Guidelines for Sustainable Forest Management of Silver fir

(Abies alba Mill.)

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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 detailed protocols: https://www.lifesystemic.eu/

LIFE SySTEMiC

1. Introduction

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Silver fir is a monoecious wind pollinated and usually allogamous tree species from temperate (including Mediterranean and continental) European mountainous forests (see the distribution map in Figure 1.1, EUFORGEN 2009 (www.euforgen.org)).

Figure 1.1. Silver fir distribution range (EUFORGEN 2009, www.euforgen.org).

It can grow on a wide range of soil types, except hydromorphic and compressed soils. It is very shade tolerant and can survive under the tree cover for decades. It can grow to a height of 50 (60) m in pure stands, but usually it is mixed with Norway spruce and/or pine trees at the upper forest range, and with European beech in lower elevations. It may reach its reproductive phase at 20 years, but usually after 60 years of age. The female flowers are mainly on the upper-most branches, while male flowers appear a little lower in the crown. It is considered a week seed producer since few cones reach maturity due to insects and late frosts. It flowers from April till June, depending on the elevation, and the cones reach maturity in 90 to 120 days. The mature cones are of yellowish - brownish colour, growing upwards on the branches and fall apart when the seeds ripen, so that only the main axis remains. Depending on the site conditions, cones disintegrate, and the seeds are dispersed with wind between September and October. Seed collection needs to be well timed, so that the matured cones can be collected (by climbing from standing or from felled trees) before they disintegrate (in Slovenia in mid September). Mast years usually occur periodically (every 4-6 years), but some trees, also depending on the site, can bear cones every year (Kavaliauskas *et al.*, 2020).

The cones can be collected for economical purposes if at least 50% of full seeds are visible on longitudinal cross-cut. One liter of fresh seeds weighs usually around 400 g and the seeds have 8-11% water content. In 1 kg of cones can be 15-30 cones, and in 1 kg of seeds about 14.000-23.000 de-winged seeds. Each cone can bear 260-290 seeds. Seed storage at around 8% water content is possible for 3 to 5 years in hermetically sealed containers at -10 to -15oC. Silver fir embryo is dormant, cold stratification for 3-7 weeks is needed prior to sawing (Kraigher 2024; Regent, 1980; USDA 2008).

Silver fir, especially its saplings, is susceptible to temperature regime, late frosts and prolonged drought. Its regeneration is also highly endangered by browsing, and the changing climate influences its lower resistance to pests and diseases, especially close to the Mediterranean regions. Among pests and diseases, Kavaliauskas *et al.* (2020) specifically mention Ips typographus L., *Cinara pectinata* Nördlinger and *Epinotia nigricans* Herrich-Schäffer damage to its bark and buds, and *Armillaria mellea* P. Kumm agg. and *Heterobasidium annosum* Bref. responsible for root and lower trunk rot, leading to damaged silver fir inclination to windthrows.

The silver fir gene pools are well structured latitudinally into a Balkan-South Italian, a Central European-North Italian, an Alpine, a Southern French and a Pyrenean gene pool (GenTree 2020), which is later subdivided into an Eastern and a Western one (Scotti-Santaigne *et al.*, 2021). However, the pattern of distribution of genetic diversity differs depending on the molecular markers used (FORGENIUS 2023; GenTree 2020; Piotti *et al.*, 2017; Teodosiu *et al.*, 2019).

2. GUIDELINES ON SUSTAINABLE FOREST MANAGEMENT AND ADAPTATION OF FOREST TO CLIMATE CHANGE

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2.1. Sustainable, Close-to-Nature and Multifunctional Forest Management

Sustainable, close-to-nature and multifunctional forest management is planned in a way to preserve forests and all forest functions and ecosystem services, while at the same time guaranteeing profit to forest owners.It can be described by the principles of the "Slovenian Forestry School" as described by Kraigher *et al.* (2019):

- forest management is adapted to site characteristics and natural development of forests;
- active protection of natural populations of forest trees;
- protection and conservation of biodiversity in forests (including genetic diversity);
- supporting the bio-ecological and economic stability of forests by increasing the growing stock;
- tending of all developmental stages and all forest forms for supporting of vital and high-quality forest trees, which could fulfill optimally all functions of forests;
- natural regeneration is supported in all forests;
- if seed or seedlings are used, they should derive from adequate sources/provenances, and only adequate species can be used.

Close to nature forestry is based on detailed forest management planning, adapted to individual site and stand conditions as well as forest functions, and considering natural processes and structures specific to natural forest ecosystems; it continuously learns from processes in unmanaged forest reserves. Natural processes are altered as little as possible, while still maintaining the financial profitability and social sustainability of forest management (Forest management by Mimicking nature, 2014).

Close-to-nature forestry mimics natural processes and structures as far as possible. Forest stands should be renewed naturally and should imitate a mixture of tree species and forest stands of natural forests. Forest management can directly influence tree stands in a forest ecosystem. Through natural regeneration of forest stands, trees' adaptability to conditions of specific growing sites and natural dynamics is preserved. Silvicultural systems should be carefully selected in order to promote close-to-nature approaches and mimic natural processes in forest stands.

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 their 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 as well as means of recreation and other social benefits related to forests.

Adaptation to individual growing site characteristics is the main direction of close to nature forest development, which has been studied within LIFE SySTEMiC through a variety of sites. Directed development of forest stands adapted to individual site and stand conditions, and forest functions, demands great flexibility in selection of a proper system (method) of forest management and careful planning of measures.

The main measures to adapt forest management to climate change are focusing on adaptation of tree composition in forest stands, increase of forest resilience by diverse structures of forest stands on all levels, especially genetic, through advanced forest regeneration and reforestation measures, and increase of their stability by early enough tending measures (e.g. thinning), formation of multilayered and selective forest structures in suitable stands, and (last but not least) monitoring and conservation of forest biodiversity, starting at genetic diversity (Bajc *et al.*, 2020).

2.2 Overview of silvicultural systems for Silver fir

The silvicultural practices currently applied in *Abies alba* stands over the mediterranean area differ from uniform shelterwood system to irregular shelterwood approach and individual tree selection system. In areas where *Abies alba* stands originated from planting, like in the Apennine mountains in Italy, clearcutting with artificial regeneration is used. However, forest management practices with moderate intensity prevail. Regeneration is often natural, stands are selectively thinned, cut sizes in final cuts are small (i.e. < 1 ha). Silvicultural systems that are most suitable for silver fir stands are selection system (individual tree selection) and irregular shelterwood system (group selection system) on small areas. In such conditions, fir can compete with beech, spruce, maples and other tree species in mixed forest stands (ZGS, 2021).

In a individual tree selection system with continuous felling in intervals from 5 to 15 years an optimal wood stock and stand conditions are maintained that are favorable for the regeneration of fir trees. In such forests, the felling amount is approximately equal to the wood increment (Wolf *et al.*, 2010).

In an irregular shelterwood system (group selection system) (Figure 2.2.1) a longer regeneration period (>30 years) is needed for the successful regeneration and overgrowth of fir trees. This means that in places where we want to promote fir trees, we regenerate and regulate the light conditions gradually and in the long term, by gradually removing trees in overstory. In areas where regeneration goals are different, regeneration is possible in a shorter period and also in a larger area. Such a method requires careful and differentiated forest management planning. Continuous felling and permanent, but spatially limited, regeneration is also important in an irregular shelterwood system (group selection system).

From this point of view, management focused on intensive increase of growing stock, as well as an intensive regeneration on big areas, is not suitable for the fir stands. It is possible to contribute to the regeneration of fir trees by preserving vital (younger) overstory of fir trees in areas regenerated with beech (Wolf *et al.*, 2010).

Due to significant differences in the growth of fir trees, as well as in the ecology of regeneration, guidelines regarding silviculture, cutting cycles and target dimensions have to be adapted to forest type, site and stand conditions. But in comparison with beech stands, due to the dynamics of growth, the production age and target dimensions in silver fir stands are generally higher than in beech forests (ZGS, 2021).

In LIFE SySTEMiC project 4 main SFM systems have been studied, from unmanaged to individual tree selection system, irregular and uniform shelterwood system as well as silver fir forests corresponding to 4 European Forest Types.

Figure 2.2.1. Selection and irregular shelterwood silvicultural systems are the most suitable for management of silver fir stands.

2.3. Silvicultural characteristics of Silver fir

Occurrence of silver fir in forest stands is limited with late frosts, drought, summer heat and winter cold. The main advantage of the silver fir in comparison with other forest tree species is in its requirement for light. It is a shade tolerant species and it is far more effective in unfavorable light conditions than its competitors. Young growth of silver fir can survive long periods in a deep shade of a selection forest. Fir is on the other hand very sensitive regarding warmth and moisture and belongs to the species with narrow ecological valency. Further, silver fir is very susceptible to late frost, lateral shots are usually damaged since they appear earlier in spring (Prpić, 2001).

Water requirements of silver fir are quite high and it is very sensitive to drought, especially at a young age. On the other hand, in some cases silver fir surprising tolerance to drought has been observed, especially in central and southern Europe (Carrer *et al.*, 2010).The soils of silver fir sites are very diverse in all their characteristics. It grows on limestone as well as on silicate bedrock (Prpić, 2001).

2.4. Threats

Due to negative consequences of climate change silver fir will most likely be among the more threatened tree species, especially due to the special requirements regarding stand climate and difficulties in natural and also artificial regeneration caused by the game browsing. The share of silver fir in forests and thus the number of populations and/or the density of fir trees has been decreasing for several decades. Small populations or populations with sparsely planted trees are subject to genetic drift and self-fertilization and a consequent decrease in the fitness of the population and their genetic diversity (Wolf *et al.*, 2010). The reduction of the share of fir is faster on fir-beech than on fir-spruce and pure fir sites, where regeneration is often more successful, browsing damage is smaller, and the age classes structure promises more successful preservation of fir in future forests. Predictions about the reduction of the fir share in forest communities in future scenarios, where an increase in temperatures and a decrease in the amount of precipitation are predicted, are also worrying, especially in the combination with difficulties in regeneration (Wolf *et al.*, 2010).

In the 1970s and 1980s widespread decline and even dieback of silver fir was observed in Central Europe, a phenomenon that was called “fir dieback”. There was a range of opinions regarding the reasons for fir mortality, but the prevalent notion was that growth depression of fir between 1970 and 1990 was caused by SO_2 in a complex interaction with climatic and biotic factors (Abies, 2016).

Climate change is believed to have had an adverse impact on the growth performance of autochthonous fir populations in Europe in the last decades. Threats due to climate change consists mainly of an increase in the possibility of negative impacts of abiotic and biotic (pests, diseases) factors. A decrease in the proportion of fir due to white rot (*Sclerotinia sclerotiorum*) is also expected, as a result of the sudden opening of a large area (large-scale felling due to natural disasters) and thus a rapid change in the microclimate. There is also a danger of weeding of regeneration gaps with non-native invasive plant species and thereby of limiting the possibility of natural rejuvenation of native species. Due to the invasion of non-native invasive plant species, the properties of the soil will change and deteriorate, the impoverishment of habitats will increase, biodiversity will decrease, and the predation of autochthonous young growth by herbivorous game will increase (ZGS, 2021).

2.5. Assessment of the adaptation potential of Silver fir forests to climate change

The adaptation potential of the silver fir forests depends on forest site, stand structure and tree species composition. Due to the appropriate structure of the forests (group selection and selection structure), the appropriately structured forest edge, the presence of selective thinning of stands, implemented medium-term thinning of stands, a high degree of preservation of tree composition and fairly undisturbed natural rejuvenation it can be very high. Adaptation potential is strongly reduced by the low level of implementation of tending measures in the younger developmental stages, by uniform stand structure, by altered tree species composition and by the excessive ungulate browsing (ZGS, 2021).

2.6. Regeneration of Silver fir stands

Due to the long regeneration periods in fir stands, it is necessary to start with the regeneration process earlier than in the case of tree species with short regeneration periods. Big differences in the growth of trees that are the same dimensions, point to the need to decide on felling at the level of individual trees (ZGS, 2021).

The restoration of stands should take place on small regeneration areas, as this enables the rejuvenation of key tree species in particular. Even the needs for the tending measures of young growth are reduced with a small-area approach. The size of the gaps regulates the composition of the young growth: lower intensities provide a greater proportion of fir, more light is needed by spruce, and even more deciduous trees with the exception of beech, which is a shade-tolerant species. In the drier areas, it makes sense to open up larger areas to ensure the restoration of more drought tolerant species such as pine and larch, which can substitute silver fir and beech. At the same time when regeneration felling is executed, it is necessary to remove non-vital trees in understorey and shrubs.

Problems with regeneration can occur with large-scale restorations after natural disasters. In these cases, it is necessary to intensify the preparation of the stand for natural regeneration, and in some cases also to intervene with regeneration through planting.

Planting is also used where it is not possible to provide a suitable proportion of deciduous trees naturally.

On non-carbonate forest sites, where silver fir is the dominant species, there are no problems with regeneration. Here, we only preserve its natural share in tree composition. On carbonate sites, for example on high karst in Slovenia, in fir-beech forests, the beech is once again increasing its share in the anthropogenically modified tree structure in cyclical succession. Here, among all tree species, silver fir is the most endangered by browsing of herbivorous game. In the light conditions in which fir competes with other species, it grows relatively slow and is therefore exposed to browsing for a longer period. In such conditions, without special attention given to fir, we cannot expect a further increase in its share, which has been steadily decreasing in recent decades. On such sites, we direct the development of the forest through natural forest regeneration, where the fir trees are successfully regenerated in fenced areas and/or by planting fir trees (Figure 2.6.1). The individual protections of seedlings from game browsing is also important (ZGS, 2021)

Figure 2.6.1. In some areas protection against ungulate browsing is essential for silver fir regeneration.

2.7. Tending and protection of Silver fir stands

Most suitable tending and protection measures are summarized on the basis of SFM guidelines in Slovenia (ZGS, 2021) and LIFE SySTEMiC results. The most common tending measure in young growth is the gradual removal of shrubs and overgrowths while simultaneously regulating the mixture of target tree species in forest stands. In individual tree selection forests tending measures are focused on smaller groups of young growth. With tending measures in young growth we are building a varied vertical and horizontal structure of the stands and thereby the stability of forests against harmful abiotic influences (wind, frost, sun, wet snow).

It is important to shorten the production period in fir stands (cutting down a fir tree when its growth begins to decline, i.e. between 80 and 100 years).

Productive silver fir sites require more intensive thinning, especially of younger development stages (between 20 and 25%). Thinning must be early and aimed at regulating the tree composition and strengthening the stability of the stands. Special care should be taken during thinnings to ensure the stability of stands and the preservation of deciduous trees in the drier parts of the forest stand. Thinning of medium aged stands should range between 15 and 20%.

In selection forests felling should be aimed at maintaining the selection forest structure.

In the adult stands thinnings intensity should be lower (between 10 and 15% of growing stock) and shouldn't produce larger gaps in forest stands.

A sufficient proportion of silver fir in future forests is ensured mostly by control of light conditions on forest floor. The species mixture of the main tree species should be in groups, and the admixture of noble deciduous trees should be individual or group. In addition to the main tree species, the understory layer is also important.

An important measure is to translate one-dimensional stands into more structured ones by means of selective thinning. The transformation is carried out in stands built by tree species that are unsuitable for the given forest site (plantations of spruce for example), namely when the vitality of the stands or the state of health of the stands deteriorates so much that it threatens the normal forest management.

These weakened and non-vital stands must first be thinned out and thereby ensure a greater inflow of light, which will result in the natural formation of an understory layer of meliorative tree and shrub species, which will improve the properties of the soil. This will ensure that the stands will develop in the direction of potential vegetation in a progressive successional process. During the transformation, special attention is paid to minority tree species, which have a meliorating ability, which indirectly improves and increases forest production. Particularly important are the tree species that combine the melioration function and at the same time have an economic value (beech, sycamore maple, mountain elm, large ash, linden, hornbeam, wild cherry, wild pear, larch, chestnut, black alder, aspen, etc.).

A balanced structure of individual tree selection stands is much more resistant to negative abiotic factors than a uniform structure. That is why it makes sense to convert uniform stands into selection ones by means of selection thinnings. Transformation by thinning should be started as early as possible, release the crowns to the selected ones and create a network of trees that supports the stability of the stands.

Forest protection measures in silver fir stands consist mostly of game browsing protection with repellents or individually. Protection with a fence is used mainly in areas with a higher concentration of game. Sanitary felling should be regular and quick - all heavily attacked trees by pests and diseases (e.g. white mistletoe, frostbite and fir canker) should be removed. In individual selection stands it is important to take care of a balanced distribution of trees by diameter classes, thereby preventing the silver fir from the loss drying out in stands with an excessive proportion of thick trees (thickness class over 50 cm).

2.8. Adaptation of Silver fir stands to climate change

Among the most important measures, with which we can contribute to the preservation of fir trees in climatically unstable environment are:

- selective thinning, which can enable the social rise of fir trees in even-aged stands,
- tending measures in younger stands in which we can increase the number of fir trees by regulation of mixture and later by positive selection,
- planting of fir trees under the canopy (e.g. in spruce cultures) and
- maintaining gaps within forests, maintaining a structured forest edge and sufficient proportion of seed trees.

Genetic variability of silver fir is one of the most important factors in its response to climate change (Oggioni *et al.*, 2024) since the adaptability and growth characteristics of trees can vary depending on their origin. SFM of silver fir stands should therefore support their natural migration and adaptation process by assisted migration, by planting of local provenances in the most favorable places for the future.

Figure 2.8.1. Silver fir rejuvenation in selection stands.

3. Landscape genomics

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We used Landscape Genomics approaches to analyze the neutral and adaptive components of genetic diversity to highlight possible patterns of local adaptation in the populations. Neutral and adaptive molecular markers were used in combination with spatial data and bioclimatic indicators. As a result of *Abies alba* Mill. target re-sequencing, about 1500 SNPs were observed in 24 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 higher number of site-specific and region-specific SNPs for Italian sites. This could be interpreted as a sign of adaptation to a Mediterranean bio-climatic regime that characterizes the Italian peninsula and sets it apart from the more continental climate found in Slovenia and Croatia.

To identify a signature of local adaptation, we conducted Genome Environment Associations (GEA) analyses. The results of the analysis showed the presence of an association between 78 allelic variants and 12 bioclimatic indicators considered for these analyses (as reported in deliverable Action B3: Handbook for Sustainable Forest Management). These associations could be interpreted as the basal adaptation genotype of silver fir spread in the Central European range. Moreover, 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). Furthermore, the genetic structure of populations was analyzed using STRUCTURE (Pritchard *et al.*, 2000) and GENELAND software (Guillot, 2008). In general, we found a moderate to high number of specific allelic variants in unmanaged sites (i.e. Site 30 – La Verna). The presence of a high number of SNPs associated with adaptation to bioclimatic indicators 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). A similar situation was observed in stands managed with individual tree selection system. Once again, the number of site-specific allelic was high. Analyzing the pattern of genetic diversity distribution based on SSR data, we observed that silver fir stands managed according to individual tree selection system have a complex and heterogeneous spatial genetic structure. This can be attributed to the nonrandom mating between closely related individuals. An interesting finding is the number of allelic variants associated with bioclimatic indicators that characterize the local environment found at the Site 07 - Tre Termini (Figure 3.1).

From the results obtained for each studied stand it was possible to observe a simplified spatial genetic structure in unmanaged/old-growth fir forests to other sites. Sites managed according to individual tree selection system reported the most complex spatial genetic structure among the managed sites as well as, the highest number of SNPs associated with bioclimatic indicators. The complexity reported for those sites implies a dynamic and adaptable ecosystem capable of responding to environmental changes by generating new genetic variability through recombination and gene flow between subpopulations. In addition, we observed a high number of SNPs correlated with bioclimatic indicators across sites. The presence of these allelic variants associated with bioclimatic indicators that best characterize the local environment is important. 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 favorable genotypes.

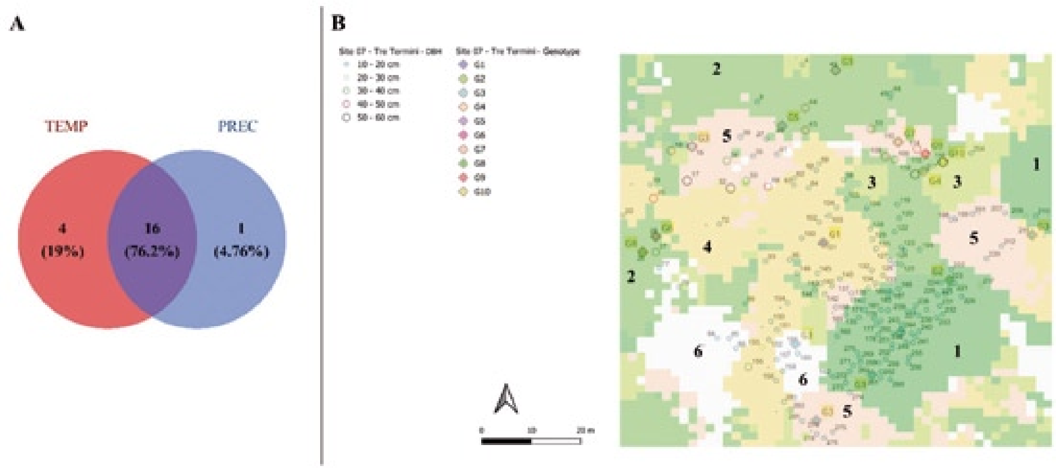

Figure 3.1. LFMM analysis results and genotype distribution map of Site 07 – Tre Termini. (A) Venn diagram showed the overlapping between SNP associated with temperature-related and precipitation-related bioclimatic indicators, as a result of LFMM analysis. (B) Spatial distribution of genotype and spatial organization in 6 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 colored circles according to the genotype observed. Identical colors mean identical genotypes.

4. Browsing

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In the last century, the density and spatial distribution of large herbivores, especially roe deer (*Capreolus capreolus*, (Linnaeus, 1758)) and red deer (*Cervus elaphus*, (Linnaeus, 1758)) has increased significantly in most of European countries (Hafner *et al.*, 2020). Ungulate browsing is known to have significant impacts on forest ecosystems. Ungulate game selectively target certain tree species or individuals, giving an advantage to other species that are less preferred by browsing animals. Therefore, browsing can strongly impact the structure, composition, growth and succession of forest. That may in the long run lead to species diversity reduction and threaten the resilience of the forest to future disturbances.

As part of the B3 activity in LIFE SySTEMiC project, we aimed to investigate whether the impact of ungulate browsing in areas with high wildlife density, and consequently high browsing pressure, can also be detected in the genetic diversity of natural regeneration.

In silver fir sites with high densities of ungulate animals, the impact of browsing on natural regeneration is well-known among forest managers. In our study, this primarily concerns the experimental sites Leskova dolina and Faltelli, where we observed various effects of browsing:

- Low abundance of silver fir saplings in higher height classes, particularly in the height class above 150 cm, which was sometimes completely absent in our research sites. This threshold height is crucial, as it marks the point where the impact of browsing ungulates on forest composition becomes negligible. This height class thus provides a foundation for shaping future forest stands (Hafner *et al.*, 2020). The absence of saplings in this class suggests that browsing pressure might be hindering the successful establishment of certain species. Ideally, natural regeneration would be represented across all height classes. The presence of saplings in the lowest height class indicates sufficient seed production and initial establishment. However, successful growth into higher height classes signifies the saplings' ability to withstand environmental disturbances and remain competitive.

- Lower proportion of silver fir in natural regeneration compared to the adult population. This disparity is most evident in Leskova dolina and can be attributed, at least in part, to ungulate browsing. Preferred species lose their competitiveness primarily due to browsing of terminal buds. Strong ungulate browsing results in a decrease in the height of these browsed species in the regeneration layer, significantly impacting their competitive ability (Horsley *et al.*, 2003; Tremblay *et al.*, 2007). Browsing heavily impacts palatable species, leading to a dominance of less palatable species such as Norway spruce (*Picea abies* (L.) H. Karst.). This shift can reduce overall biodiversity and affect forest regeneration processes (D'Aprile *et al.*, 2020).

- High damage to saplings. The highest share of damaged saplings was observed in silver fir, with the most browsing damage occurring in the height classes 11-50 cm and 51-150 cm. Among deciduous trees, sycamore maple (*Acer pseudoplatanus* L.), rowan (*Sorbus aucuparia* L.), and holm oak (*Quercus ilex* L.) were the most palatable species on our research plots, while European beech was mostly undamaged by browsing. Studies from Central and Southeastern Europe (Shulze *et al.*, 2014) illustrate that deer, by preferentially consuming certain species, contribute to the homogenization of the forest understory, potentially impacting long-term forest structure and biodiversity.

Despite the noticeable effects of ungulate browsing on natural regeneration structure and composition, no significant genetic effects were detected. Genetic diversity did not differ significantly between adult silver fir trees and their regeneration, whether in fenced or unfenced plots.

The impact of ungulate browsing on different species and growth stages of forest trees varies significantly. Young forests, particularly during early growth stages, often face heightened browsing pressure, severely affecting the survival and growth rates of tree saplings. Species such as oak and beech, more resistant to browsing, might withstand this pressure better than fir and pine, which are more susceptible. Differential browsing impacts can lead to changes in forest composition over time, favouring more resistant species and potentially altering the forest ecosystem (Hafner *et al.*, 2020).

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 thanks to collected data from other tasks of the project. In *Abies alba* Mill. stands, we observed that unmanaged or old-growth forests conserved and increased biodiversity. Based on our analysis using nuclear microsatellite (nSSR), we observed that Site 07 - Tre Termini and Site 26 - Smolarjevo, both managed according to individual tree selection thinning, had a complex and heterogeneous spatial genetic structure. Numerous SNPs correlated with environmental conditions were identified, particularly in Site 16 - Gorski Kotar, Skrad (unmanaged), and Site 07 - Tre Termini presented a higher number of SNPs correlated with bioclimatic indicators. Dendrometric data indicated the best structure was a multi-layered uneven-aged forest, found in all managed sites. Site 16 - Gorski kotar, Skrad have a mono-stratified structure, while Site 30 - La Verna have a bi-stratified structure. Unmanaged sites have the highest deadwood volume and many saproxylic microhabitats, especially around old trees. All analyzed sites were mixed fir stands. We hypothesized that single-tree selective thinning best maintains biodiversity by mimicking old-growth conditions and promoting natural regeneration, thus enhancing genetic diversity and climate change adaptation. 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 1.6.1).

Table 1.6.1. 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 the 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 07-Tre Termini (Fig. 1.6.1).

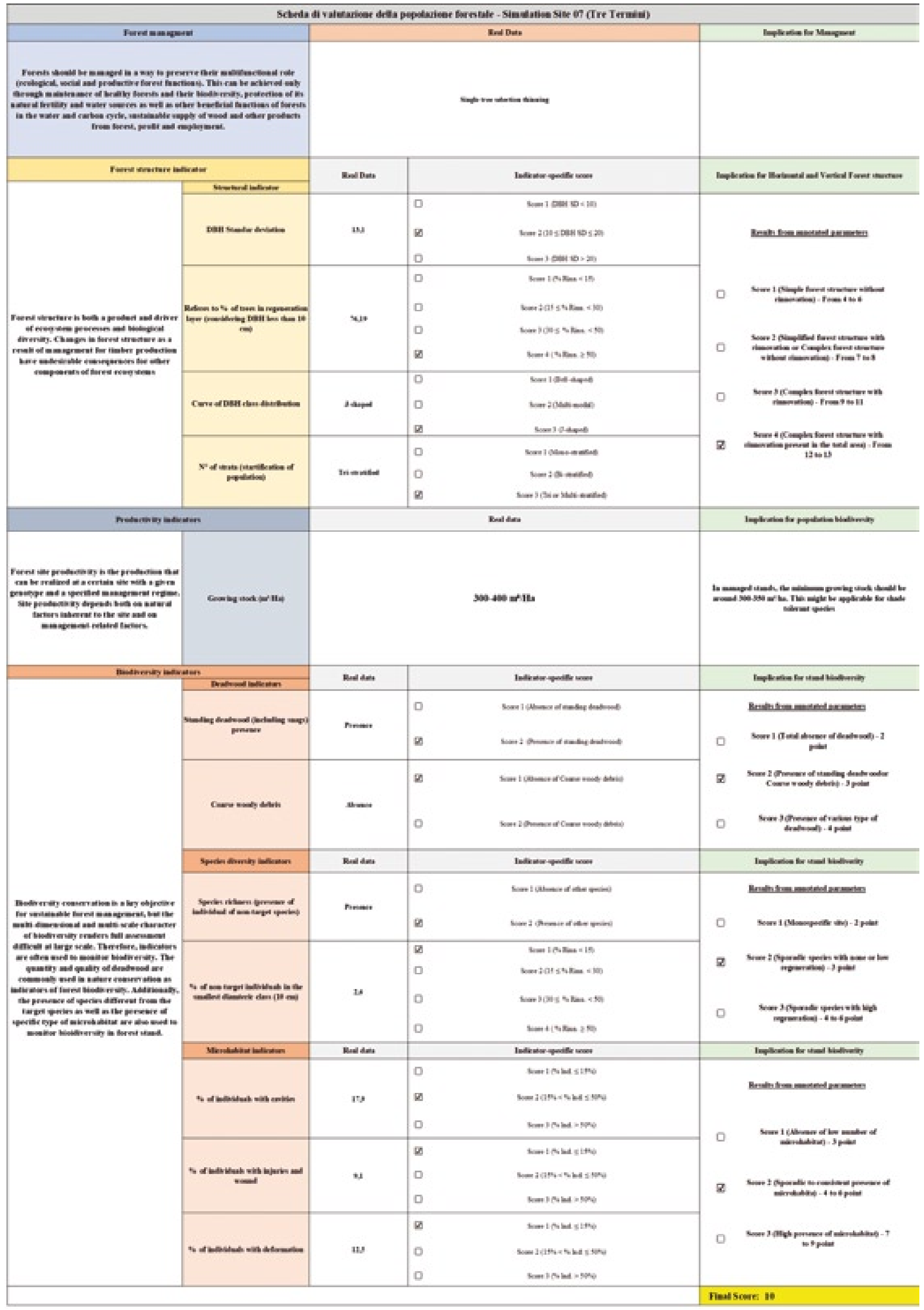

Figure 1.6.1. Forest population assessment form structure with Site 07-Tre Termini data.

6. Recommendations for Sustainable Forest Management of Silver fir (*Abies alba* Mill.)

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Recommendations for Sustainable Forest Management:

- Due to significant differences in the growth of fir trees, as well as in the ecology of regeneration, guidelines regarding silviculture, cutting cycles and target dimensions have to be adapted to forest type, site and stand conditions.
- Selection and irregular shelterwood silvicultural systems are the most suitable for management of silver fir stands.
- In individual tree selection silvicultural system with continuous felling in intervals from 5 to 15 years an optimal wood stock and stand conditions are maintained that are favourable for the regeneration of fir trees.
- In an irregular shelterwood system (group selection system) a longer regeneration period (>30 years) is needed for the successful regeneration and overgrowth of fir trees. This means that in places where we want to promote fir trees, we regenerate and regulate the light conditions gradually and in the long term, by gradually removing trees in overstory. In areas where regeneration goals are different, regeneration is possible in a shorter period and also in a larger area. Such a method requires careful and differentiated forest management planning. Continuous felling and permanent, but spatially limited, regeneration is also important in an irregular shelterwood system (group selection system).
- The contribution to the regeneration of fir in areas regenerated with beech is by preserving vital (younger) overstory of fir trees (Wolf *et al.*, 2010).
- Due to the long regeneration periods in fir stands, it is necessary to start with the regeneration process earlier than in the case of tree species with short regeneration periods.
- Big differences in the growth of trees that are the same dimensions, point to the need to decide on felling at the level of individual trees (ZGS, 2021).
- The restoration of stands should take place on a small regeneration areas, as this enables the rejuvenation of key tree species in particular.
- Problems with regeneration can occur with large-scale restorations after natural disasters. In these cases, it is necessary to intensify the preparation of the stand for natural regeneration, and to intervene with regeneration through planting.
- In areas where there is a high pressure from ungulate browsing, protection is essential for silver fir regeneration (e.g. individual or group protection with fences, repellents).
- Sanitary felling should be regular and quick - all heavily attacked trees by pests and diseases (e.g. white mistletoe, frostbite and fir canker) should be removed.
- The most common tending measure in young growth is the gradual removal of shrubs and overgrowths while simultaneously regulating the mixture of target tree species in forest stands.
- Productive silver fir sites require more intensive thinning, especially of younger development stages (between 20 and 25%). Thinning must be early and aimed at regulating the tree composition and strengthening the stability of the stands. Special care should be taken during thinnings to ensure the stability of stands and the preservation of deciduous trees in the drier parts of the forest stand. Thinning of medium aged stands should range between 15 and 20%.

- In selection forests felling should be aimed at maintaining the selection forest structure.
- In the adult stands thinning intensity should be lower (between 10 and 15% of growing stock) and shouldn't produce larger gaps in forest stands.
- It is important to shorten the production period in fir stands (cutting down a fir tree when its growth begins to decline, i.e. between 80 and 100 years).
- A balanced structure of individual tree selection stands is much more resilient to negative abiotic factors than a uniform structure. That is why it makes sense to convert uniform stands into selection ones by means of selection thinning. Transformation by thinning (re-cultivation of the stand) should be started as early as possible, release the crowns to the selected ones and create a network of trees that supports the stability of the stands.
- During the transformation, special attention is paid to minority tree species, which have a meliorating ability, which indirectly improves and increases forest production. Particularly important are the tree species that combine the melioration function and at the same time have an economic value (beech, sycamore maple, mountain elm, large ash, linden, hornbeam, white hornbeam, wild cherry, wild pear, larch, chestnut, black alder, aspen, etc.).
- Landscape Genomics, important to assess neutral and adaptive genetic diversity for understanding the signature of local adaptation in the populations, has indicated that sites managed according to individual tree selection reported the most complex spatial genetic structure among the managed sites and the highest number of SNPs associated bioclimatic indicators which are important for the resilience to climatic changes.
- 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.
- For *Abies alba* Mill. 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.
- 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 *Abies alba* Mill. 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. In our study these characteristics are found in stands managed according to individual tree selective thinning.
- 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.

Among the measures with which we can contribute to the preservation of fir trees in climatically unstable environment are:

- Selective thinning, which can enable the social rise of fir trees in even-aged stands.
- tending measures in younger stands in which we can increase the number of fir trees by regulation of mixture and later by positive selection and planting of fir trees under the canopy (e.g. in spruce cultures).
- Maintaining gaps within forests, maintaining a structured forest edge and sufficient proportion of seed trees.
- Genetic variability of silver fir is one of the most important factors in its response to climate change (Oggioni *et al.*, 2024) since the adaptability and growth characteristics of trees can vary depending on their origin. SFM of silver fir stands should therefore support their natural migration and adaptation process by assisted migration, by approved mixing and planting of selected tested provenances in the most favourable places for the future.

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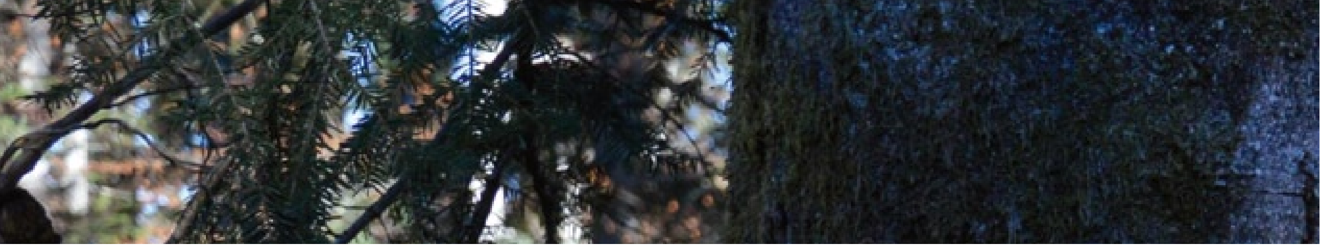

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