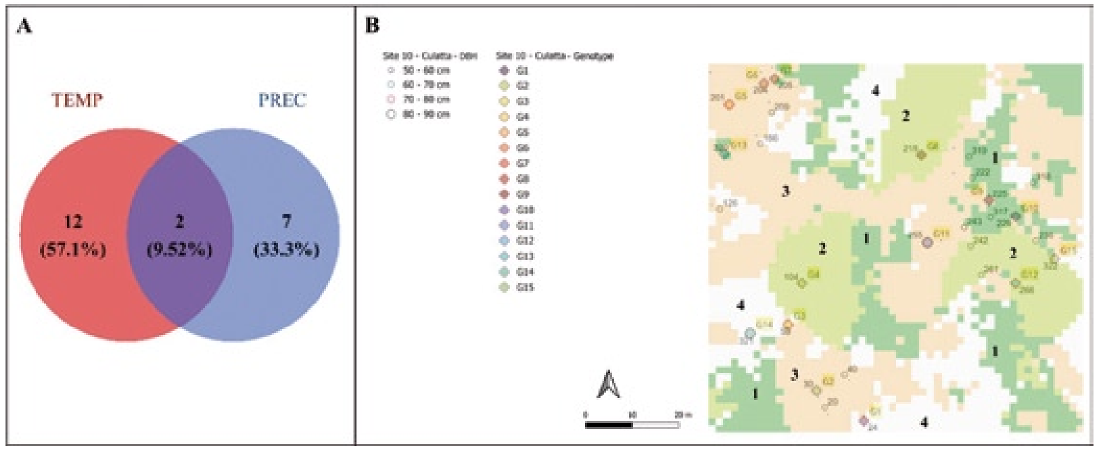

Figure 3.1. LFMM analysis results and genotype distribution map of Site 10 - Culatta. (A) Venn diagram showed the overlapping between SNPS associated with temperature-related and precipitation-related bioclimatic indicators, as a result of LFMM analysis. (B) Spatial distribution of genotype and spatial organization in 4 clusters (GENELAND results). The map displays the individuals present within the study site (circle with black border) and the sequenced individuals. The latter is characterized by coloured circles according to the genotype observed. Identical colours mean identical genotypes.

A similar situation was observed for Site 13 – Nova Gradiška. This site is characterized by a complex spatial genetic structure along with the lowest number of associated SNPs. However, the results for Site 28 – Krakovo (managed with Irregular shelterwood systems) reported a simplified spatial genetic structure with one of the highest numbers of associated SNPs. Management applied to oak stands seems to report simplified spatial genetic structure in response to those observed in the unmanaged sites and in old-growth forest. The results reported in this study could be important in silvicultural management planning, where knowledge of genetic variability from an adaptive perspective could help decision-making processes. In addition, this knowledge could also be used in anticipation of assisted migration works. This is important to preserve the current Forest Genetics Resources (FGR), but also to enrich the existing stand with potentially favourable genotypes.

4. Oak mildew

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Pedunculate oak (*Quercus robur* L.), a keystone tree species in Europe, faces an uncertain future in (near-) natural forests due to challenges in natural regeneration. One of the primary factors contributing to this uncertainty is a fungal disease known as oak mildew (Erysiphe alphitoides complex) (Figure 4.1). The fungi significantly affects the shade tolerance and vertical growth of seedlings and saplings, leading to a marked reduction in their vitality and competitiveness. As a result, natural regeneration under the oak canopy is often hindered by mildew infections (Demeter *et al*., 2021).

When oak powdery mildew infects immature leaves, the powdery coating spreads across the entire leaf surface, leading to uneven development or potential drying. This proliferation is particularly detrimental to saplings, limiting their growth and causing significant mortality. In contrast, the powdery coating on adult leaves remains localized, resulting in moderate damage to mature trees (Thomas *et al*., 2002; Marçais and Breda, 2006). The fungi produce spores (conidia) that are easily dispersed by wind, insects, and splashing water. These spores germinate and infect new plant tissues, especially under conditions of high humidity and moderate temperatures.

Figure 4.1. Pedunculate oak seedling with an oak mildew infection.

As part of the LIFE SySTEMiC project different ways of controlling oak mildew at one of our experimental sites in Krakovo Forest were tested. Krakovo Forest is the largest lowland floodplain forest in Slovenia, dominated by pedunculate oak. The presence of powdery oak mildew is so extensive that it represents one of the limiting factors of natural regeneration. The objective of the study was to assess the impact of planting density and varying concentrations of AQ-10 biopesticide on powdery mildew infection in seedlings. The experiment involved planting in a fenced area, following the 'Protocol for planting experiment: oak powdery mildew control protocol'.

Our results did not show differences between the various treatments, neither in height growth nor in mortality, which averaged between 29.2% and 31.9% across all treatments after two years. Infection intensity proved to be an inappropriate measure in our case because, at the beginning of the growing season during the biocontrol spraying, a large proportion of the leaf area was already damaged or missing due to defoliators (Figure 4.2, right), which hindered reliable assessment. Later in the growing season, 'lammas' growths (second and third flush in mid-summer) replaced most of the leaf area that had developed in spring, leaving the newly formed leaf area untreated. Based on our results, the biofungicide AQ-10 did not exhibit the desired effects against oak mildew, and planting density had no impact.

Figure 4.2. Experimental plot in Krakovo forest (left) and gypsy moth larva (Lymantria dispar L.) (right).

Despite our discouraging results, it remains crucial to explore various methods for protecting against oak mildew, which are primarily implemented in forest nurseries. Effective control of powdery mildew on pedunculate oak seedlings and young oak plants is vital for regeneration areas during regeneration cutting phases. Well-established one- and two-year-old oak plants tolerate powdery mildew well, and the fungus no longer hinders their growth (Pap *et al.*, 2012).

5. GenBioSilvi model

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To investigate biodiversity in forest ecosystems, we analyzed indicators including genetic diversity, forest structure, deadwood, soil diversity, and microhabitat conditions using collected data from other task of the project. In English oak stands (*Quercus robur* L.) we observed that unmanaged or old-growth forests conserved and increased biodiversity. Based on our analysis using nuclear microsatellite (nSSR) data, we observed that Site 10 - Culatta and Site 13 - Nova Gradiška, both unmanaged oak stands, had a complex and heterogeneous spatial genetic structure. Numerous SNPs correlated with bioclimatic indicators were identified, particularly in Site 10 - Culatta (unmanaged) presented a higher number of SNPs correlated with bioclimatic indicators. Dendrometric data indicated the best structure was a multi-layered uneven-aged forest, considering all the species present. Infact, all analyzed sites are mixed English oak stands and these species should be preserved. 28B - Krakovo (Reserve) had the highest deadwood volume and many saproxylic microhabitats, especially around old trees. Based on the obtained results, management types that allow for complex forest structures characteristic of uneven-aged and multilayered stands increase the probability of observing different microhabitat forms. Our model focuses on key indicators like deadwood, microhabitat, and species diversity, guiding sustainable management practices without the need for genetic and soil diversity data collection (Table 5.1).

Table 5.1. Description of selected indicator useful for users to describe the status of the stand.

Categories	Indicators	Description
Forest structure	DBH standard deviation	Variability in tree DBH within the stand
	Percentage of trees in regeneration layer	Presence of the target species natural regeneration
	DBH class distribution curve	Complexity of horizontal and vertical forest structure
	No. of population strata	
Deadwood	Standing deadwood presence	Description the presence of deadwood functioning as microhabitat
	Coarse woody debris	
Species diversity	Species richness	Number of all species present in the stand regarding both the presence of adults' individuals and regeneration
	Percentage of non-target individuals regeneration	
Microhabitat	Percentage of individuals with cavities	Presence of key microhabitat form for biodiversity
	Percentage of individuals with Injuries and wounds	
	Percentage of individuals with Deformation	

Below is the example of the form that showed the compiled form based on the actual data obtained from the Site 10-Culatta (Fig 5.1).

Scheda di valutazione della popolazione forestale - Simulation Site 10 (Culatta)				
Forest managment		Real Data		Implication for Managment
Forests should be managed in a way to preserve their multifunctional role (ecological, social and productive forest functions). This can be achieved only through maintenance of healthy forests and their biodiversity, protection of its natural fertility and water sources as well as other beneficial functions of forests in the water and carbon cycle, sustainable supply of wood and other products from forest, profit and employment.		Unmanaged		
Forest structure indicator	Structural indicator	Real Data	Indicator-specific score	Implication for Horizontal and Vertical Forest structure
Forest structure is both a product and driver of ecosystem processes and biological diversity. Changes in forest structure as a result of management for timber production have undesirable consequences for other components of forest ecosystems	DBH Standar deviation	14,81	☐ Score 1 (DBH SD < 10) ☑ Score 2 (10 ≤ DBH SD ≤ 20) ☐ Score 3 (DBH SD > 20)	Results from annotated parameters ☑ Score 1 (Simplified forest structure without rinnovation) - From 4 to 6 ☐ Score 2 (Simplified forest structure with rinnovation or Complex forest structure without rinnovation) - From 7 to 8 ☐ Score 3 (Complex forest structure with rinnovation) - From 9 to 11 ☐ Score 4 (Complex forest structure with rinnovation present in the total area) - From 12 to 13
	Referes to % of trees in regeneration layer (considering DBH less than 10 cm)	9	☑ Score 1 (% Rinn. < 15) ☐ Score 2 (15 ≤ % Rinn. < 30) ☐ Score 3 (30 ≤ % Rinn. < 50) ☐ Score 4 (% Rinn. ≥ 50)	
	Curve of DBH class distribution	Bell-shaped	☑ Score 1 (Bell-shaped) ☐ Score 2 (Multi-modal) ☐ Score 3 (J-shaped)	
	N° of strata (startification of population)	Bi-stratified	☐ Score 1 (Mono-stratified) ☑ Score 2 (Bi-stratified) ☐ Score 3 (Tri or Multi-stratified)	

Productivity indicators		Real data		Implication for population biodiversity
Forest site productivity is the production that can be realized at a certain site with a given genotype and a specified management regime. Site productivity depends both on natural factors inherent to the site and on management-related factors.	Growing stock (m^3/ha)	367,5 m^3/ha		In managed stands, the minimum growing stock should be around 250-350 m^3/ha.
Biodiversity indicators	**Deadwood indicators**	**Real data**	**Indicator-specific score**	**Implication for stand biodiversity**
Biodiversity conservation is a key objective for sustainable forest management, but the multi-dimensional and multi-scale character of biodiversity renders full assessment difficult at large scale. Therefore, indicators are often used to monitor biodiversity. The quantity and quality of deadwood are commonly used in nature conservation as indicators of forest biodiversity. Additionally, the presence of species different from the target species as well as the presence of specific type of microhabitat are also used to monitor biodiversity in forest stand.	Standing deadwood (including snags) presence	Presence	☐ Score 1 (Absence of standing deadwood) ☑ Score 2 (Presence of standing deadwood)	Results from annotated parameters ☐ Score 1 (Total absence of deadwood) - 2 point ☐ Score 2 (Presence of standing deadwood or Coarse woody debris) - 3 point ☑ Score 3 (Presence of various type of deadwood) - 4 point
	Course woody debris	Presence	☐ Score 1 (Absence of Coarse woody debris) ☑ Score 2 (Presence of Coarse woody debris)	
	Species diversity indicators	**Real data**	**Indicator-specific score**	**Implication for stand biodiversity**
	Species richness (presence of individual of non-target species)	Presence	☐ Score 1 (Absence of other species) ☑ Score 2 (Presence of other species)	Results from annotated parameters ☐ Score 1 (Monospecific site) - 2 point ☐ Score 2 (Sporadic species with none or low regeneration) - 3 point ☑ Score 3 (Sporadic species with high regeneration) - 4 to 6 point
	% of non-target individuals in the smallest diameteric class (10 cm)	38,63	☐ Score 1 (% Rim. < 10) ☐ Score 2 (10 ≤ % Rim. < 30) ☑ Score 3 (30 ≤ % Rim. < 50) ☐ Score 4 (% Rim. ≥ 50)	
	Microhabitat indicators	**Real data**	**Indicator-specific score**	**Implication for stand biodiversity**
	% of individuals with cavities	29,8	☐ Score 1 (% Ind. ≤ 15%) ☑ Score 2 (15% < % Ind. ≤ 50%) ☐ Score 3 (% Ind. > 50%)	Results from annotated parameters ☐ Score 1 (Absence of low number of microhabitat) - 3 point ☑ Score 2 (Sporadic to consistent presence of microhabitats) - 4 to 6 point ☐ Score 3 (High presence of microhabitat) - 7 to 9 point
	% of individuals with injuries and wound	5,14	☑ Score 1 (% Ind. ≤ 15%) ☐ Score 2 (15% < % Ind. ≤ 50%) ☐ Score 3 (% Ind. > 50%)	
	% of individuals with deformation	6,62	☑ Score 1 (% Ind. ≤ 15%) ☐ Score 2 (15% < % Ind. ≤ 50%) ☐ Score 3 (% Ind. > 50%)	
				Final Score: 9

Figure 5.1. Forest population assessment form structure with Site 10 - Culatta.

6. Recommendations for Sustainable Forest Management of Oaks (*Q. robur* L., *Q. pubescens* Willd., *Q. ilex* L.)

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Recommendations for Sustainable Forest Management:

- Oaks are among the most diverse species of forest trees, they are closely related, they can mix, compete, and naturally hybridize with one another.
- Silvicultural system that is most suitable for pedunculate oak forests is irregular shelterwood with larger openings between 0.5 and 2 ha or uniform shelterwood system, which covers oak demand for light.
- Silvicultural systems that are rarely used in the area are the intensive management of even-aged forests, while the coppice system is common in Italy, especially in downy oak and holm oak forests.
- Oak site characteristics can change in short distances. If we want to preserve these characteristics and benefit from their specifics to the maximum extent, suitable mixed tree and forest stand structures should be used.
- All oaks are light-demanding species and at a young age grow quickly in height.
- With the increase of average annual temperatures, oak sites will gradually become drier which will lead to the reduction of suitable areas especially for pedunculate oak.
- The big threat to genetic diversity of the oaks is the introduction of exotic genotypes through plantations. White oaks have very large ecological niches and sometimes occupy extreme habitats (rocky slopes in mountains, dunes, saline soils, peat bog, garigues). These populations are at high risk of disappearing because the number of individuals is low, habitats are unstable and human impact is often considerable.
- Pests and pathogens such as Oak mildew (*Microsphera alphitoides*) represent a serious threat. Mediterranean oaks are facing additional threat in overharvesting and overgrazing and climate change, indiscriminate cutting, improper silvicultural management (coppices or clear cuttings over large areas) and intensive ungulate browsing.
- Since natural regeneration can also be a problem for oaks, regeneration of preserved pedunculate oak stands should be done after the mast oak seed year, with series of feelings and intensive tending of young growth.
- Oak stands are restored where necessary also by planting and sowing, where problems with natural regeneration occur (seed trees are missing, abundant competing vegetation, damages due to natural disasters).
- Intensive tending of young trees is necessary to ensure the proper stand structure and mixture of tree species of the future forest as well as to reduce the competition of fast-growing understory layer.
- Genetic resources of oaks are endangered by the loss of natural ecosystems, by limitation of seed sources and by by long-term climate changes.
- Landscape Genomics is essential to assess neutral and adaptive genetic diversity for understanding the signature of local adaptation in the populations to drive the appropriate silvicultural system.
- Knowledge of genetic variability from an adaptive perspective can improve forest management decisions and anticipate assisted migration efforts. This is important for preserving Forest Genetic Resources (FGR) and enriching stands with favorable genotypes, ensuring forest resilience and genetic diversity.
- For *Quercus robur* L. stands, we observed that the management applied to oak stands seems to report simplified spatial genetic structure in response to those observed in unmanaged sites and old-growth forests.
- The monitoring and study of biodiversity in all its components is crucial for understanding forest ecosystem resilience. For this reason, it is important to collect information regarding genetic diversity, forest structure, deadwood, soil diversity, and microhabitats conditions.
- For *Quercus* spp. stands that showed similar characteristics to those included in our study, we suggest using a type of management that increases forest stand complexity with a multi-layered vertical structure that facilitates pollen dispersal, promotes genetic diversity, and increases new allelic variants crucial for climate change adaptation.
- The use of the GenBioSilvi model could support forest users in checking the status of stand biodiversity and providing guidelines for sustainable management. In fact, we identified key indicators that indirectly describe genetic diversity and represent biodiversity, focusing on deadwood, microhabitat, and species diversity. We concentrated on observable key indicators to describe the status of the analyzed stand.
- The forest restoration system in oak stands needs to be adapted to the increasingly frequent natural disasters, mostly with diversification of the size of the areas for restoration, as this ensures the mosaic structure of future stands and increases their resilience.
- Where possible, natural regeneration is used, as this way the evolutionary process remains less disturbed, and the main orientation remains rejuvenation under the canopy and indirect care with the help of the mature stand.
- With appropriate regeneration, sufficiently frequent and intensive tending of oak stands, we can facilitate the improvement and diversification of the structure of stands, reduce susceptibility to natural disturbances and negative impacts of biotic and abiotic factors as well as conservation and enhancement of genetic diversity of oak stands which significantly reduces risks of oak management in climatically unstable environment.

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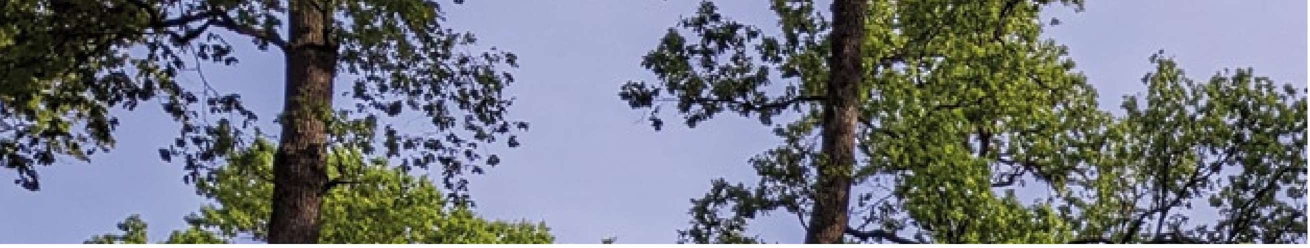

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