Guidelines for Sustainable Forest Management of Pines

(*Pinus nigra* J.F. Arnold, *Pinus pinea* L., *Pinus pinaster* Aiton)

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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 aim of LIFE SySTEMiC Project (Close-to-nature Forest Sustainable Management under Climate Changes) is to use the "modeling 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

Miran Lanšćak

Croatian Forest Research Institute (CFRI), Croatia

Pines in Europe are among the most significant ecological and economic tree genera in the Mediterranean and sub-Mediterranean regions. Globally, they are one of the largest genera taxonomically, with over one hundred species primarily growing in the Northern Hemisphere. Pines inhabit well-lit areas and are adaptable to various ecological conditions, including temperature, moisture, and soil. They can live up to 250 years. Pines are evergreen conifers with characteristic needles, which can be in pairs (two-needled), in threes (three-needled), or in fives (five-needled). Their cones (fruit) mature in the second or third year.

Within LIFE SySTEMiC project, three species of pines were studied in the areas of Croatia, Italy, and Slovenia. Studied species are *Pinus nigra* J.F. Arnold. (Black pine), *Pinus pinaster* Aiton (Maritime pine) and *Pinus pinea* L. (Stone pine). Those three species usually form pure stands, but can be found in mixed stands with other pines. All the mentioned species have a wide distribution range throughout the entire Mediterranean region, as can be seen on the areal distribution maps below (Figures 1.1, 1.2., and 1.3).

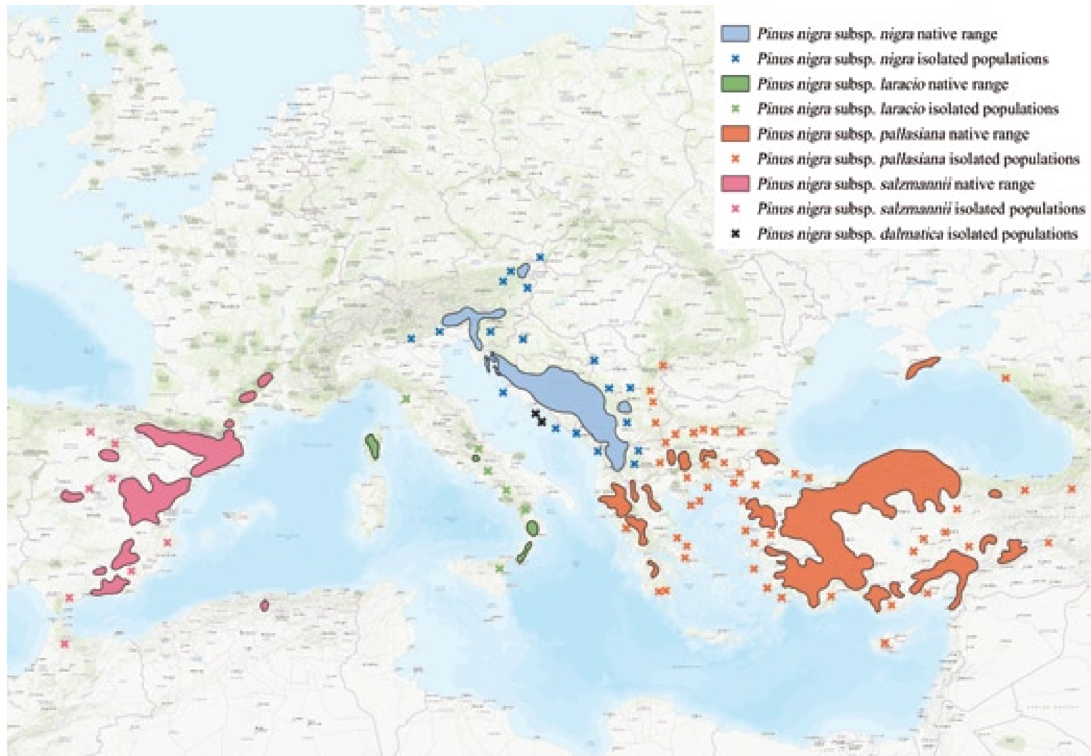

Figure1.1 Black pine distribution range (www.euforgen.org)

Figure 1.2. Stone pine distribution range (www.euforgen.org)

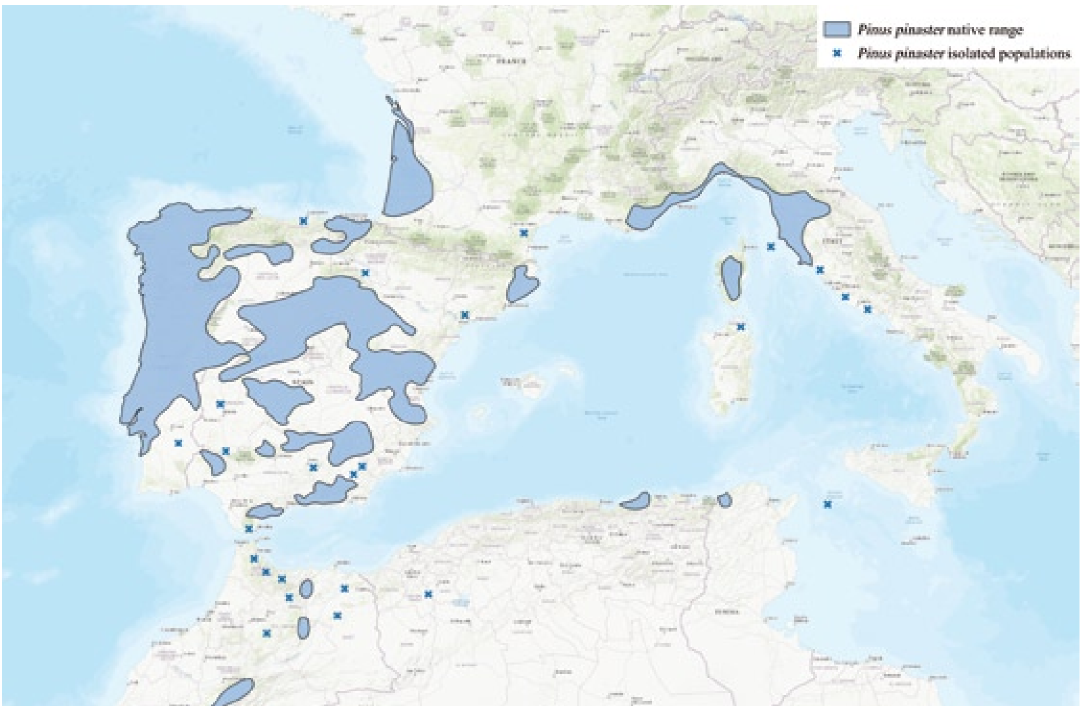

Figure 1.3. Maritime pine distribution range (www.euforgen.org)

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

Miran Lanšćak; Anđelina Gavranović Markić; Sanja Bogunović; Zvonimir Vujnović, Barbara Škiljan, Mladen Ivanković

Croatian Forest Research Institute (CFRI), Croatia

Sustainable and close-to-nature forestry uses forest management methods that promote the conservation of nature and forests to preserve it as a natural ecosystem of all its diverse life forms and relations formed therein. It is based on detailed forest management planning, adapted to individual site and stand conditions and forest functions, and considering natural processes and structures specific to natural forest ecosystems (Veselič, 2008). Silvicultural systems for pine stands should be carefully selected to promote close-to-nature approaches and mimic natural processes in forest stands. Within LIFE SySTEMiC four silvicultural approaches in pine stands have been analysed (Table 2.1). In LIFE SySTEMiC project 10 pine stands, which correspond to 4 European Forest Types (EFT) have been studied: 3.3 Alpine Scots pine and Black pine forest; 10.1 Mediterranean pine forest; 10.2 Mediterranean and Anatolian Black pine forest and 14.1 Plantations of site-native species.

Table 2.1. List of the sites for *Pinus nigra* J.F. Arnold., *Pinus pinea* L. and *Pinus pinaster* Aiton of the LIFE SySTEMiC project.

Id	Site name	Country	Species	EFT*	Structure	Sylvicultural system
08	Terminaccio	Italy	*P. pinea*	10.1	Even-aged	Clear-cutting and planting
9A	Fossacci	Italy	*P. pinea*	10.1	Even-aged	Clear-cutting and planting
9B	Fossacci	Italy	*P. pinea*	10.1	Even-aged	Clear-cutting and planting
9C	Fossacci	Italy	*P. pinea*	10.1	Even-aged	Clear-cutting and planting
15	Zadar	Croatia	*P. pinea*	10.1	Even-aged	Clear-cutting and planting
17	Klana	Croatia	*P. nigra*	3.3	Even-aged	Uniform Shelterwood
18	Brač	Croatia	*P. nigra*	10.2	Even-aged	Irregular shelterwood
19	Pelješac	Croatia	*P. pinaster*	10.1	Even-aged	Post fire, seed trees remaining; Irregular shelterwood
22	Mlake	Slovenia	*P. nigra*	14.1	Even-aged	Individual tree selective thinning
31	Mljet	Croatia	*P. pinea*	10.1	Uneven-aged/ Old-growth	Irregular shelterwood

* EFT = European Forest Type: 3.3 Alpine Scots pine and Black pine forest; 10.1 Mediterranean pine forest; 10.2 Mediterranean and Anatolian Black pine forest and 14.1 Plantations of site-native species).

As part of the LIFE SySTEMiC project, three species of pine trees were studied; *Pinus nigra* J.F. Arnold with subspecies *Pinus nigra* subsp. *dalmatica* (Vis.) Franco, *Pinus pinea* L. and *Pinus pinaster* Aiton.

Pinus nigra J.F. Arnold and *Pinus nigra* subsp. *dalmatica* (Vis.) Franco

Black pine (*Pinus nigra* J.F. Arnold) is a evergreen conifer native to the Mediterranean region and parts of Europe. It can be subdivided into five subspecies based on geographical distribution, needle length, and needle stiffness: *P. nigra* J.F. Arnold subsp. *nigra*, distributed in southeastern Austria, northern Italy, the Balkan Peninsula, Bulgaria, Romania, Turkey-in Europe; *P. nigra* subsp. *Salzmannii* (Dunal) Franco, distributed in southwest Europe, France (Hérault, Pyrenees), Spain, Algeria and Marocco, *P. nigra* subsp. *larico* (Poir.) Palib. Ex Maire, distributed in France and Italy; *P. nigra* subsp.

dalmatica (Vis.) Franco, distributed in Croatia; *P. nigra* subsp. *pallasiana* (Lamb.) Holmboe, distributed in Greece, Cyprus, southwest Bulgaria, southeast North Macedonia, south Albania, and from Crimea along the Black Sea coast to Turkey (Gaussen *et al*. 1993, Farjon 2017). The species grows in association with *Pinus sylvestris* L., *Pinus mugo* Turra, *Pinus halepensis* Mill., *Pinus pinea* L. and *Pinus haldreichii* Christ (Burns and Honkala 1990).
Black pine typically forms pure stands but can also be found in mixed stands together with other pines, especially with *Pinus* sylvestris (Isajev *et al*., 2004). This medium-sized pine that can grow up to 30 meters (rarely 40-50 meters) tall. Young black pine trees are tall and slender in shape, becoming rounder as the tree gets older, in some cases even developing a flattened, umbrella-shaped crown (Isajev *et al*. 2004.). Western varieties exhibit pale plaques, while eastern subspecies have darker, almost black grooves. In older trees the fissures become very deep, and the plaques are much bigger (Eckenwalder 2009). Buds are ovoid, pointed and resinous. Needles, which are growing in pairs, are 8-15(19) cm long, 1-2 mm thick, strait or curved and finely serrated. The colour is green, from pale to deep according to provenance, and have on each of the two sides 12-24 rows of stomata. They persist on the tree for 3-4 (8) years (Willis *et al*. 1998).
Black pine is a monoecious species. Reproductive maturity is reached at the 15-20 years of ageMast seeding occurs every two to five years. Black pine stands exist at altitudes ranging from 350 m to 2200 m, with optimal altitudinal range being between 800 and 1500 m (Praciak *et al*. 2013). It can grow on a variety of soils, from podzolic sands to limestone, often dependent on region and climate (Farjon and Filer, 2013). Black pine can grow in both extremely dry and humid habitats with considerable tolerance of temperature fluctuations. It is phytophilous, shade intolerant and can tolerate well winds, drought and salty soils.

Figure 2.1. Forest seed object of *Pinus nigra* J.F. Arnold subsp. *dalmatica* (Vis.) Franco on island Brač, Croatia

Figure 2.3. Forest seed object of *Pinus nigra* J.F. Arnold in Klana, Croatia

Pinus pinea L.

Stone pine (*Pinus pinea* L.), also known as umbrella pine, is an evergreen conifer native to the Mediterranean region, distributed from Portugal to Syria and along some coastal areas of the Black Sea (Farjon and Filer, 2013). Its original natural distribution is challenging to determine due to extensive cultivation and diffusion since pre-Roman times, making it difficult to distinguish indigenous areas from those where it was planted. Due to its economic importance, human activity has significantly influenced its current geographical and genetic diversity.
Stone pine is widely cultivated in Spain, Portugal, Italy, and Turkey for purposes such as fruit and wood production, environmental protection, and amenity planting. It has also been introduced successfully to North Africa, Argentina, and South Africa (Bussotti, 1996).
Stone pine is a medium-sized tree, growing up to 25-30 meters with trunks exceeding 2 meters in diameter. The crown is globose and shrubby in youth, becoming umbrella-shaped in mid-age and flat and broad in maturity. The trunk is often short with numerous upward-angled branches with foliage near to the ends. The bark has a complex structure. It is ash grey and fissured in young trees, later it is reddish brown and separated by deep, longitudinal fissures between long grey and flat scaly plates. Buds are about 1 cm long, with brown scales. Needles are bright green, in fascicles of two, on average 8-15 cm long with an sharp apex and stomata on each side. They persist on the tree for 2-3 years. Stone pine is monoecious species. Reproductive maturity in isolated trees begins when trees are 15-20 years of age, and in forest stands when trees are about 20-30 years of age. Yellow pollen catkins are located in clusters at the base of the seasons shoot and ovulate cones are erect and about 2 cm long. Pollination is *anemophilous*, occurring from May to June when the pollen is released in great quantity. Fertilization takes place two years post-pollination, with cones maturing in the third year. Mature cones, which are 8-14 cm long, broadly ovoid, sessile, and isolated, remain attached for several years post-opening. Seeds are pale brown, covered with a black powder, 15-20 mm long,

heavy, with easily detachable wings that are ineffective for wind dispersal. Stone pine exhibits mast seeding with significant variation in seed production (Eckenwalder, 2009; Johnson and More, 2006).
Stone pine occupies a broad range of climate and soil conditions along the Mediterranean basin. It can be found from sea level up to 500-600 m in the northern Mediterranean and up to 800-1400 m in the east Mediterranean. It predominantly forms pure stands, naturally regenerating by seeds. Stands are found within the thermo- and meso-Mediterranean climate zones and subhumid bioclimates, characterized by hot, dry summers and rainy, mild winters. It is light-demanding and prefers acidic or neutral sandy soils although it tolerates slightly calcareous soils (Montero *et al*. 2008).

Figure2.4. Old trees of *Pinus pinea* L. on island Mljet, Croatia

Pinus pinaster **Aiton**

Pinus pinaster Aiton, the maritime pine, is a widespread evergreen tree native to the southern Atlantic Europe region and parts of the western Mediterranean.
The maritime pine range is primarily concentrated in the western Mediterranean Basin and the southern Atlantic coast of Europe. It occurs in the Iberian Peninsula, southern France, western Italy, western Mediterranean islands, northern Morocco, Algeria and Tunisia. Its presence has expanded due to artificial plantations and naturalization, reaching southwestern France's coast, Adriatic countries, and even northern Europe, including the United Kingdom and Belgium (Jalas and Suominen 1973, Critchfield and Little 1966, Pereira 2002, Farjon and Filer 2013). Two primary factors have influenced the current fragmented distribution of *P. pinaster*: the discontinuity and altitude of mountain ranges, which isolate even nearby populations, and significant human impact through deforestation and land use changes (Alía and Martín 2003). Despite these challenges, the species continues to be widely planted and cultivated in various countries, both within and beyond its natural range. It ranges from sea level in coastal lowlands to moderate elevations up to 1600 m in the Iberian Peninsula and island Corsica, and up to about 2000 m in Morocco (Wahid *et al*. 2006, Farjon 2010). This elevation range showcases the species' adaptability to different altitudes and climatic conditions. Naturally, it grows in warm temperate areas with oceanic climatic influences, particularly in humid and sub-humid regions with annual rainfall exceeding 600 mm. However, it can survive in regions with only 400 mm of annual precipitation if there is adequate atmospheric moisture. It is not tolerant to shade and exhibits preference for siliceous soils with a coarse texture, especially sandy soils, dunes and other poor substrates (Viñas *et al*. 2016).

In today's era of extreme climate conditions, particularly high summer temperatures and prolonged droughts in areas where pines grow, forest fires pose a significant threat to pine forest stands. Fortunately, nature has shown many times that it can fend for itself and ensure its natural regeneration, which is especially evident with pines. Pines produce orthodox seeds that can be stored for many years with a high germination rate and vitality. If collected in a timely manner and stored properly, these seeds can be crucial for the continued production of forest reproductive material (seedlings) for forest restoration after fires. Additionally, forest fires heat mature cones to high temperatures, causing the cones to slowly open and disperse seeds across the burned area, ultimately leading to very good natural regeneration of the stands.

Figure 7. Forest Site 19 - Pelješac of *Pinus pinaster* Aiton in five-year period (week after forest fire in 2015 and site in 2023) on peninsula Pelješac, Croatia.

3. Landscape genomics

Cesare Garosi[1], Cristina Vettori[1,2], Miran Lanšćak[3], Marko Bajc[4], Donatella Paffeti[1]

[1] *Department of Agriculture, Food, Environment and Forestry (DAGRI), University of Florence (UNIFI), Italy*
[2] *Institute of Bioscience and Bioresources (IBBR), National Research Council (CNR), Italy*
[3] *Croatian Forest Research Institute (CFRI), Croatia*
[4] *Slovenian Forestry Institute (SFI), Slovenia*

We used Landscape Genomics approaches to analyze the neutral and adaptive component of genetic diversity to highlight possible patterns of local adaptation in the populations. Neutral and adaptive molecular markers was used in combination with spatial data and bioclimatic indicators. Single Nucleotide Polymorphism (SNPs), genotyped using a target re-sequencing approach of candidate genomic regions, were analysed as a measure of adaptive genetic variation in the studied population. As a result of *Pinus pinea* L. target re-sequencing, about 500 SNPs were genotyped in 28 genomic regions relevant for response to one or more abiotic stresses (results reported in deliverable Action B1: SNP road-map of each study site). Moreover, as a result of *Pinus nigra* J.F.Arnold target re-sequencing, about 2000 SNPs were observed in 21 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 and national-specific SNPs for all the black pine sites studied. Despite the different bioclimatic region of each analyzed site, the high number of site-specific SNPs reported could be interpreted as a sign of adaptation to local environment.

In order to identify local adaptation signature, we conducted Genome Environment Associations (GEA) analyses. The global analysis allowed us to identify possible patterns of adaptation to the bioclimatic conditions that characterize the range of *Pinus* spp. The results of the analysis showed the existence of three different clusters for *P. pinea*, and four clusters for *P. nigra*, present in Italy, Croatia and Slovenia. Additionally, an even more interesting finding is the presence of association between some allelic variants and the mean values of the 12 bioclimatic indicators considered for these analyses: 39 SNPs for *P. pinea* and 14 for *P. nigra* (as reported in Deliverable Action B1: Production of maps of spatial distribution of genetic diversity and of correlation between allele distribution and environmental variation).

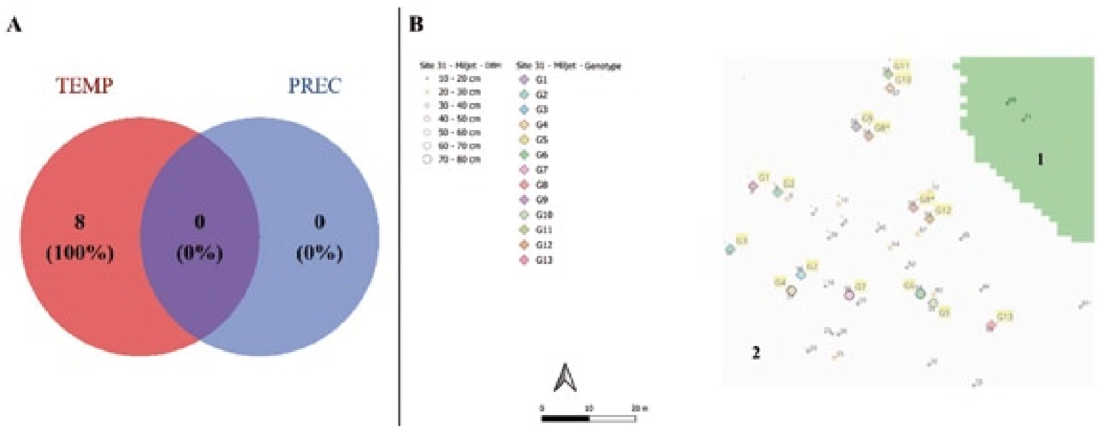

Figure 3.1. LFMM analysis results and genotype distribution map of Site 31 - Mljet. (A) Venn diagram showed the overlapping between SNP associated with temperature-related and precipitation-related bioclimatic indicators, as a result of LFMM analysis. (B) Spatial distribution of genotype and spatial organization in 3 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.

The presence of these associations could be interpreted as the basal adaptation genotype of *Pinus* spp. spread in the Central European range. The presence of site-specific allelic variants 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). The genetic structure of populations was analyzed using STRUCTURE (Pritchard *et al.*, 2000) and GENELAND software (Guilllot, 2008). For *P. pinea*, we found a low to moderate number of correlated allelic variates in each sites. In particular, we found that Site 09 - Fossacci presented a higher number of SNPs correlated with bioclimatic indicators (20 SNPs). Despite the highest number of correlated SNPs reported for Site 09, the spatial genetic structure is simplified (1 cluster, results reported in deliverable Action B1: Production of maps of spatial distribution of genetic diversity and of correlation between allele distribution and environmental variation). Instead, as reported in Figure 3.1, we had observed a less simplified spatial genetic structure and a high number of correlated SNPs in Site 31 - Mljet. Based on the results obtained, it is possible to assume that favouring the natural regeneration of *P. pinea* could produce good results in terms of genetic diversity and adaptation of populations to future environmental changes.

For *P. nigra*, a completely different situation was observed. Comparing managed to unmanaged sites, we have observed a general complex spatial genetic structure with reduced number of correlated SNPs. Site 18 – Brač (Figure 1.3.2) and Site 22 - Mlake, reported the highest values of adaptive genetic diversity. Less impactful management types, such as individual tree selection, appear to report population with a high number of allelic variants associated with response to bioclimatic indicators. Instead, simplified spatial genetic structure and low number of correlated SNPs were reported for unmanaged stands. 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. This is important to preserve the current Forest Genetics Resources (FGR), but also to enrich the existing stand with potentially favourable genotypes.

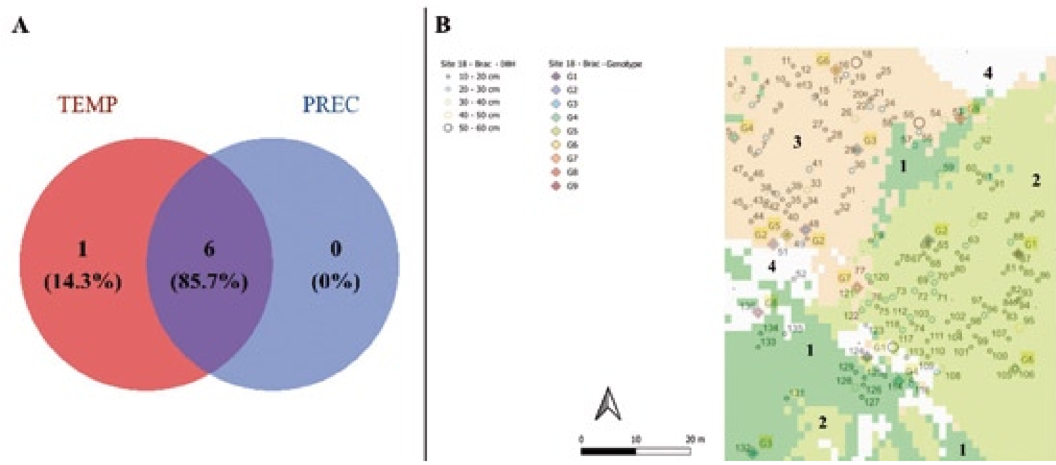

Figure 3.2. LFMM analysis results and genotype distribution map of Site 18 – Brač. (A) Venn diagram showed the overlapping between SNPS associated with temperature-related and precipitation-related bioclimatic indicators, as a result of LFMM analysis. (B) Spatial distribution of genotype and spatial 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.

4. GenBioSilvi model

Roberta Ferrante[1,2], Cesare Garosi[1], Cristina Vettori[1,3], Davide Travaglini[1], Donatella Paffetti[1]

[1] *Department of Agriculture, Food, Environment and Forestry (DAGRI), University of Florence (UNIFI), Italy*
[2] *NBFC, National Biodiversity Future Center, Italy*
[3] *Institute of Bioscience and Bioresources (IBBR), National Research Council (CNR), Italy*

To investigate biodiversity in forest ecosystems, we analyzed indicators including genetic diversity, forest structure, deadwood, soil diversity, and microhabitat conditions thanks to collected data from other tasks of the project. Several studies have highlighted the reduced genetic variability of stone pine (*Pinus pinea* L.) compared to other conifer species (Vendramin *et al.*, 2008; Carrasquinho *et al.*, 2013; Sáez-Laguna *et al.*, 2014; Mutke *et al.*, 2019), attributing this to historical population bottlenecks, limited gene flow, clonal propagation, and its patchy distribution in the Mediterranean region. Despite its low genetic diversity, *P. pinea* exhibits phenotypic plasticity allowing adaptation to diverse environmental conditions through mechanisms such as epigenetic modifications. As reported in deliverable Action B2: Forest ecosystem biodiversity and modelling, based on the results obtained, we assessed that stone pine stands exhibited a low level of biodiversity.
Based on our analysis using nuclear microsatellite (nSSR) data, all sites exhibited simplified spatial genetic structures. However, we observed high genetic diversity in SNPs associated with genes involved in responding to abiotic stress.

Site 09 – Fossacci, managed through clearcutting and planting, showed the highest adaptive genetic diversity values. Favouring the natural regeneration of *Pinus pinea* L. could enhance genetic diversity and adaptability to future environmental changes. Through dendrometric data, we found that the optimal forest structure was multi-layered with natural regeneration, observed in all managed sites except Site 15 – Zadar, which displayed predominantly adult trees with limited regeneration. Multilayered uneven-aged forests create ideal conditions for natural regeneration by creating canopy gaps and promoting sporadic species occurrence and pollen dispersal, thereby enhancing genetic diversity. The volume of deadwood was low in all sites but Site 09 – Fossacci exhibited the highest amount of deadwood. Regarding the frequency of microhabitats, epixylic microhabitats were less frequent than saproxylics across all sites, with epixylic serving as crucial indicators of ecosystem conditions and biodiversity. Management practices promoting complex forest structures, such as uneven-aged and multi-layered stands, increase microhabitat diversity.
Pinus nigra J.F. Arnold is commonly used in challenging environments due to its resilience. It has been commonly used for reforesting areas with challenging soils and severe climatic conditions (Dias *et al.*, 2020).
Based on the analysis reported in Deliverable Action B2 of the GenBioSilvi model, it was found that all sites exhibited high genetic diversity, but significant differences between sites were not conclusive despite varying management types. Specifically, in managed forests using individual tree selection system and in unmanaged forest, the analysis of genetic diversity based on nSSR data revealed a simplified genetic structure in the unmanaged site, suggesting management influences on regeneration potential. Moreover, we observed the presence of high genetic diversity in SNPs associated with abiotic stress response genes, particularly in Site 22 - Mlake, which reported the highest values of adaptive genetic diversity.
Based on our findings, promoting natural regeneration of *Pinus nigra* J.F. Arnold could significantly enhance genetic diversity and improve population adaptation to future environmental challenges. The analyzed sites consistently exhibited a bell-shaped distribution of tree diameters and a vertical stratified structure dominated by non-target, hard deciduous species. However, there was limited regeneration of the target species observed across all locations. Unmanaged sites, particularly Site 22 - Mlake, displayed the highest volume of deadwood, which is crucial for supporting biodiversity. In addition to deadwood, we observed varying levels of saproxylic microhabitats in managed sites; for instance, at Site 22 - Mlake, saproxylic microhabitats were more prevalent than epixylic microhabitats, whereas at Site 18 - Brač, the opposite was observed. These microhabitats are vital indicators of ecosystem health and contribute significantly to biodiversity.
Furthermore, management practices such as individual tree selection promoted diverse microhabitat forms, enhancing overall ecological resilience. While all studied sites primarily consisted of pure black pine stands, Site 22 - Mlake stood out for its high diversity of non-target species, suggesting beneficial associations for optimal growth conditions alongside black pine.
We did not pursue developing the form for *P. nigra* and *P. pinea* due to an insufficient number of sites, which prevented us from accurately representing and distinguishing multiple scenarios necessary for a comprehensive assessment of biodiversity.
Similarly, *Pinus pinaster* Aiton underwent analysis using methodologies similar to those for *P. nigra* and *P. pinea*. However, the challenge of having only one site for each species limited our ability to achieve statistically significant results.

5. Recommendations for Sustainable Forest Management of Pines (*P. nigra* J.F. Arnold., *P. pinea* L., *P. pinaster* Aiton)

Miran Lanšćak[1], Anđelina Gavranović Markić[1], Sanja Bogunović[1], Zvonimir Vujnović[1], Barbara Škiljan[1], Davide Travaglini[2], Cesare Garosi[2], Cristina Vettori[2,3], Donatella Paffetti[2], Roberta Ferrante[2,4], Mladen Ivanković[1]

[1] *Croatian Forest Research Institute (CFRI), Croatia*
[2] *Department of Agriculture, Food, Environment and Forestry (DAGRI), University of Florence (UNIFI), Italy*
[3] *Institute of Bioscience and Bioresources (IBBR), National Research Council (CNR), Italy*
[4] *NBFC, National Biodiversity Future Center, Italy*

General recommendations

- Landscape Genomics is essential to assess neutral and adaptive genetic diversity for understanding the signature of local adaptation in the populations which can drive the sylviculture practices.
- Knowledge of genetic variability from an adaptive perspective can improve forest management decisions and anticipate assisted migration efforts. This is crucial for preserving Forest Genetic Resources (FGR) and enriching stands with favorable genotypes, ensuring forest resilience and genetic diversity.
- 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 microhabitat conditions.
- For *Pinus* spp. stands with characteristics like those in our study, which typically show low levels of biodiversity, except for *Pinus nigra* J.F. Arnold, 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 important for climate change adaptation.

Recommendations for Sustainable Forest Management of *Pinus nigra* J.F. Arnold (black pine)

- Pioneer and heliophilous species and due to its characteristics as a pioneer species, it has been used in reforestation projects for soil protection.
- Silviculture of black pines in the Mediterranean Countries varies between clearcutting and various types of clear felling (strip or patch), irregular or uniform shelterwood systems, and selection cuttings.
- Clearcutting with planting is usually carried out on 1-3 hectares. Clear felling (strip or patch) with natural regeneration by lateral dissemination is carried out on small areas; natural regeneration by lateral dissemination is facilitated by the burning of utilisation residues and the

scarification produced on the soil by the dragging of logs. In the absence of regeneration, planting is used.

- When irregular or uniform shelterwood systems are used, the natural regeneration takes place under the shelter and protection of the mature stand.
- The small group selection method has been reported for *P. nigra* subsp. *larico* (Poir.) Palib. Ex Maire in Calabria, Southern Italy. This method has contributed to the maintenance of pure pine stands with complex uneven-aged structures in private forests (Ciancio *et al.*, 2006).
- For *Pinus nigra* stands, we recommend less impactful management practices, such as individual tree selective thinning, which are associated with populations having a high number of allelic variants in response to environmental variables. Instead, simplified spatial genetic structure and a low number of correlated SNPs were reported for unmanaged stands.
- Based on the experiences of the LIFE SySTEMiC project, forest management systems based on the natural regeneration of pines are best suited to promote genetic diversity and forest adaptation to future environmental changes.
- In case of reforestations carried out for soil protection, renaturalisation is used as a silvicultural and management approach which tends to favour natural evolutionary processes through the system's ability to autonomously increase its complexity and biodiversity (Nocentini, 2006).

Recommendations for Sustainable Forest Management of *Pinus pinea* L. (stone pine)

- Implement natural regeneration-based silviculture as a reliable option for sustainable management (Manso *et al.*, 2014).
- Fence out livestock to ensure natural regeneration, or use artificial regeneration in gaps or old areas (Montero et Cañellas, 1999).
- Manage for uneven, multi-aged structures using group selection systems to stimulate gene flow, especially in locations with abundant advanced regeneration (Barbeito *et al.*, 2008,; Ciancio *et al.*, 2009; Mechergui *et al.*, 2021).
- Select and plant genotypes that are better adapted to projected climatic conditions, focusing on those with traits that enhance drought resistance and overall resilience
- For *Pinus pinea* stands, it is possible to assume that favoring natural regeneration of *P. pinea* could increase genetic diversity important for adaptation of populations to future environmental changes.
- Target stand densities of 125-150 stems/ha at the beginning of regeneration fellings and replace intense uniform shelterwood systems with more gradual fellings to ensure seed arrival into gaps (Calama *et al.*, 2017).
- Use selective thinning to manage stand density, which can improve light conditions and support the regeneration of *Pinus pinea* and other species.
- Control understory vegetation density simultaneously with regeneration fellings (Ciancio *et al.*, 1986).
- Regular monitoring and control measures are essential to manage pests like the pine tortoise scale (*Toumeyella parvicornis*) and the western conifer seed bug (*Leptoglossus occidentalis*). Integrated pest management (IPM) strategies that include biological control, chemical treatments, and habitat manipulation should be implemented to manage pest populations effectively.
- Increase awareness and preparedness for fire risks, especially in tourist areas during the summer.
- Implement measures to protect against coastal erosion and prevent seawater infiltration, which can stress *Pinus pinea* stands.
- Diversify income sources by promoting ecotourism, sustainable harvesting of non-wood forest products, and exploring market opportunities for certified wood products.
- Implement adaptive management practices that allow for modifications based on monitoring results and new research findings.

Recommendations for Sustainable Forest Management of *Pinus pinaster* Aiton (maritime pine)

Pinus pinaster Aiton, the maritime pine, is an adaptable and resilient tree species native to the southern Atlantic Europe region and parts of the western Mediterranean. In order to ensure Sustainable Forest Management, the following recommendations are proposed:

- Site selection: choose sites with warm temperate climates influenced by oceanic conditions. Maritime pine grows in humid and sub-humid regions with annual rainfall exceeding 600 mm, although it can survive in areas with only 400 mm of annual precipitation if atmospheric moisture is sufficient (Viñas *et al.*, 2016).
- Soil: select siliceous soils with a coarse texture, especially sandy soils, dunes and other poor substrates (Viñas *et al.*, 2016). Avoid shaded areas as *P. pinaster* is not tolerant to shade.
- Elevation range: *P. pinaster* can be planted across a wide elevation range, demonstrating its adaptability to different altitudes and climatic conditions. It ranges from sea level in coastal lowlands to moderate elevations up to 1600 m in the Iberian Peninsula and island Corsica, and up to about 2000 m in Morocco (Wahid *et al.*, 2006, Farjon 2010).
- Forest structure: *P. pinaster* is managed in pure stands. The preference for even-aged stands is related to easier management, the enhancement of wood quantity and quality, and disturbances such as fires, which typically lead to a single generation of new trees shortly after the distur-

bance, provided there are sufficient seeds available.

- Post-fire management: in areas affected by forest fires, leave seed trees to facilitate natural regeneration. *P. pinaster* cones slowly open after being heated by a forest fire (Idžojtić, 2013), releasing seeds and aiding regeneration.
- Dead wood and tree-related microhabitats: maintain an adequate amount of deadwood in the forest. Deadwood plays a crucial role in biodiversity by providing habitats for various species. In post-fire areas, higher volumes, up to 42 m^3/ha, can be beneficial. Preserve tree-related microhabitats such as cavities, injuries, and wounds to support wildlife diversity.

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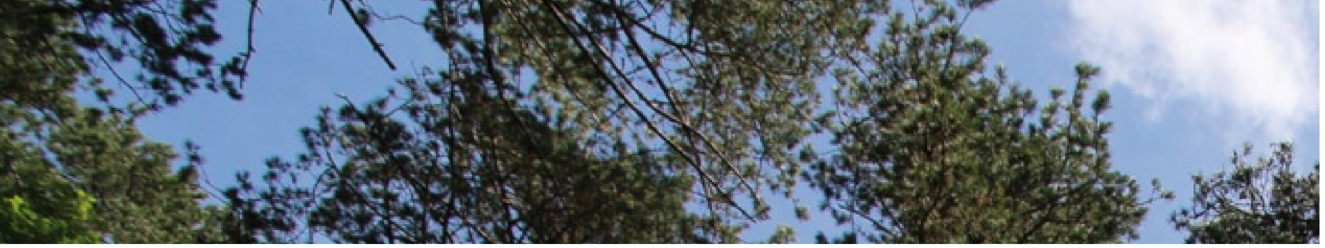

Beneficiary's name
Department of Agriculture, Food, Environment and Forestry (DAGRI), University of Florence (UNIFI), Italy (Coordinator)
Croatian Forest Research Institute (CFRI), Croatia
D.R.E.A.M., Italy
Ente Parco Regionale Migliarino San Rossore Massaciuccoli (MSRM), Italy
Slovenian Forestry Institute (SFI), Slovenia
Slovenia Forest Service (SFS), Slovenia
Unione dei Comuni Montani del Casentino (UCCAS), Italy

Contributors
DAGRI-UNIFI: Cristina Vettori (IBBR-CNR), Roberta Ferrante, Cesare Garosi, Francesco Parisi, Davide Travaglini, Donatella Paffetti
CFRI: Sanja Bogunović, Mladen Ivanković, Anđelina Gavranović Markić, Barbara Škiljan, Zvonimir Vujnović, Miran Lanšćak
MSRM: Francesca Logli
SFI: Marko Bajc, Rok Damjanić, Natalija Dovč, Tijana Martinović, Tanja Mrak, Tina Unuk Nahberger, Nataša Šibanc, Marjana Westergren, Hojka Kraigher
SFS: Andrej Breznikar, Kristina Sever

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Project's contact details
Coordinator and scientific responsible of the project
Donatella Paffetti - DAGRI-UNIFI
Via Maragliano, 77
50144 Firenze
Italy
donatella.paffetti@unifi.it

Project Manager
Cristina Vettori – IBBR-CNR
Via Madonna del Piano, 10
50019 Sesto Fiorentino (FI)
Italy
cristina.vettori@cnr.it

Communication Manager
Davide Travaglini – DAGRI-UNIFI
Via San Bonaventura, 13
50145 Firenze
Italy
davide.travaglini@unifi.it

Website
https://www.lifesystemic.eu

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