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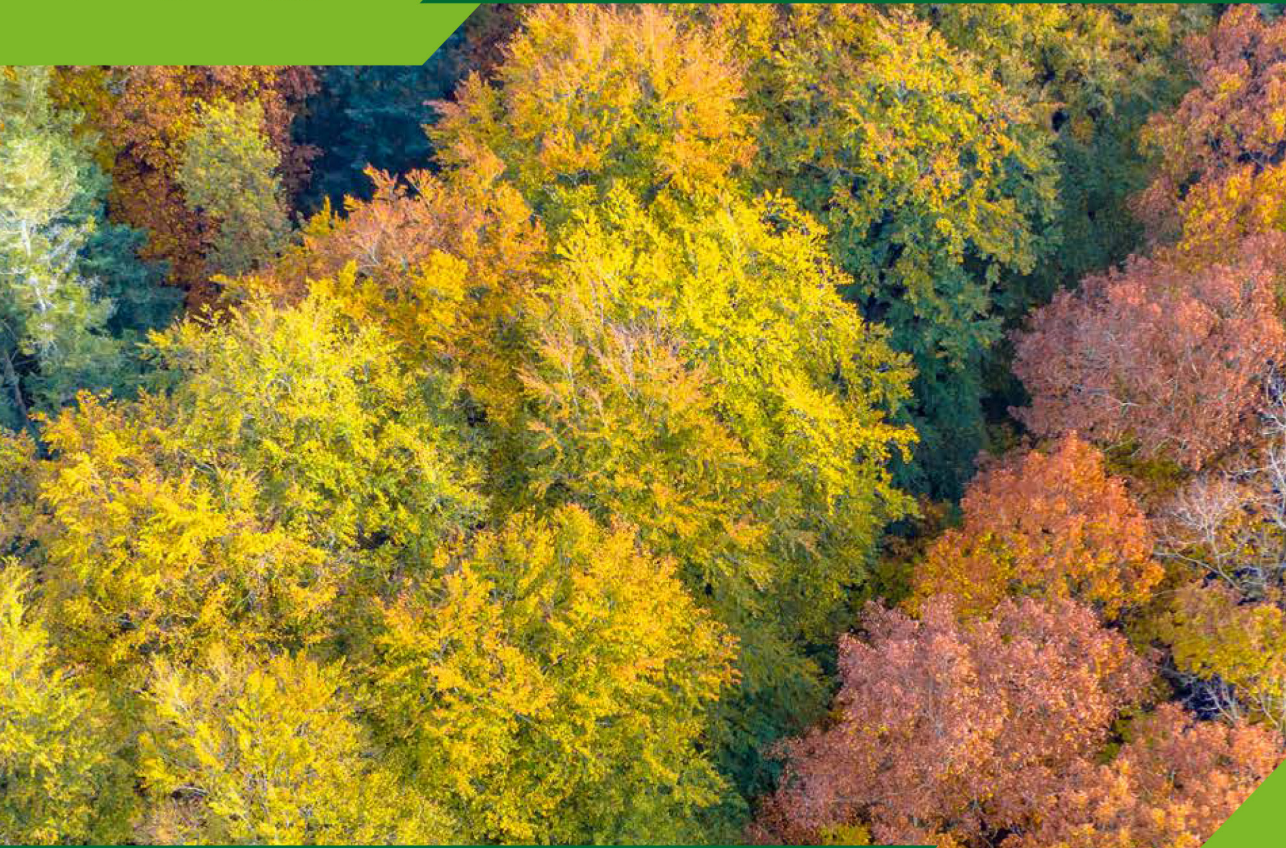

# Adaptive and close-to-nature management in mixed sub-humid Mediterranean forests: holm oak, chestnut, common oak and pine woods

**LIFE MIXFORCHANGE**

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2016-2022

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With the support of:

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# Introduction

This publication is based on the experience and knowledge acquired in the framework of the LIFE MixForChange project, whose purpose is to augment the adaptive capacity of mixed sub-humid Mediterranean forests to climate change through the design, implementation and transfer of an innovative form of silviculture which maintains and promotes these forests' ecological and socioeconomic functions. The project has been implemented in mixed forests dominated by holm oak, chestnut, oak and pine, distributed across four geographical areas in Catalonia (northeast Spain): the massif of Montnegre and Corredor, massif of Montseny, Bellmunt-Collsacabra range and valleys of Ripollès county, in a total of 39 demonstrative stands with a total of 197 ha.

The silviculture method applied is based on reducing competition and promoting the most vital trees, augmenting forest complexity (on both a species and structural level), conserving biodiversity and promoting the forests' productive value, diversifying products. In addition, the application of this form of silviculture incorporates close-to-nature and single-tree management principles, supporting multi-layered structures, a high level of detail in the interventions and an increase in the presence of sporadic broadleaf trees, including cherry, ash, maple, sorb, etc., and other potentially useful species for valuable timber production or from the point of view of biodiversity (rare species, trees with relevant microhabitats, etc.).

The publication has been structured into four Blocks:

Block I presents the handbook's context: Mediterranean forests, climate change and the concepts of adaptive, close-to-nature and mixed-stand silviculture.

Block II describes, through case studies, how this adaptive and close-to-nature silviculture approach has been planned and implemented in nearly 200 ha of sub-humid Mediterranean forest, more specifically, mixed formations of holm oak, chestnut, common oak and pine, as well as the main lessons learned during its implementation.

Block III shows the results of applying the silviculture method described on crucial ecosystem services associated with adapting to and mitigating climate change and with economic sustainability.

Finally, Block IV discusses opportunities and challenges for promoting the application of adaptive and close-to-nature silviculture in the Mediterranean context.

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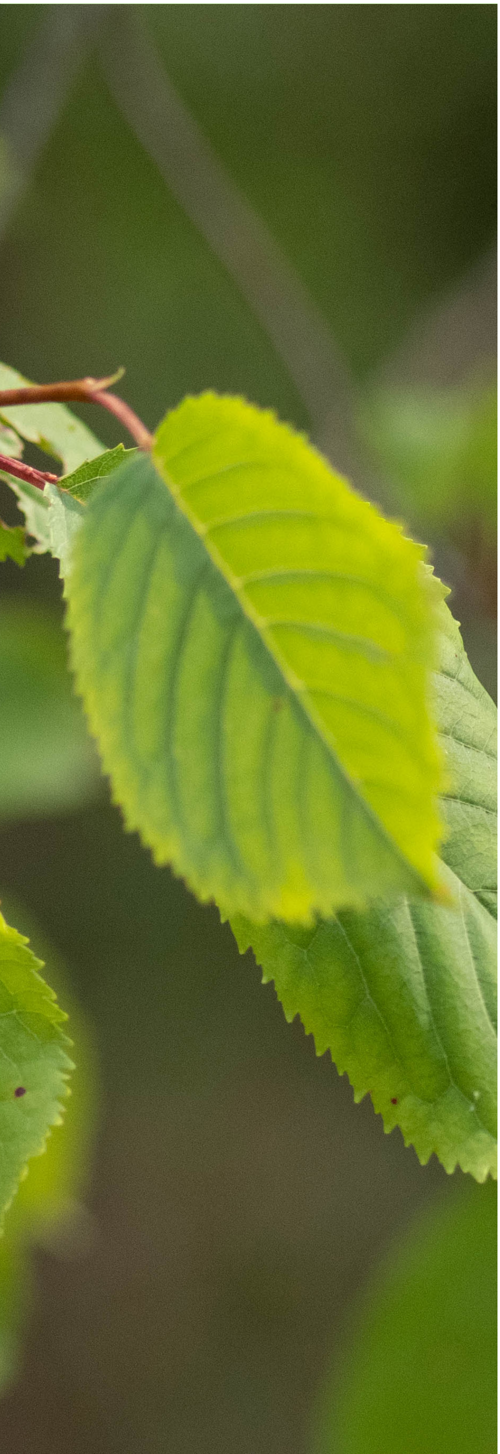


# I. Introduction

The first Block introduces this publication's working context: the particularities of Mediterranean forest, the threats climate change pose to this ecosystem and how silviculture is an essential tool for strengthening its capacity to adapt. Thus, the text explains the general principles upon which adaptive silviculture is based and how it may be combined with other approaches, such as close-to-nature and mixed-stand silviculture.

# 1. Mediterranean forest and climate change

## 1.1. Mediterranean forest: an essential ecosystem

The Mediterranean bioclimatic region is characterised by a long history of human interaction with ecosystems and by a mild climate with dry summers. The prevailing ecological conditions in this area are quite diverse due to its uneven terrain, which gives rise to multiple bioclimates (defined by the diverse orientations, slopes and ranges of altitude; Figure 1); to the diversity of soils and to the greater or lesser degree of influence of other bioclimates: oceanic in the west/northwest, continental in the north, arid in the south and east.

This diversity of edaphic and climatic conditions makes the Mediterranean the most biodiverse region in Europe, with some 25,000 plant species (Myers *et al.*, 2000), 60% of which are endemic (Thompson, 2005). Mediterranean landscapes, including forests, have been modified for millennia by different societies to satisfy their needs for raw materials and land for agricultural and pastoral uses. The current configuration of the landscape and the current composition of Mediterranean forests are, therefore, the result of the great diversity of past and present conditions and uses.

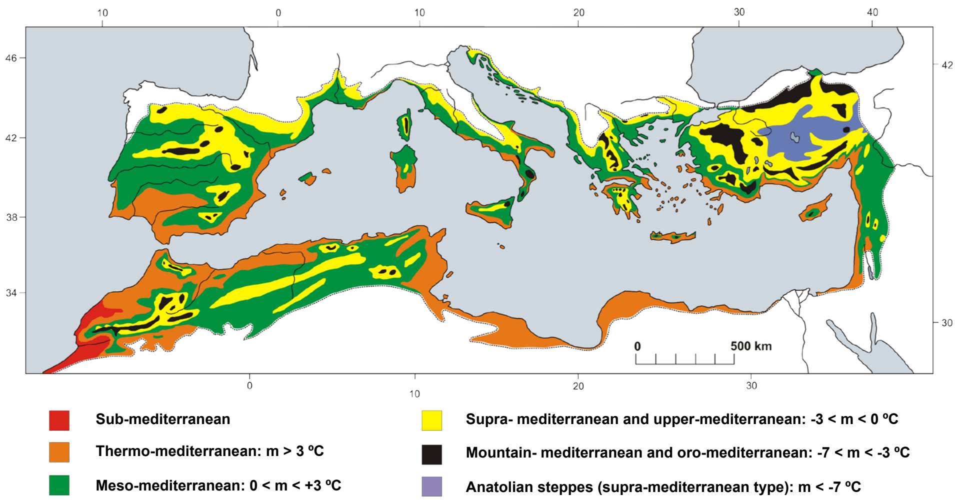



*Figure 1. Distribution of the main types of vegetation in the Mediterranean basin according to phytoecologic and bioclimatic criteria, in particular the average minimum temperatures of the coldest month of the year (m). Source: adapted from Médail (2016).*

In the western Mediterranean, one of the main causes of the current composition of the landscapes and forests was the rural exodus and the abandonment of traditional activities, mainly from the second half of the 20th century onwards, after centuries of intense use. As a result, a major expansion and densification of forest ecosystems has occurred. In Spain, the tree-covered area grew by 56% between 1975 and 2015, while the timber growing stock increased by 133% (Bravo *et al.*, 2017). This generalised forest growth and encroachment represents a challenge to its persistence: firstly, the increase in accumulated biomass and the competition for water, light and nutrients leads to a reduction in vigour and an augment in mortality. The resulting woods are more vulnerable to high-intensity wildfires, with devastating effects in terms of human lives, infrastructure damage, impacts on biodiversity and $CO_2$ emissions. Secondly, this excessive density reduces the quantity of blue water, that is, the water which reaches aquifers and rivers and is available for human use. Finally, the expansion and homogenisation of the forested area causes the loss of a landscape in mosaic and more structural diversity, which endangers the biodiversity associated with these habitats (Ameztegui *et al.*, 2022).

The threat to these forests' persistence also puts the multiple and growing demands of the ecosystem services they offer at risk, including the regulation of water and nutrient cycles, prevention of erosion, biodiversity conservation, recreational and landscape use and the generation of a wide range of raw materials (Figure 2), such as timber, firewood, mushrooms, cork, pine nuts, pastures, resin, acorns and aromatic and medicinal plants, among others.

*Figure 2. Wood, cork, chestnuts, resin, pine nuts, rosemary, berries, essential oils...are just a few of the numerous products from the Mediterranean forest.*

> *In the context of global change in which we are immersed, which is likely to increase the water vulnerability of the Mediterranean basin and accentuate the main threats facing its forest ecosystems (wildfires, droughts, pests and diseases), forest management is crucial to maintaining the woods' vitality, fostering their adaptive capacity, maintaining their role as carbon sinks –mitigating the effects of climate change– and providers of essential goods and services.*

## 1.2. Climate change and the forests

The Earth's climate is in constant evolution, with a record of fluctuations over the course of millions of years. Nonetheless, we are currently in a phase of variation at a pace with no precedents in the last 10,000 years. Since the 19th century, human activities have been the driving force behind climate change, due mainly to the use of fossil fuels like coal, petroleum and gas as sources of energy. This activity generates greenhouse gas emissions which make it difficult for the heat reflected by the earth's surface to dissipate, global temperatures having risen by an average of 1.1°C from 1950 to the present day (Figure 3) and altering other climate-determining atmospheric processes.

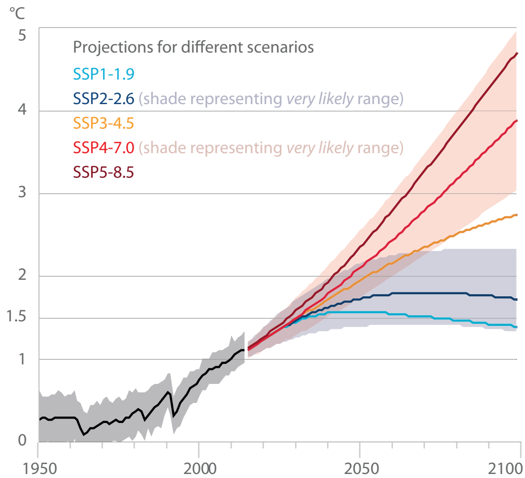



*Figure 3. Evolution of average global temperature in the 1950-2020 period (black line) and predictions through 2100 (lines of other colours). SSP: shared socioeconomic trajectories; SSP1: sustainability; SSP2: intermediate situation; SSP3: regional rivalry; SSP4: inequality; SSP5: prolonging development based on fossil fuels. (IPCC, 2022).*

The Mediterranean region is especially sensitive to the effects of climate change, with the average annual temperature having risen 1.5°C since the preindustrial period. Furthermore, this region is expected to see a rise in the frequency and intensity of droughts, storms, heat waves and other extreme episodes as well as a slight-to-moderate reduction in precipitation (IPCC, 2022).

Like all ecosystems, forests are affected by climate change directly (more water stress, damages from storms and droughts) and indirectly (proliferation of pests and diseases, more virulent fires). The main observed and projected impacts of climate change on forests in general, and Mediterranean forests in particular, are the following (Carnicer *et al.*, 2011; Vericat *et al.*, 2012; Hanewinkel *et al.*, 2013; Calama, 2017):

- **Loss of vitality:** the most limiting factor for vegetative growth in the Mediterranean is the availability of water. Its reduction, a result of the increase in temperatures and in the frequency and intensity of droughts, leads to a reduction in growth, greater susceptibility to pests and diseases and a rise in mortality. Moreover, the rise in the proportion of stressed, dry vegetation is translated into a greater quantity of fuel capable of generating high-intensity wildfires.
- **Regeneration problems:** lower quantity and quality of seeds and fruit, phenological changes and increasingly limiting conditions for the germination and survival of regrowth, especially during the first few summers.
- **Exposure to new and/or more intense disturbances:** the climate change adaptation strategies of insects and moulds are faster than those of trees. Consequently, forests may end up being exposed to pathogens against which they lack effective defences. In addition, a growing rate of fires has been observed in forests poorly adapted to this disturbance, such as temperate Central European and boreal forests. Even in the Mediterranean, where the vegetation is adapted to wildfires and droughts, the growing severity of these disturbances may overwhelm the woods' capacity to tolerate them or spontaneously recover after they occur.
- **Changes in the distribution of species and local extinctions:** the three previously mentioned impacts, along with the modification of the thermal and pluviometric regime, cause the species' area of distribution to shift. As the temperature rises, forest formations need to advance to progressively higher altitudes and latitudes. The speed of the migration depends on the species and the environment, leading to processes of local extinction when the physical conditions (orography, soil characteristics) make it impossible for certain species to continue advancing.

These processes may significantly alter the capacity of forest ecosystems to provide essential ecosystem services to society: wood and non-wood products (bioeconomy), soil and water protection, air quality, biodiversity conservation, recreational and landscape use, as well as their capacity to mitigate climate change (Peñuelas *et al.*, 2017; Morán-Ordóñez *et al.*, 2021). Evidently, many of the effects of climate change on forests feed into each other, which is why it is essential to reinforce forests' defence mechanisms in the face of these disturbances, as is explained in the following section.

*Forest affected by drought*

# 2. Silviculture: an essential tool for adapting forests to climate change

## 2.1. Forest defence mechanisms

Forests present a series of defence mechanisms against the disturbances with which they have evolved, including the previously described impacts of climate change. These mechanisms confer, on an individual and collective level:

- **Resistance:** capacity to tolerate a disturbance.
- **Resilience:** the capacity, after suffering a disturbance, to recover the conditions (structure and functionality) prior to it.

The mechanisms of resistance and resilience in forest stands are multiple, and they vary from physiological adaptations on a tissue level to dynamics of the forest stand (Figure 4). The mechanisms present in any given forest are the result of the adaptation to the environment in which the species present have evolved. Mediterranean forest species are especially adapted to tolerate drought and forest fires (Valladares *et al.*, 2004; Pauses & Keeley, 2014).


*Figure 4. Key defence mechanisms in the Mediterranean forest.*

## 2.2. Principles of adaptive silviculture for climate change

Adaptive silviculture aims to promote forest resistance and resilience to the current and projected impacts of climate change (Bravo *et al.*, 2008). The previously mentioned defence mechanisms must be **actively reinforced** for a number of reasons, especially:

- The speed and intensity of climate change and its associated impacts surpass forest ecosystems' spontaneous ability to adapt.
- Mediterranean forest landscapes are closely linked to the use human populations have made of them. Not being the result of natural selection alone, the variety and quantity of defence mechanisms is limited (Nocentini & Coll, 2013).
- The cost of not taking action, especially in the face of a disturbance like forest fires, could prove insurmountable for society in terms of human lives, infrastructure damage and the loss of economic and natural resources over the course of decades.

Here follows a summary of the range of **adaptive silviculture measures** proposed for various types of forests (Brang *et al.*, 2014; Tognetti *et al.*, 2022) and specific to Mediterranean forest (Vericat *et al.*, 2012; Calama, 2017; Vilà-Cabrera *et al.*, 2018):

**a) Maintaining and promoting a diversity of species, ages and structures**

Species diversity refers both to the total number of taxa and to their functional diversity (genera, families and diverse vital strategies) and functional redundancy, that is, the presence of diverse species with similar characteristics (Sánchez-Pinillos *et al.*, 2016).

A forest with a diversity of ages and structures will contain **multiple vertical strata**, with trees and bushes at different life stages and heights, mixed tree by tree and also by group, alternating with small open patches. This structure, vertically and horizontally diverse, enables the complementary use of resources (light, water, soil nutrients), resulting in greater productivity and vitality (Figure 5). This diversification also includes fomenting the **presence of dead trees**, of various sizes and in various states of decay, and individuals with microhabitats of relevance for biodiversity conservation (Bütler *et al.*, 2000).

The basic tool for promoting the diversity of species, ages and structures are **interventions regulating competition** (thinning, sucker cutback and undergrowth clearing), which must be applied in a clearly selective manner, in addition to interventions aimed at inducing natural regeneration (Martín-Alcón *et al.*, 2014). In extremely simplified woods, it may be necessary to rely on enrichment plantations and/or assisted migration.

*Figure 5. Simplified structure (pure, even-aged, lacking undergrowth) on the left, facing a complex structure (diversity of species, multi-layered, with undergrowth).*

**b) Maintaining individual and collective vitality and stability**

A forest's vitality and stability depend on the trees which comprise it and on the interactions between them, both physicochemical (relationships of competition or facilitation) and mechanical (collective protection and resistance). Vitality is associated with the adaptation of a tree to its environment, which refers, mainly, to (micro)climatic conditions and the competitive context. Both factors can be regulated through the previously mentioned **competition-regulating interventions**, it being possible to promote the individuals and species which are most vital and most well-adapted to current and future climatic conditions.

As has also been previously mentioned, the presence of dead trees, especially when large in size and in various states of decay, is very favourable for biodiversity (Lassauce *et al.*, 2011). However, an excess of dead and dying individuals may become a focal point for the proliferation of diseases and xylophagous insects which, in the event of demographic explosion, could attack healthy trees and cause serious losses in the ecosystem (for example, attack of *Matsucoccus* where affectation from *Tomicus* and *Ips* is also observed, described in Catalonia by Torrell *et al.*, 2022). Furthermore, forests with a large accumulation of deadwood are more prone to the generation and propagation of large forest fires due to the large quantity of potentially available fuel.

Stability is mainly associated with tree **shape**, and it is advisable to avoid a predominance of extremely slender trees, with a compressed and/or unbalanced crown, the result of very high density during an excessive amount of time. At the collective level, extremely capitalised stands should be avoided to limit vulnerability to massive windthrow, droughts and high-intensity fires.

**c) Promoting sexual regeneration**

Sexual regeneration makes it possible to maintain and increment genetic and phenotypic diversity, and also to possess a pre-installed cohort able to progressively occupy any gaps generated in the stand, for example, due to windthrow or snow breakage. Similarly, it is worth noting the presence of **advanced regeneration** and contributing to its consolidation, if local conditions are suitable. Moreover, in the vein of the previous points, the natural regeneration of diverse species should be induced by creating patches of various sizes and availability of direct and indirect light.

**d) Maintaining the structural integrity and protection of the soil**

Structural integrity refers to applying **treatments of low or moderate intensity**, proposed according to the principles of reversibility and progressiveness. The maintenance of a continuous cover reduces the desiccating impact of sunshine and wind (and the mechanical impact of the latter) and guarantees the functions of ecological connectivity. In addition, this dark environment may help limit the excessive proliferation of undergrowth, which has a negative effect on walkability, competition for water and vulnerability to fires, although this effect is less noticeable in the Mediterranean than in colder environments where light is a limiting factor.

**e) Reducing vulnerability to wildfires**

Wildfires are a phenomenon inherent to Mediterranean ecosystems, although in recent years they have shown an unprecedented virulence and a growing presence in other, cooler bioregions. Silviculture can prepare the woods to withstand wildfires with as little damage as possible and maximise their ability to recover. To do so, it is essential to prevent low-intensity fires (propagated along the surface and through the shrub layer) from becoming crown fires, high in intensity and with devastating effects over large areas. It is fundamental to **break vertical fuel continuity**, that is, to limit the presence of fuel ladders, and also to **reduce total fuel** through thinning, clearing or debris slashing. In addition, horizontal discontinuities must be generated to curb propagation, maintaining or creating mosaic landscapes, with the presence of open spaces or areas of low fuel accumulation.

## 2.3. Application of adaptive silviculture and integration with other silvicultural trends

Like any other approach, adaptive silviculture must take into account the context of uncertainty and complexity typical of forest systems. Moreover, it must be framed within a broader concept of **sustainable forest management**, designed and applied in accordance with the specific characteristics of each forest and with the primary objectives and their social and economic context – most relevant ecosystem services, types of ownership, technical capabilities of the management staff and forest workers, legal framework, logistics and commercialisation of the products obtained – while simultaneously considering and promoting all natural phenomena favourable to the management goals and monitoring regularly to assess whether the foreseen results are being achieved.

Coordinating some of the measures proposed so far is a challenge for the planning and implementation of management. For example, it can prove complex to strike a balance between maintaining a stand's multi-layered structure and reducing its vulnerability to fires or to decide what to do with sporadic species that present serious problems of site adaptation. It is not possible to apply all the aforementioned principles simultaneously in all parts of the managed area. Rather, some principles must be prioritised over others in each part of the stand, with the goal of keeping all of them, in general, in view. It can be concluded that adaptive silviculture must be **flexible and detailed**, from the diagnosis of the stand to the planning, implementation and assessment of the results. Thus, adaptive silviculture is especially well-suited in the framework of **stand-based forest management** (González *et al.*, 2006) (Figure 6) and with the incorporation of the principles of **close-to-nature silviculture**.

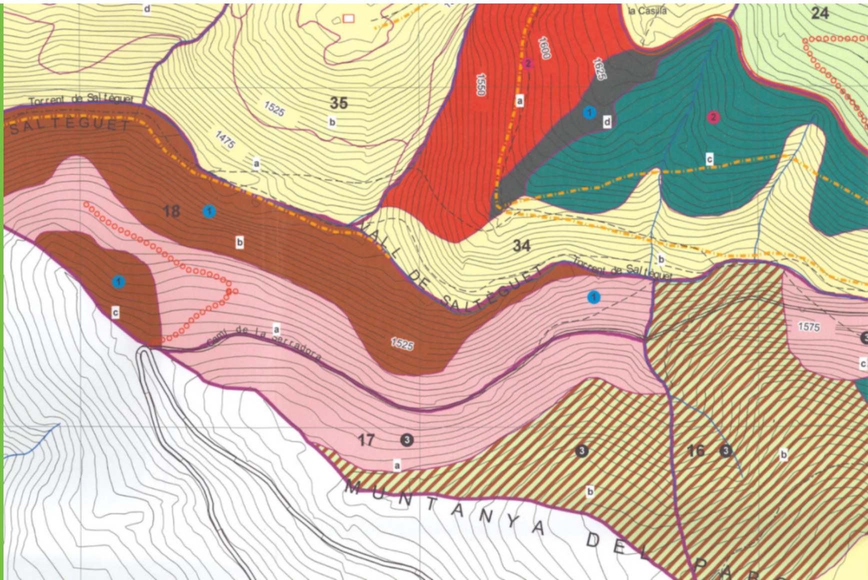



*Figure 6. Detail of the planning in a stand-based arrangement (Forest of Saltèguet and mountain of Vilallobent, Cerdanya, Catalan Pyrenees). Every stand is managed with its own form of silviculture*

**Silvicultural trends: adaptive, close-to-nature, climate-smart, close(r)-to-nature, systemic, continuous-cover, single-tree...**

Recent decades have seen the formulation of different silvicultural trends, based on the evolution of the conventional silvicultural principles, to provide a response to the growing social demands for ecosystem services. Many of these trends (see Puettmann *et al.*, 2015) are mutually compatible and can be considered simultaneously, as they are based more on guiding principles than on objective figures of silvo-dasometric indicators.

At the same time, many of these trends have sprung from contexts different from the Mediterranean forest, which is why it is important to understand the problems and opportunities which have inspired them. Beyond the trend or trends considered, the basic premise of any form of silviculture is its adherence to a general model of sustainable forest management, that is: “a dynamic and evolving concept, which aims to maintain and enhance the economic, social and environmental values of all types of forests, for the benefit of present and future generations” (FAO, 2022).

Block 2 of this handbook contains an introduction to the silviculture methods applied in the LIFE MixForChange project, based on the ORGEST - Sustainable Forest Management Guidelines for Catalonia (Piqué *et al.*, 2017), incorporating aspects of adaptive silviculture for climate change (principles shown in Section 2.2), close-to-nature silviculture (Bauhus *et al.*, 2013, Beltrán *et al.*, 2020), mixed-stand silviculture (Bravo-Oviedo *et al.*, 2018) and single-tree silviculture (Wilhelm & Rieger, 2017).

## 3. Mixed forest management

In a natural way, forest ecosystems tend to be comprised of several species, although biogeographical differences exist, linked, among other factors, to the regimes of disturbances, the heterogeneity of habitats or the historical climate (Bauhus *et al.*, 2017a). From a global perspective, European forests are found among the least diverse forest ecosystems: more than 80% of the continent's forested area (excluding the Russian Federation) presents less than four arboreal species (Forest Europe, 2020). The aforementioned biogeographical causes are joined by anthropic factors, such as the long European (and Mediterranean) tradition of exploiting forest resources, which has contributed to simplifying forests by systematically favouring the species most welcomed by human beings (Nocentini & Coll, 2013). Moreover, the social and economic changes which occurred in the second half of the 20th century led to the conversion into forest, spontaneous or intentional, of large areas previously used as cropland or pasture. The main trees involved are pioneer species which constituted, in general, dense, monospecific and structurally simple forests. Consequently, and in spite of the progressive natural diversification of the forests taking place in recent years (Coll *et al.*, 2022), the European and Mediterranean landscape is dominated by pure forest stands with diversity levels far below their potential.

In the context presented in the previous sections, of growing environmental uncertainty and the need for adaptive forest management strategies, the maintenance and promotion of **mixed stands** versus pure ones presents itself as one of the most promising adaptation options, due to:

- The greater productivity and stability in the growth presented by mixed stands when they are made up of species with different structural (at canopy and root system levels), functional and phenological patterns (Vilà *et al.*, 2013; Morin *et al.*, 2014; del Rio *et al.*, 2017).
- The greater resistance and resilience they show in the face of disturbances, both abiotic (wildfires, winds, extreme droughts) and biotic (pests, diseases), provided they are composed of species with different functional traits (sprouting capacity, root depth or bark thickness; Puettmann, 2011; Sánchez-Pinillos *et al.*, 2016).
- Mixed formations' greater multifunctionality and ability to provide goods and services (Figure 7).

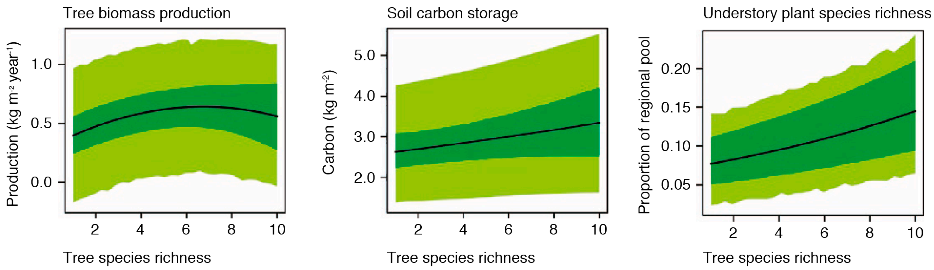



*Figure 7. Relationship between the provision of diverse ecosystem services and number of tree species. The black line shows the mean relationship and the green areas show the confidence intervals and variation of residuals. Adapted from Gamfeldt et al. (2013).*

Despite the evident benefits presented by mixed formations, **few management models** for this type of formations exist (Coll *et al.*, 2018). Moreover, the few existing guidelines on silviculture are, in general, little specific and markedly qualitative (Pretzsch *et al.*, 2021). The scarcity of silvicultural models for mixed stands is mainly due to:

- The complexity associated with establishing silvicultural guidelines for stands made up of species with different environmental requirements: light, water, etc.
- The great diversity of possible combinations of compatible species in an area, in terms of the proportion between them as well as spatial arrangement. For example, in the case of Catalonia, Piqué *et al.* (2014) defined 204 typologies of forest, considering 22 species or dominant functional groups.
- The limited empirical evidence available on the field results of silvicultural treatments in this type of stand (Bauhus *et al.*, 2017b).

***Block II of this handbook introduces the silvicultural principles applied for the promotion and management of mixed formations, in the context of an adaptive and close-to-nature silvicultural system, in four predominant forest typologies in the sub-humid Mediterranean: holm oak, chestnut, oak and pine woods. The intention is to improve the technical body of knowledge to support decision-making in the planning and management of these formations.***

# II. MixForChange silviculture: adaptive and close-to-nature management of mixed holm oak, chestnut, common oak and pine woods

This Block presents how a system of adaptive and close-to-nature silviculture has been defined, planned and applied in 200 pilot hectares of mixed sub-humid Mediterranean forest in the context of the LIFE MixForChange project. Apart from the general approach and in terms of forest formation (holm oak, chestnut, common oak and pine), detailed files are included which describe the intervention in specific stands, as well as a summary of the practical lessons learned during this process.

# 4. General principles of the MixForChange silviculture

## 4.1. The area of work

The LIFE MixForChange project has been used to develop and apply a mixed-stand silviculture system based on the ORGEST models (Piqué et al., 2017) and incorporating criteria of climate change adaptation and close-to-nature management, in line with the general principles presented in Block I. These interventions have been applied in 197 ha of mixed forest in the Catalan sub-humid Mediterranean, in four geographical areas in northeast Spain (Montnegre-Corredor, Montseny, Bellmunt-Collsacabra and valleys of south Ripollès) and in the four main forest formations: holm oak, chestnut, common oak and pine woods (Figure 8).

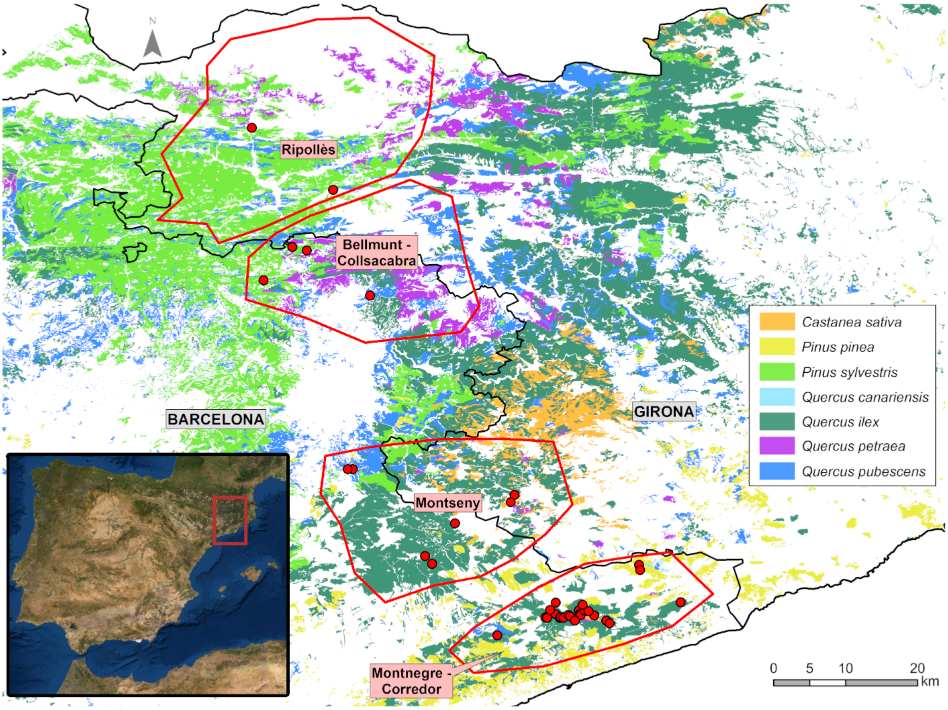



*Figure 8. Location of the massifs and demonstrative stands in LIFE MixForChange, and dominant species.*

There are some **characteristics common** to the whole area of intervention:

- Although the stands are, in general, mixed and show a certain degree of stratification, the prevailing form of management has progressively led them to a certain point of structural and species simplification. The holm oak and chestnut stands present an abundance of coppices which, in the case of chestnut, tend to present low vigour. The pine stands often show an advanced senescence process.
- The main threat posed by climate change in this context is the rise in the intensity of droughts and forest fires. Many of the species present (including ash, maple, chestnut and some oaks) are poorly adapted to these disturbances, making them especially vulnerable.
- Many of these forests are found in a state of abandonment, with no silvicultural intervention in recent decades, after long periods of somewhat intense use.
- These forests tend to be found in peri-urban settings, especially in the case of Montnegre-Corredor and Montseny, which makes the task of managing them more complex.

## 4.2. General silvicultural criteria

The interventions' general aim is to promote the stands' **resistance and resilience** in the face of the main impacts of climate change, in a way which is compatible with **economic and ecological sustainability** in the medium and long term. To accomplish this, a series of **general principles** have been established to guide the silvicultural approach:

- Promote the most **vital** trees and tree groups, of different species and sizes, taking their (current and potential) economic and/or ecological **value** into account.
- Foster the **multistratification** of the stands in a way which is compatible with the creation of a certain amount of vertical discontinuity between the strata, aiming to prevent, to the extent possible, the vertical fuel continuity.
- Facilitate the implantation and development of **sporadic broadleaf** species of high economic and/or ecological interest: cherry, ash, maple, sorb, wild service, lime, holly, etc.
- Maintain a **diverse undergrowth** community, with coverage and dimensions that allow this layer's ecological functions to be maintained, but limiting its competitiveness against the trees and also the stand's structural vulnerability to high-intensity fires.

These general principles are modulated during the different phases of planning on a stand level (Sections 5 through 8) until their thorough field application, given the circumstances of each case, following the description of adaptive, close-to-nature and single-tree silviculture described in Chapter 2.

One fundamental criterion is to align the interventions with the forest's natural processes and dynamics, to minimise the costs and maximise the return of ecosystem services, including biodiversity and the generation of high market value goods, which would be based generically on the principles of **close-to-nature forestry**. The basic principle of this silviculture approach is to maintain, at all times, a cover which generates a dark, moist "forest microenvironment", coordinating it with the opening of patches or spaces to promote the installation or development of a new cohort in specific parts of the stands. The fundamental tool of this silviculture form is **selective thinning with prior marking**, taking into account the characteristics and the role (current and potential) of each tree and its relationship to the present natural processes to be reinforced or regulated and the nonexistent processes intended to be reactivated.

The interventions applied with this approach tend to be lower in intensity, more detailed in design (including complete marking) and execution (including product classification on the forest road) and also more frequent (applied every 6 to 10 years) than the interventions prescribed with the silvicultural approach based on full-stand level decisions.

*MixForChange demonstrative stand, just intervened. The maintenance of a forest microenvironment, the species diversity of the tree and undergrowth layers and the presence of trees promoted because of their vitality and structure can all be observed.*

*The silviculturist's role is fundamental to the correct application of these general principles, seeking a balance among them so they may be achieved globally, even if, locally, some may be prioritised over others. In the application of this form of silviculture, qualified professionals are also required for the marking and execution of the operations*

## 4.3. Field application

In the detailed application of this silvicultural approach, special attention is paid to **each tree's role** in the stand and not to the fulfilment of pre-established, stand-level parameters; nor is the aim to achieve a given structure or homogeneous arrangement of the trees in the space. The basic premise consists, therefore, in **identifying** the trees of most interest, whether from an economic or environmental point of view, and **promoting** them through specific interventions to favour their vitality and development, even if it is necessary to perform actions which represent an investment in the medium term. This acceptance of individualised investments is aligned with a **single-tree silviculture** approach.

In the silviculture strategy applied in the MixForChange project, the trees of **high economic interest** are well-shaped and free of defects, of species with the potential to produce valuable timber (oak, maple, ash, chestnut, sorb, wild service, cherry, pear...). While the trees are still small (up to 10-15 cm in normal diameter), they are kept in a phase of fierce lateral competition, to encourage them to grow straight and minimise knot size; shaping them through pruning may also be considered. When they surpass 15-20 cm in diameter they are identified and marked as high-value trees (also called "future crop trees") and progressive selective thinning operations (release) are applied to promote the expansion of their crown and, along with it, vigorous and regular diameter growth (Figure 9). Thus, in these thinning operations, the future crop trees' main competitors on the canopy level are identified and eliminated, but other trees around them which cast lateral shade on their trunks are maintained, thereby preventing an abrupt entry of sunlight which could give rise to epicormic shoots or an excessive increase in transpiration caused by direct exposure to desiccating sun and wind.

*Tree selected for its potential to produce quality wood*

*Figure 9. Diagram of progressive release of the space of a high-value tree (marked in yellow). The dotted blue lines represent the passing of time between two consecutive interventions. Adapted from Mori & Pelleri (2014).*

The trees of high **ecological or environmental interest** correspond to individuals with a relevant role in the ecosystem, whether because they host microhabitats of interest (Larrieu *et al.*, 2018; Figure 10) or possess rare traits in the stand: large-sized trunks, standing deadwood, underrepresented species, etc. Specific measures of promotion are also applied to these trees, such as selective thinning operations to promote their vigour and the expansion of their canopy, or else, in the case of dead trees, maintaining the trees surrounding them to delay their spontaneous collapse.

*Figure 10. Some prominent microhabitats: these trees are maintained and promoted in MixForChange silviculture*

In the areas of the stand in which no particularly relevant trees on an economic or ecological level have been identified, **generic density-regulating interventions** are considered, given the general criteria of intervention.

*The silvicultural interventions are designed taking into account the general principles exposed in the previous Block, as well as the characteristics and objectives of each formation, later specified at the stand level. In addition, the ORGEST management models of reference may be used to guide the intensity of the intervention: for example, basal area to extract.*

*In any event, the first intervention performed according to these principles, like the one implemented in the MixForChange demonstrative stands, has a marked character of adaptation toward the structures sought (heterogeneous, complex and diverse), as each stand's initial characteristics and natural dynamics and processes tend to diverge from these target structures. In general, multiple successive interventions will be required to progressively change the conditions and dynamics, and it will also occasionally be necessary to apply silvicultural interventions which may not strictly adhere to the general criteria but which prove necessary to initiate or accelerate the change, such as, for example, intense clearings, mixed thinning operations with the felling of trees by diameter or distribution, etc.*

The following sections show the specific silvicultural criteria on the formation level, and for specific stands within them as examples.

# 5. Silviculture applied in holm oak stands

## 5.1. Description of the interventions

> ***The management of holm oak woods is centred on increasing the system's complexity, generating and maintaining irregular multi-layered structures, with a trend toward capitalisation, and supporting the development of different broadleaf species in conjunction with the holm oak layer. The development of seed trees and the regeneration of sporadic broadleaves are also actively promoted.***

Two types of holm oak management are defined according to the degree to which accompanying broadleaf trees are present:

- In **mixed holm oak stands** (basal area of holm oak between 50% and 80% of the total), the aim is to maintain an adequate proportion of the species present, especially through the dissemination of regeneration cones adapted to each species's light requirements.
- In **holm oak stands where the presence of other species is insufficient to qualify the stand as mixed** (holm oak basal area superior to 80% of the total), the aim is to promote diversification by supporting broadleaf trees which are good seeders, generating openings for deciduous species and releasing advanced regeneration.

In both cases, the interventions encourage the individuals and species of valuable broadleaves, provided they are vigorous. The main species considered are *Prunus avium*, *Quercus petraea*, *Quercus pubescens*, *Quercus canariensis*, *Sorbus torminalis*, *Fraxinus excelsior*, *Acer pseudoplatanus* and *Acer campestre*.

*Mixed holm oak stand*

This management strategy makes it possible to advance these holm oak stands into a **coppice-with-standards forest structure**, dominated by holm oak with a capitalised irregular structure, heterogeneous by patches. The accompanying species develop mainly as seed trees, by patches and forming the dominant layer if their temperament so permits.

The silvicultural interventions adapt to the characteristics of each stand to advance toward this defined final structure, which may require one or several "adaptive" or "transitional" interventions. Once the structure is vertically and horizontally heterogeneous and the desired regeneration and conformation processes have begun to occur, the conditions are maintained using selection felling (selective thinning operations on trees of all sizes).

The interventions considered in the pilot holm oak stands include:

**Selective thinning**: the first step is to perform a selection of future crop trees (some 150 to 300 trees/ha, maximum 1/3 of the total density), primarily including (see Section 4.3) vital and well-shaped valuable broadleaved trees, preferably from diametric class 15 and up but with time to grow, and also individuals with relevance for biodiversity conservation (underrepresented species, trees with relevant microhabitats, seed trees and fruit producers). In addition, occasional release and pruning may be considered for valuable broadleaved trees which fail to reach the aforementioned diameter if they show good vigour and robust, well-shaped stems.

Selective thinning consists in regulating the competition to which future crop trees are subject, eliminating their main competitors on the canopy level. The number of individuals to eliminate per future crop tree determines the intensity of the thinning: as a reference point, between 1 and 3 competitors are felled, with a lower value the more future crop trees selected and the more compressed their crown. As a guideline, the extracted basal area should not exceed 25-30%. The felled trees can either be extracted or kept in the soil, depending on their value. Another possibility is to girdle competitor trees instead of felling them to make the future crop tree's initiation of light exposure more gradual. The individuals close to the future crop trees not identified as competitors on the canopy level are maintained, thereby creating a service layer which supports the proper configuration of the selected tree and prevents the emergence of epicormic shoots.

In the stands or sections of a stand which diverge from the optimal conditions for the application of MixForChange silviculture (simplified structure, very high density and/or limited or no layering), **mixed (low and high) selective thinning** – which could reach moderate or high intensity (up to 40% of the initial basal area or 50% of the initial density) – may be considered. In this case, selective thinning is combined with low thinning to reduce the density of the dominant layer in a more or less homogeneous way.

> ***Selective thinning is the main intervention of MixForChange silviculture when candidates for future crop trees exist and to maintain proper structures once they have been achieved, as it applies the fellings according to the role of each tree in the forest.***

**Shoot selection (sucker cutback)**: intervention used to regulate competition on the tree level, applied on stumps with many shoots to concentrate growth in the best developed and positioned ones. The most common choice is to leave 1 or 2 shoots per stump, but the number may be increased to 3 if the holm oak or chestnut stumps present 8 to 10 living shoots. Thus, competition is reduced and vitality is improved on the stand level as well.

**Selective clearing**: partial elimination of the vegetation of the understorey layer, based on a prioritisation by height, species or vitality. Optionally, a range of total maximum shrub coverage to maintain may be established (more elevated, the more height the tree layer has and the less abundant the regeneration is) to reduce overall vulnerability to fires. In the demonstrative holm oak stands, it is common to see thickets of strawberry tree, heath and other woody species capable of achieving an arboreal aspect due to the availability of light after intense felling. In this case, selective clearing focuses on reducing these species' phytovolume, respecting thickets of sporadic species, with higher shade requirements and/or producers of flowers and fleshy fruit, due to their importance in biodiversity. In heath and strawberry trees of large development, a shoot selection is performed (leaving one or two shoots per stump) instead of cutting them completely, to limit posterior sprouting.

**Rejuvenation**: cutting misshapen individuals from valuable broadleaf species down to the ground in order to stimulate a new shoot which may be better shaped. The individual to be rejuvenated is typically young and must show sprouting capacity and favourable micro-site conditions. The individuals cut during rejuvenation may be extracted or left in the soil depending on their commercial value.

**Planting**: artificial regeneration of areas of low tree cover showing null or insufficient regeneration. A great diversity of species are planted, with densities between 10 and 250 trees/ha, taking advantage of the most favourable micro-sites and applying complementary planting techniques, such as individual shelters or soil conditioners, to augment success.

## 5.2. Result of demonstrative stands

In the MixForChange project, seven demonstrative holm oak stands have been intervened in, some 33 ha in total. Table 1 shows the silvicultural characterisation obtained in 16 monitored plots installed in six stands of Montnegre-Corredor and Montseny (Figure 11). The average basal area extracted (28.2 ± 8.8%) was in line with the planned intensity (20 – 30%). The intervention intensity was higher in areas with a greater initial basal area, as in the case of Montnegre-Corredor.

*Table 1. Silvicultural characterisation of the treatments performed in holm oak (Q. Ilex) stands.*

| **Massif (No. stands-plots)** | **Before treatment** | | | **After treatment** | | | **BA extracted (%)** |
|---|---|---|---|---|---|---|---|
| | N (trees/ha) | Dg (cm) | BA ($m^2$/ha) | N (trees/ha) | Dg (cm) | BA ($m^2$/ha) | |
| Montnegre-Corredor (5-13) | 1,159 ± 392 | 18.2 ± 1.7 | 33.5 ± 5.7 | 662 ± 209 | 20.4 ± 2.3 | 23.4 ± 5.3 | 30.2 ± 10.4 |
| Montseny (1-3) | 1,054 ± 169 | 16.1 ± 1.6 | 23.5 ± 5.3 | 709 ± 95 | 17.3 ± 2.4 | 19.0 ± 4.7 | 19.4 ± 5.2 |
| All (6-16) | 1,140 ± 358 | 17.8 ± 1.8 | 31.6 ± 6.8 | 671 ± 191 | 19.8 ± 2.5 | 22.6 ± 5.4 | 28.2 ± 8.8 |

A- Montnegre-Corredor holm oak stand (before)

B- Montnegre-Corredor holm oak stand (after)

C- Montseny holm oak stand (before)

D- Montseny holm oak stand (after)

*Figure 11. Demonstrative holm oak stands in the MixForChange project before and after the intervention.*

The following chart shows basic information on the intervention performed in one of these stands, as a detailed example of the application of the MixForChange silviculture.

| Location: | **Tordera (Barcelona) Montnegre-Corredor** | Area intervened: | 5.6 ha |
|---|---|---|---|

Description of initial structure and specific goal

**Capitalised irregular mixed holm oak stand (BA 30-40 m²/ha)**, where the intervention focuses on fostering the development of accompanying broadleaves (cherry, service tree, maple and others) and regulating competition between the best individuals. The intervention has mainly been performed on medium- and large-sized holm oak trees, with a BA to extract of around 30%.

| Interventions implemented | ORGEST reference model: | Qii04 QiiPL3 |
|---|---|---|

· **Selective thinning** on holm oak, centred on DC 20 to 25, with **shoot selection** of holm oak and chestnut, leaving the best 1-2 shoots/stump. Minimum total BA to maintain: 20-22 m²/ha.

· The thinning and selection of shoots release adult (dbh > 7.5 cm) individuals of cherry, other target broadleaves and well-shaped holm oaks, by eliminating holm oak, chestnut or aspen individuals which are direct crown competitors (1-2 competitors per tree to release).

· **Selective clearing** to facilitate access, not leaving more than 5 continuous meters without clearing in treed areas; heath and strawberry tree shoot selection, maintaining 1-3 shoots/stump. The aim is to significantly reduce the undergrowth sprout and the vulnerability to fires.

Shrubs from fleshy-fruit-producing species which do not interfere with the development of target trees are maintained. Juvenile cherry trees, even if they are misshapen, are maintained to the extent possible. Small, non-vital trees which impede access are eliminated.

Marking

The marking is performed in a part of the stand in a demonstrative way (training area), where the field crews who execute the interventions are accompanied and capacitated.

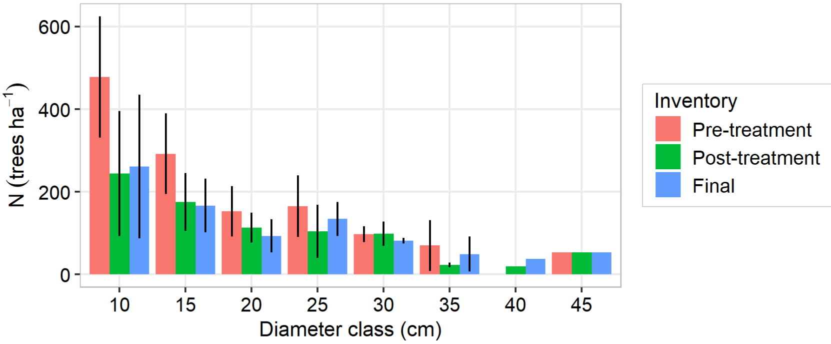
Silvo-dasometric monitoring before (Pre) and after (Post) the intervention

Stand as a whole

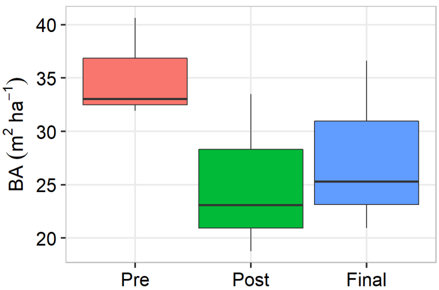
| | N (trees/ha) | BA (m²/ha) | Dg (cm) | Ho (m) | H (m) | Shrub cover (%) | H shrub (m) |
|---|---|---|---|---|---|---|---|
| Pre | 1,300 | 32 | 18 | 15 | 12 | 45 | 1.1 |
| Post | 825 | 24 | 19 | 15 | 12 | 30 | 0.5 |

| | Main species: holm oak | | | Secondary species 1: cherry | | | Secondary species 2: chestnut | | |
|---|---|---|---|---|---|---|---|---|---|
| | N (trees/ha) | BA (m²/ha) | BA (%) | N (trees/ha) | BA (m²/ha) | BA (%) | N (trees/ha) | BA (m²/ha) | BA (%) |
| Pre | 735 | 20 | 63% | 110 | 6 | 19% | 140 | 4 | 13% |
| Post | 525 | 14 | 58% | 90 | 6 | 25% | 72 | 3 | 13% |

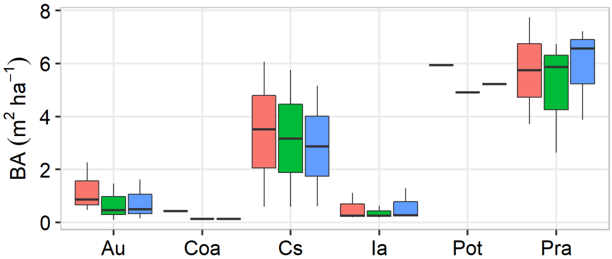
Arboreal layer (Pre and Post: before and after the intervention; Final: 3 vegetative periods after the intervention)




Total diametric distribution



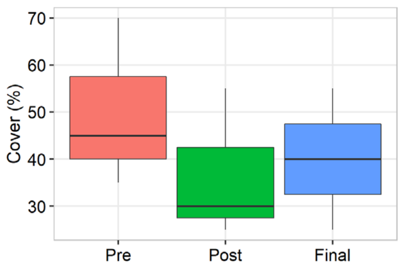

Total basal area

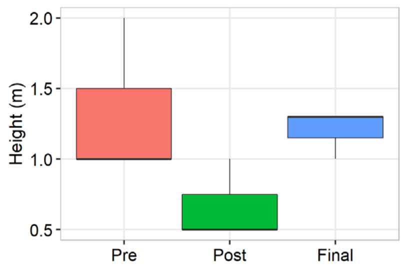



Au: *Arbutus unedo*
Coa: *Corylus avellana*
Cs: *Castanea sativa*
Ia: *Ilex aquifolium*
Pot: *Populus tremula*
Pra: *Prunus avium*

Basal area of the accompanying species

Undergrowth



Photos of the stand

Before the intervention

After the intervention

*Marking the intervention: future crop tree in blue and competitors to fell in red*

*Seed holm oak tree selected as future crop tree*

# 6. Silviculture applied in chestnut stands

## 6.1. Description of the interventions

***Most chestnut stands in Catalonia were planted in the first half of the 20th century to produce wood. Currently, many of these stands are abandoned and in a very poor state of health, generally due to the incidence of chestnut blight (*****Cryphonectria parasitica*****) and the failure to adapt to current site conditions.***

***For this reason, the management of these stands is focused on accompanying the change in dominance in favour of other broadleaf species already present (oak, holm oak, ash, cherry...) according to the micro-site, whether as individual trees or as regeneration patches. An improvement in the vitality of chestnut trees is also sought where habitat conditions so permit. Thus, heterogeneous mixed stands are generated and maintained, of a regularised or irregularised structure depending on the dominant species in the medium term, and reducing the presence of chestnut where it demonstrates less vitality.***

This management approach makes chestnut stands advance toward a **vertically and horizontally heterogeneous structure**, with a trend toward regularisation and capitalisation (where species change is in favour of oak) or toward irregularisation (change in favour of holm oak).

To the extent possible, broadleaf individuals and species with greater potential to produce valuable timber are encouraged, provided they show high vigour: *Prunus avium*, *Quercus petraea*, *Quercus pubescens*, *Quercus canariensis*, *Sorbus torminalis*, *Sorbus domestica*, *Fraxinus excelsior*, *Fraxinus angustifolia* and *Acer sp*.

As a result of the innovative silviculture, the stand takes shape as a **mixed coppice-with-standards forest**, with a regularised or irregularised structure depending on the dominant species in the medium term. The structure is primarily multi-layered: dominant chestnut trees if they are vital and trees of other already present species, intermediate stratum by patches, regeneration of accompanying broadleaves and chestnut sprouts.

*Mixed chestnut stand*

The interventions considered in the demonstrative chestnut stands include:

**Selective thinning**: the first step is to perform a selection of future crop trees (some 100 to 200 trees/ha, maximum 1/4 of the total density), primarily including (see Section 4.3) vital and well-shaped valuable broadleaved trees (including chestnut, if viable) preferably from diametric class 15 and up but with time to grow, and also individuals with interest for biodiversity conservation (underrepresented species, trees with microhabitats of interest, seed trees and fruit producers). In addition, occasional release and pruning may be considered for valuable broadleaved trees which fail to reach the aforementioned diameter if they show good vigour and robust, well-shaped stems.

Selective thinning consists in regulating the competition to which future crop trees are subject, eliminating their main competitors on the canopy level. The number of individuals to eliminate per future crop tree determines the thinning intensity: as a reference point, between 1 and 2 competitors are felled, with a lower value the more future crop trees selected and the more compressed their crown. As a general rule, the extracted basal area does not exceed 25-30%. The felled trees can either be extracted or kept in the soil, depending on their value. Another possibility is to girdle competitor trees instead of felling them to make the future crop tree's initiation of light exposure more gradual. The individuals close to the future crop tree not identified as competitors on the canopy level are maintained, thereby creating a service layer which supports the proper configuration of the selected tree and prevents the emergence of epicormic shoots.

In the stands or parts of the stand which diverge from the optimal characteristics for applying MixForChange silviculture (simplified structure, very high density and/or scarce or null stratification, abundant coetaneous regeneration), **systematic thinning** may be considered, without taking individual characteristics into account.

> *Selective thinning is the main intervention of MixForChange silviculture when candidates for future crop trees exist and to maintain proper structures once they have been achieved, as it applies the fellings according to the role of each tree in the forest.*

**Shoot selection (sucker cutback)**: intervention used to regulate competition on the tree level, applied on stumps with many shoots to concentrate growth in the best developed and positioned ones. One or two shoots are typically left per stump, although in chestnut trees, from one to four may be left regardless of the density (fewer shoots the larger their size). On these chestnut stumps, usually only the adult (dbh > 7.5 cm) living shoots are considered, leaving the dead and small-sized living shoots without cutting. On the stand level, shoot selection also reduces competition and improves vitality.

**Selective clearing**: partial elimination of the vegetation of the understorey layer, based on a prioritisation by height, species or vitality. Optionally, a total target coverage range may be established to reduce overall vulnerability to forest fires. In chestnut stands with full coverage the understory tends to be scarce, which is why clearing operations are limited to facilitating access and promoting the desired tree or shrub species, for their economic or ecological interest.

**Rejuvenation**: cutting misshapen individuals from target broadleaf species down to the ground in order to stimulate a new shoot which may be better shaped. The individual to be rejuvenated is typically young and must show sprout capacity and favourable micro-site conditions. The individuals cut during rejuvenation may be extracted or left in the soil, depending on their commercial value.

**Planting**: artificial regeneration of areas of low tree cover showing null or insufficient regeneration. A great diversity of species are planted, with densities between 10 and 250 trees/ha, taking advantage of the most favourable micro-sites and applying complementary planting techniques to augment success, such as individual shelters or soil conditioners.

## 6.2. Result of demonstrative stands

In the MixForChange project, 15 demonstrative chestnut stands have been intervened, some 46 ha in total. Table 2 shows the silvicultural characterisation performed in 18 monitored plots installed in nine stands, on the Montnegre-Corredor and Montseny massifs (Figure 12).

The basal area extracted (21.6 ± 11.8%) matched the intensity planned (20 – 30% in general), even if there is a certain variability between the different areas of work, with a greater intervention intensity in the plots of Montnegre-Corredor than on Montseny.

*Table 2. Silvicultural characterisation of the treatments performed in chestnut (C. sativa) stands.*

| **Massif (No. stands-plots)** | **Before treatment** | | | **After treatment** | | | **BA extracted (%)** |
|---|---|---|---|---|---|---|---|
| | N (trees/ha) | Dg (cm) | BA ($m^2$/ha) | N (trees/ha) | Dg (cm) | BA ($m^2$/ha) | |
| Montnegre-Corredor (8-15) | 1,375 ± 441 | 13.8 ± 2.8 | 27.3 ± 6.8 | 906 ± 271 | 15.9 ± 2.6 | 21.9 ± 6.6 | 22.1 ± 10,9 |
| Montseny (1-3) | 1,369 ± 191 | 11.8 ± 2.1 | 24.2 ± 6.7 | 1,071 ± 175 | 13.4 ± 1.9 | 20.3 ± 5.8 | 16.4 ± 3.1 |
| All (9-18) | 1,374 ± 406 | 13.5 ± 2.8 | 26.8 ± 6.7 | 937 ± 259 | 15.4 ± 2.6 | 21.6 ± 6.3 | 21.6 ± 11.8 |

A- Montnegre-Corredor chestnut stand (before)

B- Montnegre-Corredor chestnut stand (after)

C- Montseny chestnut stand (before)

D- Montseny chestnut stand (after)

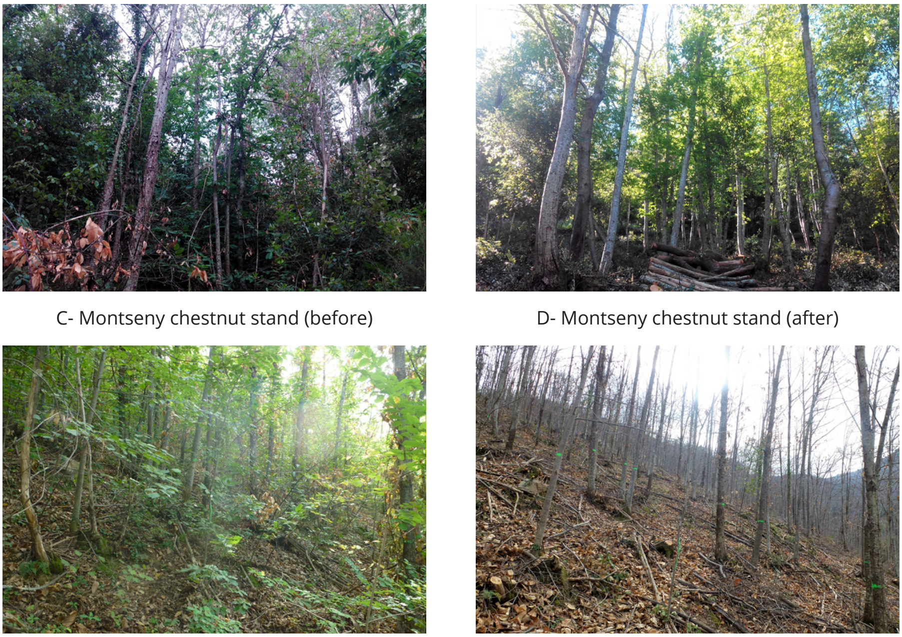


*Figure 12. Demonstrative chestnut stands in the Life MixForChange project before and after intervention.*

The following chart shows basic information on the intervention performed in one of these stands, as a detailed example of the application of the MixForChange silviculture.

| Location: | **Sant Celoni (Barcelona) Montnegre-Corredor** | Area intervened: | 2.5 ha |
|---|---|---|---|

**Description of initial structure and specific goal**

**Mixed multi-layered stand with a more-or-less-abundant, regular chestnut layer, with intermediate vitality and little mortality**. The interventions are centred on potentiating the secondary and accompanying broadleaves (oak, cherry, sorb, wild service, maple), maintaining the best chestnut trees in the medium term.

| Interventions implemented | ORGEST reference model: | Cs03<br>CsPl3 |
|---|---|---|

· **Selection of shoots** in chestnut and *Quercus sp*. leaving the best 1-3 shoots/stump, acting on both live and dead individuals. Total BA to maintain: 20-22 m²/ha (extracting approximately 30%).

During shoot selection, adult (dbh > 7.5 cm) cherry, Algerian oak and other valuable broadleaf trees are **released**, eliminating 1-2 direct competitors on the crown level.

· **Selective clearing** to facilitate access, not leaving more than 5 continuous meters without clearing in treed areas; heath and strawberry tree shoot selection, maintaining 1-3 shoots/stump. The aim is to significantly reduce the undergrowth sprout and reduce vulnerability to fires.

Shrubs from fleshy-fruit-producing species which do not interfere with the development of target tree species are maintained. Juvenile cherry trees, even if they are misshapen, are maintained to the extent possible. Small, non-vital trees which impede access are eliminated.

**Marking**

The marking is performed in a part of the stand (training area), where the field crews who execute the interventions are accompanied and capacitated.

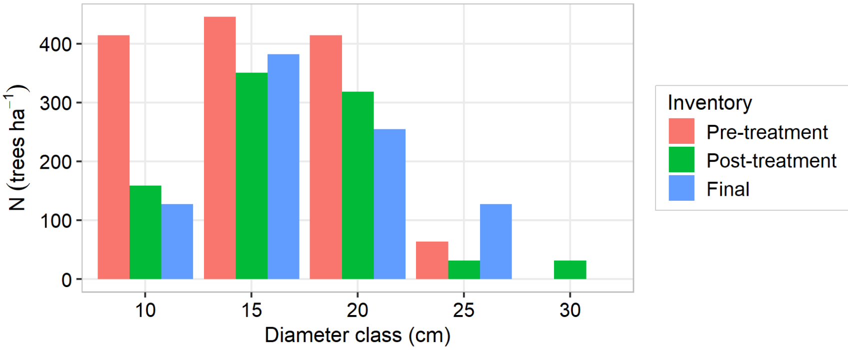
Silvo-dasometric monitoring before (Pre) and after (Post) the intervention

Stand as a whole

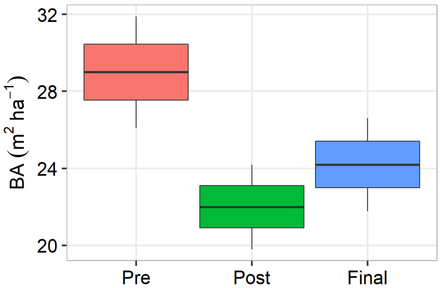
| | N (trees/ha | BA ($m^2$/ha) | Dg (cm) | Ho (m) | H (m) | Shrub cover (%) | H shrub (m) |
|---|---|---|---|---|---|---|---|
| Pre | 1,465 | 29 | 16 | 17 | 14 | 60 | 1.7 |
| Post | 950 | 22 | 17 | 17 | 14 | 25 | 1.0 |

| | Main species: chestnut | | | Secondary species 1: holm oak | | | Secondary species 2: oak | | |
|---|---|---|---|---|---|---|---|---|---|
| | N (trees/ha) | BA ($m^2$/ha) | BA (%) | N (trees/ha) | BA ($m^2$/ha) | BA (%) | N (trees/ha) | BA ($m^2$/ha) | BA (%) |
| Pre | 765 | 17 | 59% | 200 | 3,5 | 12% | 165 | 3 | 10% |
| Post | 500 | 13 | 59% | 115 | 2 | 9% | 135 | 3 | 14% |

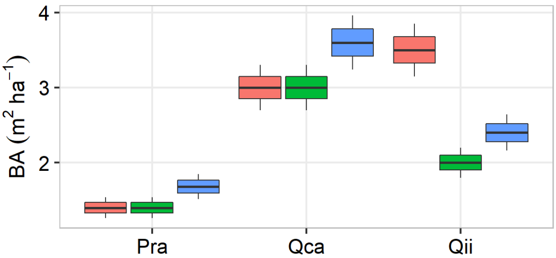
Arboreal layer (Pre and Post: before and after the intervention; Final: 2 vegetative periods after the intervention)




Total diametric distribution



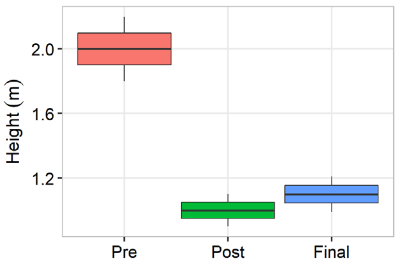

Total basal area

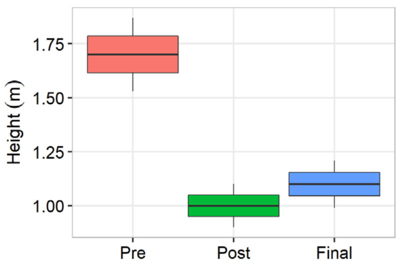



Pra: *Prunus avium*
Qca: *Quercus canariensis*
Qii: *Q. ilex*

Basal area of the accompanying species

Undergrowth



## Photos of the stand

Before the intervention

After the intervention

*Vigorous, well-shaped chestnut tree selected as a future crop tree (in the centre with green line)*

*View of the stand with the chestnut posts piled besides the road*

# 7. Silviculture applied in oak stands

## 7.1. Description of the interventions

> ***The silviculture seeks to generate and maintain diversified and multi-layered structures, with a trend toward capitalisation, where diverse broadleaf species develop in a significant way depending on the different micro-sites, preventing excessive competition.***

The interventions are focused on **regulating competition in the dominant collective of oaks**, among them and with the rest of the species, shaping the distribution of trees and species by layer (vertically) and patches (horizontally).

Where possible, the individuals and species with greater potential to produce valuable timber are promoted, provided they show high vigour. Oak trees with suitable characteristics for the production of barrels or premium sawn wood are considered part of the promoted broadleaves, along with *Prunus avium*, *Sorbus torminalis*, *Fraxinus excelsior*, *Acer pseudoplatanus* and *Acer campestre*.

This management approach makes oak stands progress toward **mixed coppice-with-standards structure**, regular or irregular. Within the prevailing high diversity, the proportion of species is variable, with oak trees remaining dominant or notably present, mixed by patches according to the micro-site conditions. The individuals of one species or another may originate from seeds or sprout. The resulting structure is capitalised (high presence of large trees with possible allocation to quality sawn wood and barrels) and may be regular or irregular depending on the relative proportions of species and their temperaments with respect to the availability of direct and indirect light.

This vertically and horizontally heterogeneous structure is maintained through selection felling (selective thinning on trees of all sizes) in the collective of oaks, applied selectively to favour the best individuals of any species.


The interventions considered in the demonstrative oak stands include:

**Selective thinning**: the first step is to perform a selection of future crop trees (some 100 to 250 trees/ha, maximum 1/3 of the total density), primarily including (see Section 4.3) vital and well-shaped valuable broadleaved trees, preferably from diametric class 15 but with timeo grow, and also individuals with interest for biodiversity conservation (underrepresented species, trees with microhabitats of interest, seed trees and fruit producers). In addition, occasional release and pruning may be considered for valuable broadleaved trees which fail to reach the aforementioned diameter if they show good vigour and robust, well-shaped stems.

Selective thinning consists in regulating the competition to which future crop trees are subject, eliminating their main competitors on the canopy level. The number of competitors to eliminate per future crop tree determines the thinning intensity: as a guideline, between 1 and 2 competitors are felled, with a lower figure the more future crop trees selected and the more compressed these trees' crown is. As a general rule, the extracted basal area should not exceed 15-30%. The felled trees can either be extracted or kept in the soil, depending on their value. Another possibility is to girdle competitor trees instead of felling them to make the future crop tree's initiation of light exposure more gradual. The individuals close to the future crop tree not identified as competitors on the canopy level are maintained, thereby creating a service layer which supports the proper configuration of the selected tree and prevents the emergence of epicormic shoots.

In the stands or parts of the stand which diverge from the optimal characteristics for applying MixForChange silviculture (simplified structure, very high density and/or scarce or null stratification), **mixed selective thinning** may be considered. The intervention has a low-to-moderate intensity (lower the larger the trees are), with a maximum extraction of 30% of the initial basal area. Selective thinning is combined with low thinning, with the goal of reducing the high density of the dominated layer, in a more or less homogeneous way in the stand. Competition is thereby reduced and the development of the most adapted and vigorous individuals is favoured, seeking to maintain, in the long term, a stable and vital coppice-with-standards structure.

> *Selective thinning is the main intervention of MixForChange silviculture when candidates for future crop trees exist and to maintain proper structures once they have been achieved, as it applies the fellings according to the role of each tree in the forest.*

**Shoot selection (sucker cutback)**: intervention used to regulate competition on the tree level which is applied on stumps with various shoots to concentrate growth in the best developed and positioned ones. In oak stands, this tends to be a low-intensity intervention, cutting a maximum of half of the living shoots of a stump and attempting, in the long term, to leave only one shoot per stump. Thus, competition is reduced and vitality is improved on the stand level as well.

**Selective clearing**: partial elimination of the vegetation of the understorey layer, based on a prioritisation by height, species or vitality. Optionally, a total target coverage range may be established to reduce overall vulnerability to forest fires. In oak stands with a history of intense harvesting for firewood, it is typical to see developed undergrowth, with an abundance of light-demanding species. In this case, the phytovolume of these species is reduced in an intense way, respecting some individuals from sporadic species with higher shade requirements and/or producers of flowers and fleshy fruit, due to their importance in biodiversity. In the case of heath, strawberry tree and boxwood shrubs, it is useful to perform a shoot selection (leaving 1 or 2 shoots per stump) instead of cutting all the shoots, to limit posterior sprout.

**Rejuvenation**: cutting misshapen individuals from target broadleaf species down to the ground in order to stimulate a new shoot which may be better shaped. The individual to be rejuvenated is typically young and must show sprout capacity and favourable micro-site conditions. The individuals cut during rejuvenation may be extracted or left in the soil, depending on their commercial value.

**Planting**: artificial regeneration of areas of low tree cover showing null or insufficient regeneration. A great diversity of species are planted, with densities between 10 and 200 trees/ha, taking advantage of the most favourable micro-sites and applying complementary planting techniques to augment success, such as individual shelters or soil conditioners.

## 7.2. Result of demonstrative stands

In the MixForChange project, 8 demonstrative oak stands have been intervened, some 57 ha in total. Table 3 shows the silvicultural characterisation on the basis of 19 monitoring plots installed in 7 stands, grouped by area of work: Montnegre-Corredor, Bellmunt-Collsacabra, Montseny and Ripollès (Figure 13). To summarise, the basal area extracted (23.3 ± 12.8%) matched the planned (15 – 30% in general), even if there is a certain variability between the different areas of work, with a decreasing intervention intensity in the plots of Montseny, Bellmunt-Collsacabra, Ripollès and Montnegre-Corredor.

*Table 3. Silvicultural characterisation of the treatments performed in oak stands (Q. pubescens, Q. canariensis, Q. petraea, Q. robur).*

| **Massif (No. stands-plots)** | **Before treatment** | | | **After treatment** | | | **BA extracted (%)** |
|---|---|---|---|---|---|---|---|
| | N (trees/ha) | Dg (cm) | BA ($m^2$/ha) | N (trees/ha) | Dg (cm) | BA ($m^2$/ha) | |
| Montnegre-Corredor (3-4) | 876 ± 256 | 20.8 ± 3.1 | 36.9 ± 14.6 | 669 ± 203 | 22.1 ± 3.2 | 31.7 ± 15.4 | 15.9 ± 17.7 |
| Bellmunt-Collsacabra (2-9) | 1,024 ± 176 | 14.0 ± 1.5 | 18.9 ± 3.5 | 688 ± 154 | 14.6 ± 1.3 | 14.2 ± 4.3 | 27.6 ± 17.6 |
| Montseny (1-3) | 1,528 ± 127 | 14.5 ± 1.7 | 35.6 ± 5.6 | 934 ± 67 | 15.1 ± 0.8 | 25.5 ± 4.0 | 28.5 ± 2.9 |
| Ripollès (1-3) | 944 ± 111 | 15.3 ± 5.5 | 29.7 ± 9.7 | 700 ± 110 | 14.8 ± 3.6 | 24.6 ± 7.0 | 16.6 ± 6.8 |
| All (7-19) | 1,060 ± 273 | 15.7 ± 3.7 | 27.0 ± 11.1 | 727 ± 168 | 16.4 ± 3.7 | 21.7 ± 10.5 | 23.3 ± 12.8 |

A- Montnegre-Corredor oak stand (before)

B- Montnegre-Corredor oak stand (after)

C- Bellmunt-Collsacabra oak stand (before)

D- Bellmunt-Collsacabra oak stand (after)

E- Montseny oak stand (before)

F- Montseny oak stand (after)

G- Ripollès oak stand (before)

F- Ripollès oak stand (after)

*Figure 13. Demonstrative oak stands in the MixForChange project, before and after intervention.*

The following chart shows basic information on the intervention performed in one of these stands, as a detailed example of the application of the MixForChange silviculture.

| Location: | **Sant Celoni (Barcelona) Montnegre-Corredor** | Area intervened: | 2.0 ha |
|---|---|---|---|

Description of initial structure and specific goal

**Oak stand dominated by sessile oak**, with variable presence of other oaks (Algerian, downy) and some other broadleaves (cherry, ash, sorb, wild service, maple), irregularised and mixed by patches, where the oak layer is vital and dominant. The interventions aim to foster the growth of the best trees while the heterogeneity of the structure is maintained.

| Interventions implemented | ORGEST reference model: | Qpe02 QcaAl1 |
|---|---|---|

· **Selective thinning** in favour of some 200 trees/ha (7-8 m between trees) of sessile oak, Algerian oak, holm oak and cherry, dominant or co-dominant and well-shaped, eliminating one direct competitor per future crop tree and maintaining a service layer. In addition, a selection of chestnut and *Quercus sp*. shoots is performed, leaving the best 1-2 shoots/stump, acting on both live and dead chestnut shoots. Total BA to maintain: 30-32 m²/ha (approximate BA to extract: 30%).

· **Selective clearing** to facilitate access, not leaving more than 5 continuous meters without clearing; shoot selection of heath and strawberry tree (maintaining 1-3 shoots/stump) and hazel (maintaining 3-4 shoots/stump). The aim is to significantly reduce the undergrowth sprout and reduce vulnerability to fires.

Shrubs from fleshy-fruit-producing species which do not interfere with the development of tree species are maintained. Juvenile cherry trees, even if they are misshapen, are maintained to the extent possible. Small, non-vital trees which impede access for silviculture tasks are eliminated.

Marking

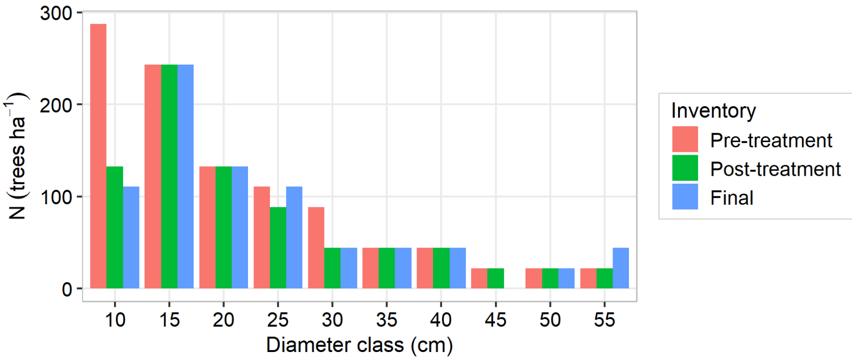
Marking is performed throughout the stand, marking the future crop trees and their competitors to fell. The field crews who execute the interventions are also accompanied and capacitated.

| Silvo-dasometric monitoring before (Pre) and after (Post) the intervention | | | | | | | |
|---|---|---|---|---|---|---|---|
| Stand as a whole | | | | | | | |
| | N (trees/ ha) | BA (m²/ha) | Dg (cm) | Ho (m) | H (m) | Shrub cover (%) | H shrub (m) |
| Pre | 1,245 | 42 | 20 | 19 | 14 | 85 | 2.0 |
| Post | 975 | 32 | 21 | 19 | 14 | 50 | 1.0 |

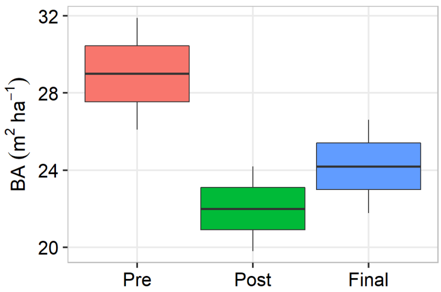
| | Main species: sessile oak* | | | Secondary species 1: Algerian oak* | | | Secondary species 2: chestnut | | |
|---|---|---|---|---|---|---|---|---|---|
| | N (trees/ ha) | BA (m²/ ha) | BA (%) | N (trees/ ha) | BA (m²/ ha) | BA (%) | N (trees/ ha) | BA (m²/ ha) | BA (%) |
| Pre | 325 | 15 | 36% | 260 | 8 | 19% | 125 | 6 | 14% |
| Post | 280 | 13 | 41% | 190 | 6 | 19% | 80 | 4 | 13% |

*The Algerian oak and sessile oak figures should be taken as a guide, it being quite difficult to distinguish between them due to the abundance of hybrid individuals. The sum of the two is representative of the presence of oaks in the stand.

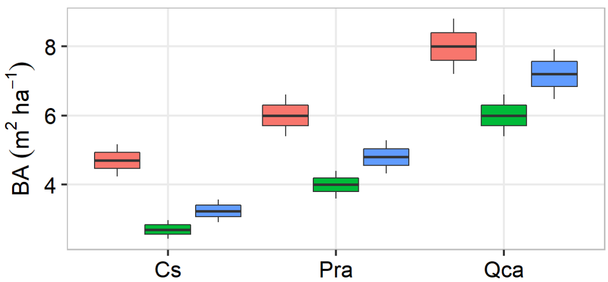
Arboreal layer (Pre and Post: before and after the intervention; Final: 3 vegetative periods after the intervention)




Total diametric distribution



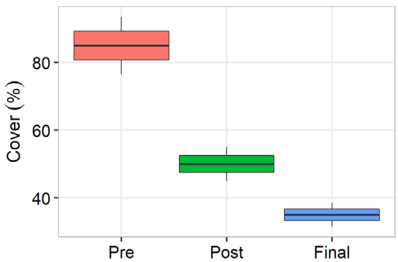

Total basal area

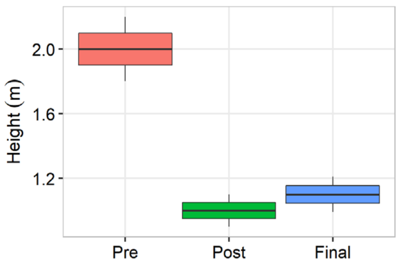



Cs: *Castanea sativa*
Pra: *Prunus avium*
Qca: *Quercus canariensis*

Basal area of the accompanying species

Undergrowth



Photos of the stand

Before the intervention

After the intervention

*Marking of future crop trees (orange line).*

*View of the stand during a technical transference session, after the execution of the works.*

# 8. Silviculture applied in pine stands

## 8.1. Description of the interventions

> ***Mixed pine and broadleaf forests tend to be structured as a canopy of pines (species promoted in the past) with a broadleaf sub-canopy layer. Currently, the broadleaves show a vigorous development, and the pine layer appears capitalised and aged, its regeneration limited by the high density of broadleaves.***
>
> ***The silviculture applied seeks to generate and maintain diversified structures in terms of layers and species, with a high presence of oaks and other broadleaf species. Pines are maintained in the most favourable locations where they do not impede the development of the rest of the species.***

The aim is to **accompany the broadleaves' development and the progressive change of dominance of the pine canopy**. In stands with a low-density tree cover and too few broadleaves to generate a full layer, enrichment plantings may be executed, introducing and reinforcing the target broadleaves and pine trees in favourable sites.

In the interventions, valuable broadleaf individuals and species are promoted, provided they show high vigour: *Prunus avium*, *Quercus petraea*, *Quercus pubescens*, *Quercus canariensis*, *Sorbus torminalis*, *Fraxinus excelsior*, *Acer pseudoplatanus* and *Acer campestre*.

The structure pursued with MixForChange silviculture in pine stands varies according to the vitality and regeneration capacity of the upper pine layer and the broadleaf sub-canopy layer:

- Pines with little vigour and in a phase close to senescence, fully established broadleaf sub-canopy with a capacity to develop: small-scale heterogeneity is promoted (individual trees or patches, depending on the species' temperament), accompanying the progressive substitution of the dominance of pine. They tend to be zones in which the broadleaf layer shows strong development, whether due to the high site quality or the deficient coverage of the pines canopy caused by their loss of vitality (advanced age, effect of recurring droughts) or the previously applied management techniques.

- Vigorous pines with the capacity to regenerate and/or not-yet-consolidated broadleaf sub-canopy layer: heterogeneity is promoted by patch or copse, regulating competition in the upper canopy and between this canopy and the broadleaf sub-canopy layer to accompany the stand's progressive development.

Depending on the stand conditions the interventions are adjusted to advance, through a variable number of interventions of adaptation or transition, towards the final desired structure. When the structure meets the general targets pursued (vertically and horizontally heterogeneous, with regeneration processes, adequately shaped future crop trees, an adequate level of capitalisation of the various species) the conditions are maintained through selection felling, that is, selective thinning on trees of all sizes.

*Mixed pine stand*

The interventions considered in the demonstrative pine stands include:

**Selective thinning**: the first step is to select some 200 to 400 future crop trees/ha (fewer the larger the proportion of broadleaves selected and tree size), regardless of total density. These future crop trees mainly include (see Section 4.3) vital, well-shaped pine trees or valuable broadleaved species, preferably of diameter class 15 and up but with time to grow, and also individuals important for biodiversity conservation (underrepresented species, trees with microhabitats of interest, seed trees and fruit producers). In addition, occasional release and pruning may be considered for valuable broadleaved trees which fail to reach the aforementioned diameter if they show good vigour and robust, well-shaped stems.

Selective thinning consists in regulating the competition to which future crop trees are subject, eliminating their main competitors on the canopy level and also on the root level if the future crop tree is a pine. Future crop trees tend to form part of the dominant layer, which is why selective thinning is frequently applied to regularised structures. The number of trees to eliminate per future crop tree determines the thinning intensity: as a guideline, between 1 and 3 competitors are felled, with a lower figure the more future crop trees selected, the more compressed their canopy and the more tolerant to shade their behaviour is. As a general rule, the extracted basal area does not exceed 20-25%. The felled trees can either be extracted or kept in the soil, depending on their value. Another possibility is to girdle competitor trees instead of felling them to make the future crop tree's initiation of light exposure more gradual. The individuals close to the future crop trees not identified as competitors on the canopy level are maintained, thereby creating a service layer which supports the proper configuration of the selected tree and prevents the emergence of epicormic shoots.

In the stands or sections of a stand which diverge from the optimal conditions for applying MixForChange silviculture (simplified structure, very high density and/or limited or no stratification), **mixed selective thinning** may be considered to potentially achieve moderate intensity, with a maximum extraction of 35% of the initial basal area. Selective thinning is combined with low thinning, seeking to reduce the high density of the dominated layer, more or less homogeneously throughout the stand, and the development of the more adapted and vigorous trees is favoured, with the goal of maintaining, in the long term, a stable, vital cover advancing toward capitalisation.

*Selective thinning is the main intervention of MixForChange silviculture when candidates for future crop trees exist and to maintain proper structures once they have been achieved, as it applies the fellings according to the role of each tree in the forest.*

**Shoot selection (sucker cutback)**: intervention used to regulate competition on the tree level (sprouting species) which is applied on stumps with many shoots to concentrate growth in the most well developed and positioned ones, generally 1 or 2 per stump. It is a typical intervention on species with high sprout capacity, like holm oak and chestnut, which are cut intensively, cutting more than half of the living shoots from each stump, while in oak and maple it is applied with less intensity. Thus, competition is reduced and vitality is improved on the stand level as well.

**Selective clearing**: partial elimination of the vegetation of the understorey layer, based on a prioritisation by height, species or vitality. Optionally, a total target coverage range may be established to reduce overall vulnerability to forest fires. In pine stands which have had a sparse tree covering for a long time, a developed undergrowth layer is typical, with an abundance of light-demanding species. In this case, the phytovolume of these species is reduced in an intense way, respecting some individuals from sporadic species with higher shade requirements and/or producers of flowers and fleshy fruit, due to their importance for biodiversity. In the case of heath, strawberry tree and boxwood shrubs, it is advisable to perform a selection of shoots (leaving 1 or 2 shoots per stump) instead of cutting all the shoots, to limit posterior sprout.

**Rejuvenation**: in the stands with a great abundance of young broadleaves, one possibility to consider is felling poorly shaped trees to generate a new shoot. The individual to be rejuvenated is typically young and must show sprout capacity and favourable micro-site conditions. The individuals cut during rejuvenation may be extracted or left in the soil, depending on their commercial value.

**Planting**: artificial regeneration in the best micro-sites, adapting the species choice to them and using complementary techniques to increase success, including individual shelters or soil conditioners. If the tree cover is sparse due to intense disturbances, one option may be to prioritise frugal conifers (maximum planting density of 400 trees/ha), which during their development will create the conditions for the establishment and consolidation of a new cohort of broadleaves requiring initial accompaniment. Broadleaves may also be planted (10-150 trees/ha) to enrich stands where they are scarce.

**Sanitary felling**: in areas affected by biotic or abiotic damage, a portion of the dead or dying trees, with symptoms of disease or pests, affected by snowfall, wind, hail, etc. are eliminated.

## 8.2. Result of demonstrative stands

In the MixForChange project, 9 demonstrative pine stands have been intervened, some 62 ha in total. Table 4 shows the silvicultural characterisation obtained in 22 monitoring plots installed in 8 stands, grouped into the four areas of work: Montnegre-Corredor, Bellmunt-Collsacabra, Montseny and Ripollès (Figure 14). To summarise, the basal area extracted (21.9 ± 15.8%) matched the intensity planned (20 – 25% in general), even if there is a certain amount of variability between the different areas of work, with a decreasing intensity in Bellmunt-Collsacabra, Montseny, Montnegre-Corredor and Ripollès.

*Table 4. Silvicultural characterisation of the treatments executed in pine stands (P. sylvestris, P. pinea).*

| Massif (No. stands-plots) | Before treatment | | | After treatment | | | BA extracted (%) |
|---|---|---|---|---|---|---|---|
| | N (trees/ha) | Dg (cm) | BA ($m^2$/ha) | N (trees/ha) | Dg (cm) | BA ($m^2$/ha) | |
| Montnegre-Corredor (4-6) | 722 ± 408 | 18.8 ± 2.3 | 23.1 ± 12.8 | 590 ± 331 | 18.7 ± 2.6 | 17.7 ± 8.8 | 14.9 ± 26.6 |
| Bellmunt-Collsacabra (2-10) | 994 ± 321 | 18.3 ± 0.7 | 30.1 ± 8.5 | 679 ± 275 | 18.5 ± 1.3 | 21.5 ± 5.5 | 27.4 ± 14.5 |
| Montseny (1-3) | 1,390 ± 319 | 14.5 ± 2.5 | 36.4 ± 10.1 | 923 ± 0 | 17.5 ± 3.5 | 30.6 ± 14.5 | 24.3 ± 11.5 |
| Ripollès (1-3) | 881 ± 157 | 21.6 ± 1.5 | 42.5 ± 9.4 | 764* | 26.0* | 47.5* | 10.5* |
| All (8-22) | 957 ± 376 | 18.3 ± 2.5 | 30.7 ± 11.5 | 681 ± 279* | 18.9 ± 2.6* | 22.7 ± 10.1* | 21.9 ± 15.8* |

* in the post-treatment inventory of the Ripollès stand, only one plot was measured

A- Montnegre-Corredor pine stand (before)

B- Montnegre-Corredor pine stand (after)

C- Bellmunt-Collsacabra pine stand (before)

D- Bellmunt-Collsacabra pine stand (after)

E- Montseny pine stand (before)

F- Montseny pine stand (after)

G- Ripollès pine stand (before)

H- Ripollès pine stand (after)

*Figure 14. Demonstrative pine stands in the MixForChange project, before and after intervention.*

The following chart shows basic information on the intervention performed in one of these stands, as a detailed example of the application of the MixForChange silviculture.

| Location: | **St Quirze de Besora (Barcelona) Bellmunt-Collsacabra** | Area intervened: | 16 ha |
|---|---|---|---|

**Description of initial structure and specific goal**

Stand with an **upper canopy of scots pine over an abundant broadleaf stratum**, mixed tree to tree. The site quality is good for all the species present which in general show high vitality. Some broadleaves reach the dominant layer in prior openings. The intervention aims to regulate overall competition and favour the development of the best trees of all species.

| Interventions implemented | ORGEST reference model | Ps08 PsQh3 |
|---|---|---|

· **Mixed selective thinning** on scots pine, oak, beech and other species of the dominant and co-dominant layer. One direct competitor is eliminated over some 300 trees/ha, dominant and co-dominant of good shape (6 m between trees), maintaining a service sub-canopy layer if an oak is selected. In the areas with no selected trees and in the sub-canopy layer, competition is regulated in a general way (low thinning) until a density of 600-650 trees/ha is reached. Total BA to maintain: 20-22 m²/ha (BA to extract: 15-20%).

The thinning is used to eliminate 1-2 direct competitors on the crown level of well-shaped adult (dbh > 7.5 cm) wild service trees, maples, sessile oaks or other relevant broadleaves. Occasionally, individuals of underrepresented species are also released, especially linden and yew.

· **Selective clearing** to reduce the scrub cover to 25% and create vertical discontinuity in the fuel, preferably eliminating shrubs greater than 1.3 m in height. On boxwood individuals with shoots of arboreal aspect, a shoot selection is performed maintaining 1 shoot/stump and pruning up to half its height. On hazel, 3-4 shoots/stump are maintained. Some individuals from fleshy-fruit-producing species which do not interfere with the development of tree species are maintained. Individuals of arboreal species are not cleared.

**Marking**

Marking the future crop trees and their competitors to fell is performed throughout the stand. The field crews who execute the tasks are regularly accompanied and capacitated.

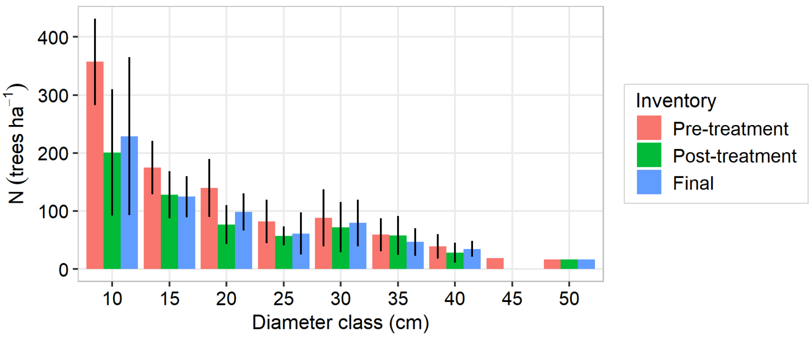
**Silvo-dasometric monitoring before (Pre) and after (Post) the intervention**

Stand as a whole

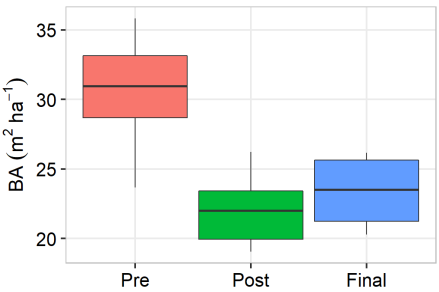
| | BA (m²/ha) | Dg (cm) | Ho (m) | H (m) | Shrub cover (%) | H shrub (m) |
|---|---|---|---|---|---|---|
| Pre | 31 | 20 | 20 | 13 | 44 | 1.0 |
| Post | 23 | 23 | 20 | 15 | 30 | 0.5 |

| | Main species: scots pine | | Secondary species 1: oak | | | Secondary species 2: maple | | |
|---|---|---|---|---|---|---|---|---|
| | BA (m²/ha) | BA (%) | N (trees/ha) | BA (m²/ha) | BA (%) | N (trees/ha) | BA (m²/ha) | BA (%) |
| Pre | 14 | 45% | 69 | 6 | 19% | 200 | 5 | 16% |
| Post | 11 | 47% | 50 | 3 | 13% | 149 | 3 | 13% |

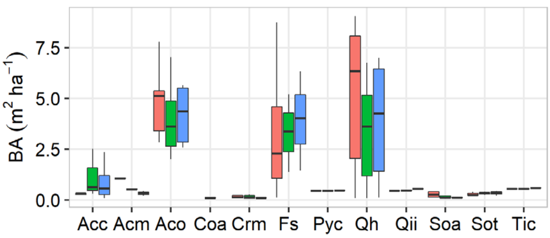
Arboreal layer (Pre and Post: before and after the intervention; Final: 2 vegetative periods after the intervention)




Total diametric distribution



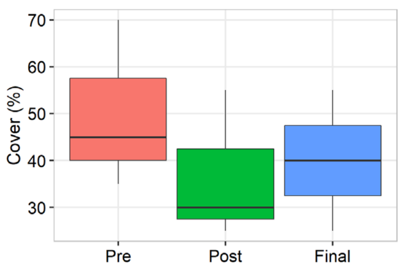

Total basal area

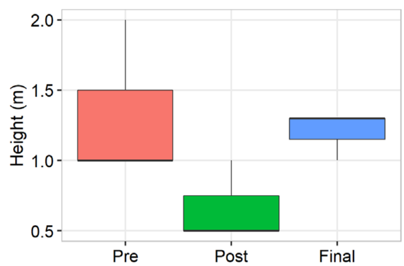



Basal area of the accompanying species

Acc: *Acer campestre*
Acm: *A. monspessulanum*
Coa: *Corylus avellana*
Crm: *Crataegus monogyna*
Fs: *Fagus sylvatica*
Pyc: *Pyrus communis*
Qh: *Quercus pubescens*
Qii: *Q. ilex*
Soa: *Sorbus aria*
Sot: *S.torminalis*
Tic: *Tilia cordata*

Undergrowth



Photos of the stand

Before the intervention

After the intervention

*Detail of the logging of two trees marked as competitors to fell (red dot).*

*Beech individual selected as a future crop tree (marked in blue), three years after the interventions. The accompanying trees to be maintained as a service layer have also been marked in green.*

## 9. Practical lessons learned during the implementation of the interventions

The demonstrative silvicultural interventions of the MixForChange project have represented a rich practical learning experience on all levels of decision-making, from the design of the treatments to their implementation and follow-up. From this experience, recommendations for replicating this innovative silvicultural approach can be extracted, considering its different phases and differences with respect to more conventional practices, as described below.

**Phase of diagnosis**

· It is essential to possess a thorough knowledge of the current conditions of the habitat, the stand and the trees composing it, as well as of the natural dynamics, both current and past. In this way, it will be possible to determine the potential and establish the management options for the goals proposed.

· To adequately capture the heterogeneity of mixed stands, the forest inventories have to be adapted, it being possible to assess the combination of plot-based inventories with an expert estimation traversing the stand. In addition to quantitative indicators, qualitative indicators should also be employed to describe the variability and potentiality observed (for example, incorporating a section of literal silvicultural description in the stand diagnosis).

**Definition of the planning on a strategic scale**

Based on the diagnosis of each stand, the general management framework is defined on the forest (property) level. The first decision is to assign overall goals for each intervention unit.

The goals in each stand must consider its context and the stands surrounding it or associated by location or by infrastructures of access and defence, seeking maximum economic efficiency. This type of silviculture does not need to be implemented in every stand, but rather various management approaches may be combined as long as the general goals on the forest level are kept in mind.

· The prioritisation of the stands in which to implement this silvicultural approach is a key decision, especially in a first application, as it entails a change in management. The best results of the MixForChange silvicultural approach are obtained in stands with high productivity and a certain level of capitalisation and social stratification, but with intermediate ages (phase of development). In these conditions the stand still has the capacity to react and time to evolve toward an adequate structure for unveiling the full potential of this form of management. Thus, it is advisable to prioritise the first application of this silviculture system in these more favourable stands, allowing the practice and results obtained to encourage and facilitate progressive replication in other stands: young homogeneous stands in the pole stage (with a lot of time ahead to adapt the structure but little current capital) and, in the last place, in more or less heterogeneous but aged stands, in which it may prove too late to achieve all the goals of this form of silviculture.

The definition of the management system to implement in each stand, whether by adopting reference management models or describing the silvicultural characteristics for the present formations, must incorporate an important component of flexibility to include all the precepts of this type of silviculture. The executive decision is made on the scale of a tree or group of trees, considering many factors observed on a small scale, which is why the rules of management must be limited to contributing the context criteria.

**Design of silvicultural interventions**

The design of the silvicultural interventions is defined in the field and never on paper alone. Thus, prior to the design, a meticulous visit of the stands must be conducted to visualise the conclusions of the diagnosis and acquire a precise idea of the dynamics in place.

The goals are proposed on a long time scale, which is why not all the changes ought to be pursued in a single intervention. In any event, the intensity proposed must make it possible to accomplish real changes in the conditions and maintain the productive capacity of the forest.

· In most of the project's stands, it was deemed necessary to reactivate natural regeneration, especially of sporadic species. Thus, the design must take the favourable micro-sites into account, paying special attention to the entrance of light and the available space.

· One key aspect is to communicate, in a practical way, the criteria for selecting future crop trees: for their commercial interest or for biodiversity. In the first case, vigorous and well-formed trees are selected to produce valuable timber, attending to their current and potential state (see Coello *et al.*, 2020a). In the case of future crop trees selected for biodiversity, trees from underrepresented species or with valuable microhabitats are prioritised. Similarly, it is also essential to ensure the adequate transfer of the identification criteria of the future crop trees' main competitors, that is, the individuals which most intensely impede the expansion of the future crop tree's crown. Thus, the main competitors are identified observing the crown layer and also taking into account the species' temperament, relative orientation and position on the slope. In general, the most competition is exercised by the trees most tolerant to shade, situated to the south and in higher positions. As for the future crop trees

Future crop trees marked with two horizontal lines

Future crop tree

selected for their commercial value, it is essential to maintain the trees placed around them which cast shade on their stems but do not compete at the crown level, as their elimination could induce the emission of epicormic shoots on the future crop tree.

**Execution of the silviculture: marking**

· In a silviculture system with a certain level of complexity, like the one proposed in MixForChange, marking is an essential intervention for transferring the goals from the planning and design to the real execution. This marking must be performed by qualified professionals in the application of this form of silviculture, and the operations of tree felling and logging (haul and extraction roads, piling sites...) must be considered during its execution.

· Apart from accomplishing a detailed application of the foreseen silviculture system, marking makes it possible to augment the productivity and safety of the crews who execute the forest works.

· The general recommendation is to perform a complete stand marking, preferably before conducting any other intervention. Nonetheless, if interior visibility and walkability is seriously impeded by undergrowth, it may prove useful to perform a clearing operation before marking, accepting that a certain amount of direct information on the growth conditions of each tree, especially juvenile trees, will have been lost. If the stand and the intervention are somewhat homogeneous and the crews are experienced, partial markings in training areas may be considered.

*Marking, a key intervention*

· The marking code (colours, shapes, position of the marks) must be clear and agreed upon by all the personnel involved. It is advisable to mark the trees to cut with forestry paint, in a single, highly visible colour, in the most visible position for the staff who executes the marking and for the staff who will perform the felling (for example, a red dot on the stem on the upstream and downstream faces, plus a dot under the height at which it will be cut, which acts as a control). The future crop trees should also be marked with another colour and shape (for example, a horizontal white line on the upstream and downstream faces) to facilitate a full view during the process of marking and to indicate to the felling staff that these trees must not be harmed. The marking of other trees which must necessarily be respected, whether for motives of biodiversity or to exert a favourable effect on the shaping of a future crop tree (e.g. nearby trees shading the stem, without competing for light), also facilitates execution and prevents misunderstandings.

· In any event, it is fundamental to ensure that the workers executing the works comprehend the management criteria applied, whose transmission must be done gradually and with periodic follow-up throughout the execution. It is advisable to work with qualified, highly professionalised crews with sufficient experience and who agree, *motu proprio*, to follow the rules of work, risk prevention, health and safety and the optimisation of methods and equipment, because it represents a determining factor for the intervention's efficiency and results (Garcia, 2022).

**Silviculture implementation: interventions in the tree and understorey layers**

· For the execution of the interventions, it is advisable to define and apply a series of good practices which have a favourable effect on maintaining the forest's functions. It consists in explaining how to implement certain actions or what not to do during felling, lopping, hauling and piling to improve the work's efficiency and safety and prevent or minimise negative impacts on the environment.

· Examples of good practices in arboreal-layer operations: in trees to fell which are in contact with a large rock or show a very pronounced basal curvature, a tall stump is left to facilitate felling and processing (in addition to generating dead wood); not cutting ivy unless they are very abundant and affect future crop trees; performing the felling and hauling without damaging future or juvenile trees and without altering mosses on trunks or rocks, areas of water accumulation or drainage, rocky spaces or terraces; not lopping over incipient regeneration or small patches with herbs (especially if there are flowering species); not hauling trees of little value if they are difficult to access; not slicing dead trees in the soil.

· Examples of good practices in interventions on understory: perform clean cuts at the base without leaving sharp points which would suppose a risk; not affecting juvenile individuals of arboreal species if it is not explicitly indicated in the design; not chopping up material which is non-woody or under 5 cm in diameter; preventing debris accumulations higher than the knee.

*Felling of a tree*

*Logging of a stem*

**Product classification**

· This form of silviculture gives rise to a wide range of wood products, which reinforces the previously mentioned need to employ qualified crews who optimise the logistics of extraction and classification, reducing idle time, avoiding excessive handling or facilitating the processes of loading and unloading.

· In the first interventions in little capitalised stands, the highest-value products will appear in very limited quantities, which is why possible options for concentrating the offer must be explored.

**Follow-up**

The assessment of results, even in the short term, makes it possible to improve the capabilities and experience of the personnel involved, both to improve the design of future interventions in the stand as well as to intervene in new stands. It is advisable to monitor on a regular basis, in addition to the diagnoses made during the revision of the planning instruments.

· In these assessments, special attention should be paid to the impact of extreme climatic phenomena on the intervened stands.

# III. Assessment of the silviculture applied

This Block presents some of the results of the monitoring actions of the MixForChange project, centred on quantifying the effect of the silviculture applied on the main ecosystem services directly or indirectly associated with to climate change adaptation (vitality, biodiversity, vulnerability to fires, water balance), with its mitigation (carbon balance) and with the economic sustainability of the management (economic balance).

To correctly interpret the results obtained, it must be understood that this form of silviculture aims to progressively improve the indicators of adaptation (in the short-medium term) and the economic sustainability of the management (in the medium-long term). In the case of the indicators of adaptation, an overall improvement has been sought, without attempting to optimise any single one alone. Moreover, the assessment made is based on a single intervention, in stands whose initial structure diverged in general from the structure pursued through this silvicultural approach. Finally, the effects of this silviculture have been assessed in the short term: two or three vegetative periods after application.

The proper assessment of this silvicultural approach can only be completed based on its repeated application in the same stands, and with medium- and long-term follow-up.

# 10. Effect of MixForChange silviculture on indicators of climate change adaptation and mitigation

The study of the effect of MixForChange silviculture on indicators of adaptation is based on the monitoring of the vitality, biodiversity, vulnerability to forest fires and water balance of the intervened stands. The carbon balance, as a sign of the capacity to mitigate climate change, has also been assessed.

This assessment has been based on monitoring the demonstrative stands since before the interventions and during the 2 or 3 (depending on the stands) vegetative periods after them. The data has been gathered in a network of 71 permanent tree-to-tree monitoring plots, with a 10-13 m radius, distributed through the various intervened stands. Furthermore, 14 of these plots have a twin control plot associated, in which no intervention has been performed, to compare the stands' evolution in the absence of treatment.

## 10.1. Stand vitality: growth

Diameter growth is one of the main indicators of the trees' vitality and response to the silviculture applied. This variable has been studied by comparing the initial and final diameter of the 14 double (intervened and control) plots, in addition to the detailed monitoring of 185 trees using dendrometers.

Despite the interventions' low or moderate intensity and the brief monitoring period, the reaction of some species in the form of increasing diameter growth, in comparison with the control plots, has been remarkable (Figure 15 and Figure 16). Such is the case of holm oak, stone pine and scots pine, or sporadic species such as maple, ash and wild service. Other species, like downy or Algerian oak or cherry, show a variable reaction according to the formation, with a limited reaction in chestnut stands, but with a noteworthy increase in growth in holm oak and pine stands. The chestnut tree, and in general the accompanying species in chestnut stands, has barely reacted to the interventions.

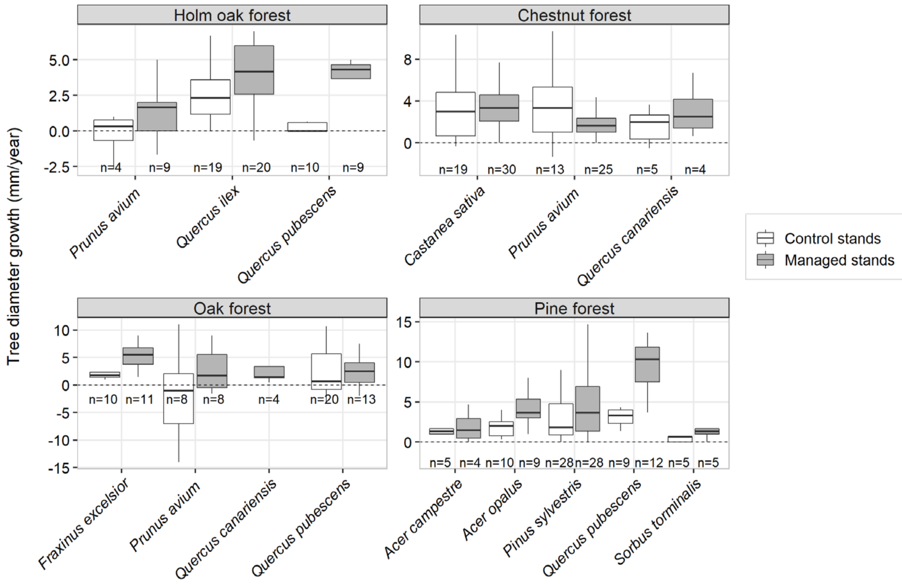



*Figure 15. Annual diameter growth of the main species, and most frequent accompanying ones, in the four MixForChange forest typologies, during the two or three vegetative periods following the silvicultural intervention. Control: results in non-intervened plots; Intervention: results in intervened plots.*

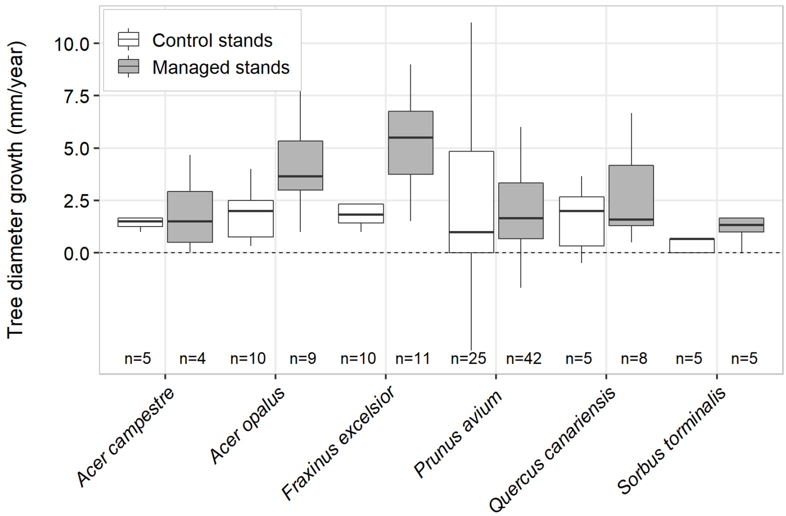



*Figure 16. Annual diameter growth of sporadic species in the MixForChange stands, during the two or three vegetative periods posterior to the silvicultural intervention. Control: results in non-intervened plots; Intervention: results in intervened plots.*

> ***The silviculture has made it possible to increase the diameter growth rate of the trees, both of the main species as well as, especially, of the accompanying species.***

## 10.2. Biodiversity indicators

**Floristic richness**

Species richness in the arboreal and understory layers has been assessed using their total number, their equitability (indicates if the species have a more or less similar representation or if a small number of species have a great predominance over the rest, according to the Index of Pielou, 1966) and the percentage of contribution to the total basal area by the accompanying arboreal species as a whole. These variables have been studied by comparing the initial (prior to the intervention) and final (two or three vegetative periods after it) inventories.

The silviculture applied has made it possible to maintain the number of species of the arboreal layer and no effect on the equitability of species has been observed. The average number of accompanying species is 4.0 ± 1.5 in holm oak stands; 3.5 ± 1.4 in chestnut stands; 4.9 ± 1.5 in oak stands and 5.3 ± 1.9 in pine stands. Similarly, in the shrub and herbaceous layers the interventions have not produced a reduction in the total number of species, although the relative proportion of them has indeed been regulated, with a reduction in the species which are most pyrophytic and the least important for fauna. In addition, spaces for the installation of new species have been created.

In general, the percentage of total basal area of accompanying species has stayed the same or increased, although this effect has been little noticeable in the stands in which the dominant species had a clearer preponderance. Thus, the basal area of the main species, between the initial and final inventories, has fallen from 93% to 91% in the Montseny chestnut stands, has held steady at 79% in the Montnegre-Corredor holm oak stands and has augmented from 75% to 77% in the oak stands of this massif. Meanwhile, in the stands which presented less preponderance of the main species, its contribution to the total basal area has fallen even further, dropping from 58% to 51% in the Montseny chestnut stands, from 32% to 28% and from 55% to 39% in the Montnegre and Bellmunt-Collsacabra pine stands, respectively, with an increase in the basal area of accompanying species, including valuable broadleaves. The exception has been the oak stands, where the main species has maintained its contribution to the total basal area in all cases, due to its consideration as a valuable species. Figure 17 displays the contribution of each accompanying species to the percentage of the total basal area, for each formation.

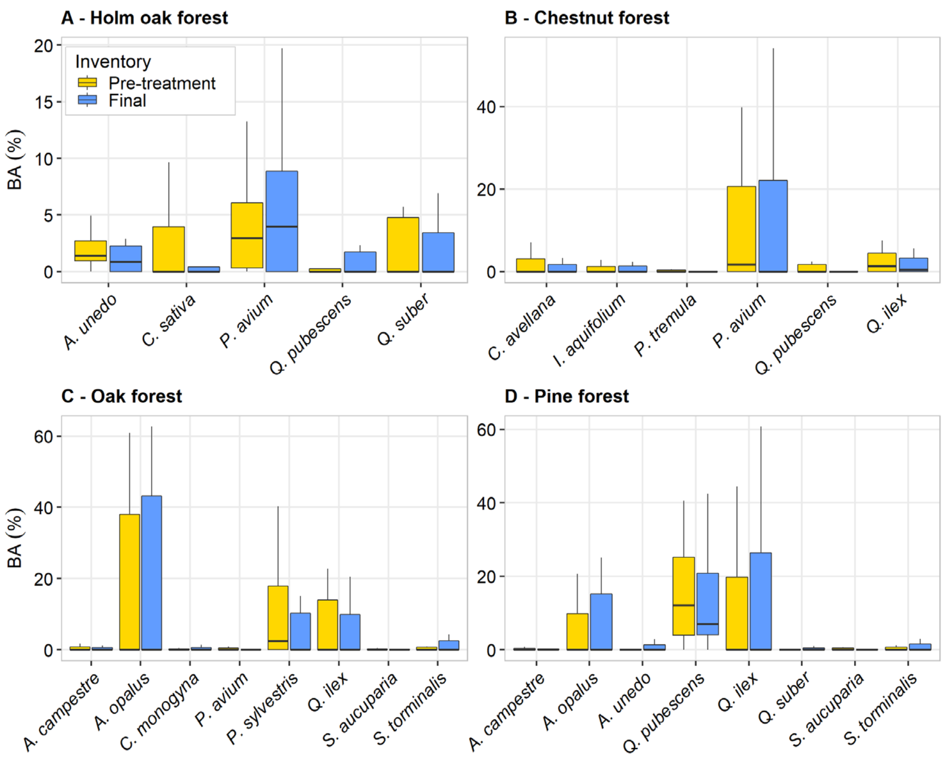



*Figure 17. Percentage of contribution to the total basal area of each accompanying species.*

> ***The treatments have made it possible to maintain the number of tree, shrub and herb species, which was one of the goals of the silviculture. Nonetheless, it has not proven possible to increase the proportion of accompanying species in the stands in which the dominant species had a strong preponderance (75% or higher of the total basal area). The proportion of accompanying species, however, has been increased in most of the stands which were already showing, from the start, a clearly mixed composition.***

**Potential Biodiversity Index (IBP)**

The IBP is an indirect indicator of a forest habitat's capacity to host animal, plant and fungal species, based on 10 structural factors. The version of the IBP applied in 32 demonstrative stands of the MixForChange project was the one established by CPF (2019), a version in development of the IBP adapted to the particularities of Mediterranean forest (Baiges *et al.*, 2019).

Of the 10 factors which compose the IBP, 7 may be modified by management practices, while the other 3 correspond to the context of the forest (Figure 18). Each factor is scored between 0 and 5 points, based on a series of indicators observed during an inspection of the stand. The sum of scores of all the factors results in the total IBP value, which may be expressed as an absolute value (total score) or relative value (percentage of points obtained with respect to the maximum possible score).

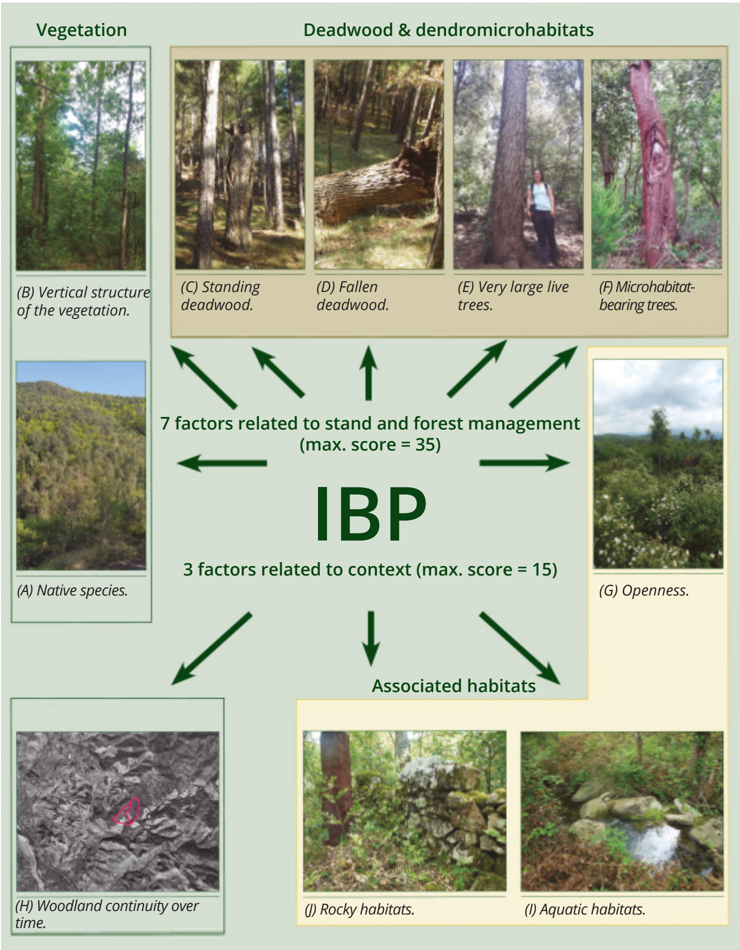



*Figure 18. Factors which compose the Potential Biodiversity Index (IBP), associated with forest management (A-G) and with the context of the stand (H-J). Adapted from Baiges et al. (2020).*

Before the intervention, the highest IBP values in the demonstrative stands occurred in the oak stands (65% for total IBP; 72% for the management factors) and holm oak stands (64% and 69%, respectively), while the chestnut stands obtained an average score of 57% and 64%, respectively, and the pine stands of 51% and 57%, respectively. The application of the MixForChange silviculture has maintained, in general, the initial IBP values, with drops in the IBP-management scores of under 2% in pine and oak stands and 8-9% in chestnut and holm oak stands, respectively (Figure 19). Reductions of up to 10% in the management factors are considered acceptable in the IBP methodology employed. These reductions are mainly due to the fact that the silviculture applied includes criteria of reducing the vulnerability to forest fires (which has caused momentary reductions of the factor B - vertical layers), and with health criteria (slight reduction in the indicator C - standing deadwood) The most significant reduction in the IBP-management score in holm oak and chestnut stands is due to the fact that these formations presented higher structural vulnerability to fires and a greater abundance of standing dead trees.

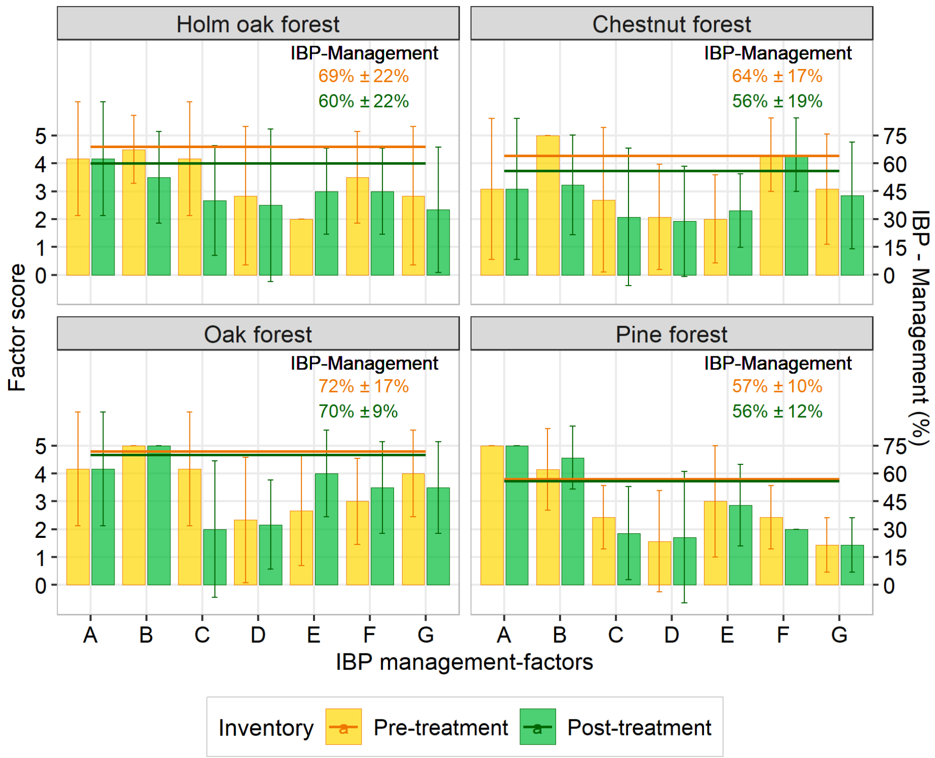



*Figure 19. Evolution, from the baseline scenario (Pre), of the seven management factors from the Potential Biodiversity Index (IBP) after applying the MixForChange silviculture in 32 demonstrative stands, grouped by formation. IBP management factors: A: native species; B: vertical vegetation structure; C: large standing deadwood; D: large lying deadwood; E: large live trees; F: live trees containing microhabitats; G: open spaces.*

*The silviculture applied has made it possible to maintain, in general terms, the system capacity to support biodiversity. In any event, the index employed (IBP) is designed for its assessment in the medium term, which is why the results must be considered a preliminary estimate.*

**Deadwood**

Deadwood may house species of high ecological relevance, which is why it is one of the indirect indicators of a forest's biodiversity. As mentioned in Block I, diverse elements of deadwood should be present (standing and lying, in a wide range of sizes and states of decay) but without accumulating so much that it threatens the stand's collective vitality and stability or increases its vulnerability to pests and wildfires.

The quantity of deadwood considered "optimal" in a forest is still up for debate, varying according to forest typology, productivity and the stand's developmental stage. In general, in Mediterranean forests, this indicator tends to be deficient, and a typical proposal is to maximise it as long as the health and stability of the forest are not compromised. An adequate benchmark level is considered to fall within 20 and 30 $m^3$/ha of total deadwood (standing and lying), or between 3 and 8% of the volume of live wood. According to MITECO (2022), the average value of these indicators in the Spanish National Forest Inventory for the formations from the MixForChange project are 1.6 $m^3$/ha (6.0%) in holm oak stands; 15.8 $m^3$/ha (8.7%) in chestnut stands; from 4.6 to 8.2 $m^3$/ha (4.6 to 10.0%) in oak stands and from 2.0 to 9.1 $m^3$/ha (3.6% to 5.1%) in pine stands.

The silviculture applied in the MixForChange stands has reduced the quantity of standing deadwood (Figure 20), especially in chestnut stands, which presented an excessive accumulation before the intervention. Table 5 displays a summary of the deadwood's characteristics before and after the silvicultural intervention.

Only the chestnut stands fall close to the recommended range (slightly surpassing it) of 20-30 $m^3$/ha, while the rest of the formations fall between 8 and 12 $m^3$/ha. The percentage with respect to the live wood volume varies between 6% (pine stands) and 24% (chestnut stands). The principal factor which limits deadwood quantity and size is the stands' developmental state, still far from a phase of maturity, none of them containing standing dead trees of more than 35 cm in diameter. The demonstrative stands of the MixForChange project present a deadwood volume greater (or in the highest values of the range) than the average values of these formations on a national level. In the intervention, all dead trees of, at least, 17.5 cm in diameter have been left standing, the felled dead trees being conserved as lying deadwood.

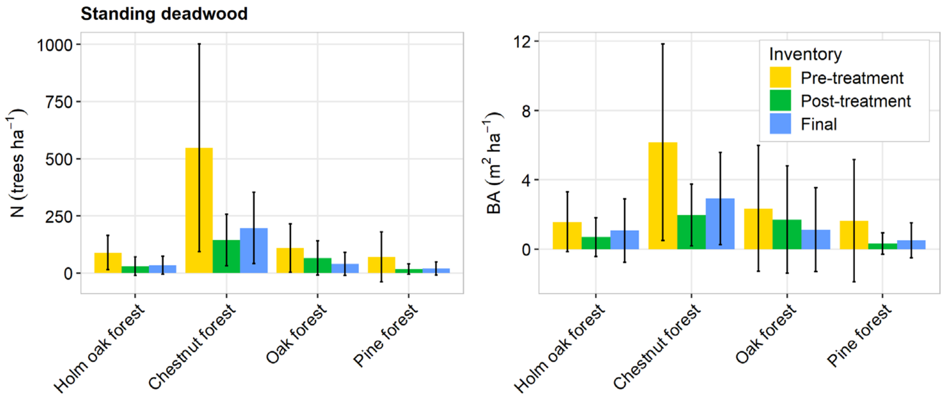



*Figure 20. Effect of the intervention on the density and basal area of standing deadwood in the various forest formations. "Pre-intervention": inventory before the intervention, "post-intervention": inventory just after the intervention and "final": inventory 2 or 3 vegetative periods after the intervention. The felled deadwood has been transformed into lying deadwood.*

*Table 5. Dasometric characteristics of the standing deadwood in the demonstrative stands of the MixForChange project, grouped by formation, after the interventions.*

| Formation | Average dbh (cm) | Maximum dbh (cm) | Standing deadwood volume (m3/ha) | Total deadwood volume (m3/ha) | Ratio deadwood / live wood volume |
|---|---|---|---|---|---|
| Holm oak stands | 15.8 | 29.9 | 4.2 | 9.0 | 7.7% |
| Chestnut stands | 12.8 | 24.9 | 11.1 | 32.8 | 23.6% |
| Oak stands | 15.9 | 33.6 | 8.7 | 12.2 | 10.2% |
| Pine stands | 14.3 | 24.2 | 1.5 | 7.9 | 6.3% |

*Figure 21. Deadwood in different states of decomposition.*

> ***The interventions have made it possible to maintain an adequate quantity of deadwood, considering the stands' current developmental stage (still far from a phase of maturity), without jeopardising the general state of health. This deadwood is, in addition, diverse in terms of its characteristics (standing and lying), sizes and states of decomposition. It is hoped that, as the stands' capitalisation advances with the application of this form of silviculture, the amount of deadwood will progressively increase.***

## 10.3. Vulnerability to forest fires

Forest fires are the principal disturbance which has shaped Mediterranean forest systems. The structural vulnerability of the MixForChange demonstrative stands has been assessed in 60 monitoring plots, classifying them using the TVFoC (type of forest structure according to its vulnerability to crown fire) methodology (Piqué *et al.*, 2011). This methodology assesses the risk of a ground fire becoming a high-intensity crown fire. There are three categories of vulnerability (Figure 22): A (high), B (moderate) or C (low). Moreover, various sub-categories (A1, A2, A3...) may be defined according to the species and forest structure.

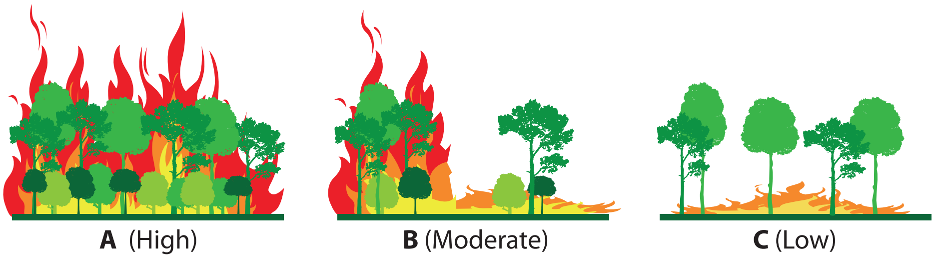



*Figure 22. Types of vulnerability to crown fire (Piqué et al., 2011).*

The variables which define the TVFoC structure are mainly the cover of three types of fuel, as well as the distances between them (Figure 23):

· **Aerial**: formed by the crowns of the trees of the dominant or co-dominant layer of greatest height.

· **Ladder**: greater than 1.30 m in height without forming part of the aerial fuel. It includes small trees, shrubs, lianes and fallen trees.

· **Surface**: height inferior to 1.30 m. It may include shrubs, herbaceous vegetation, branches, fallen trunks or interventions debris.

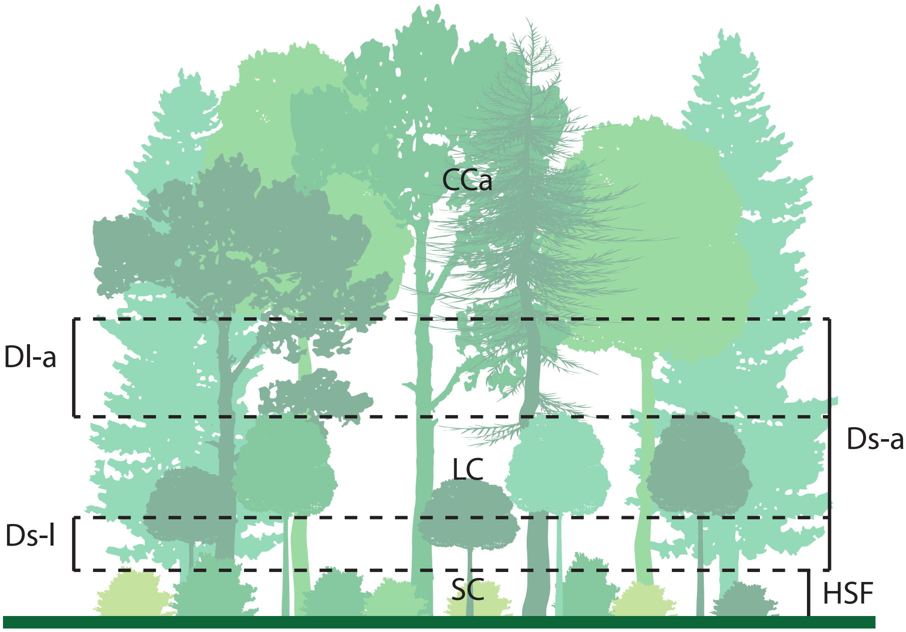



*Figure 23. Main variables considered to classify the structural vulnerability to fires with the TVFoC methodology (Piqué et al., 2011): Dl-a: distance between ladder and aerial fuels; Ds-a: distance between surface and aerial fuels; Ds-l: distance between surface and ladder fuels; HSF: height of surface fuel; CCa: canopy cover of the aerial fuel; LC: ladder fuel cover; SC: surface fuel cover.*

Most project stands had a structure with high vulnerability before the interventions (Figure 24). After the application of the MixForChange silviculture (post-intervention), vulnerability has fallen in all formations, the most notable improvements occurring the stands with the highest initial vulnerability (holm oak, chestnut and oak).

The evolution of structural vulnerability 2 or 3 vegetative periods after the intervention (between the post-intervention and final inventories) varies according to the forest formation: in holm oak and chestnut stands, vulnerability increased during this period, due to the sprout of the main species and their great preponderance. Nonetheless, the vulnerability of oak and pine stands continued to fall during this period due to the progressive settling of the felling debris and the weak sprout of the species present.

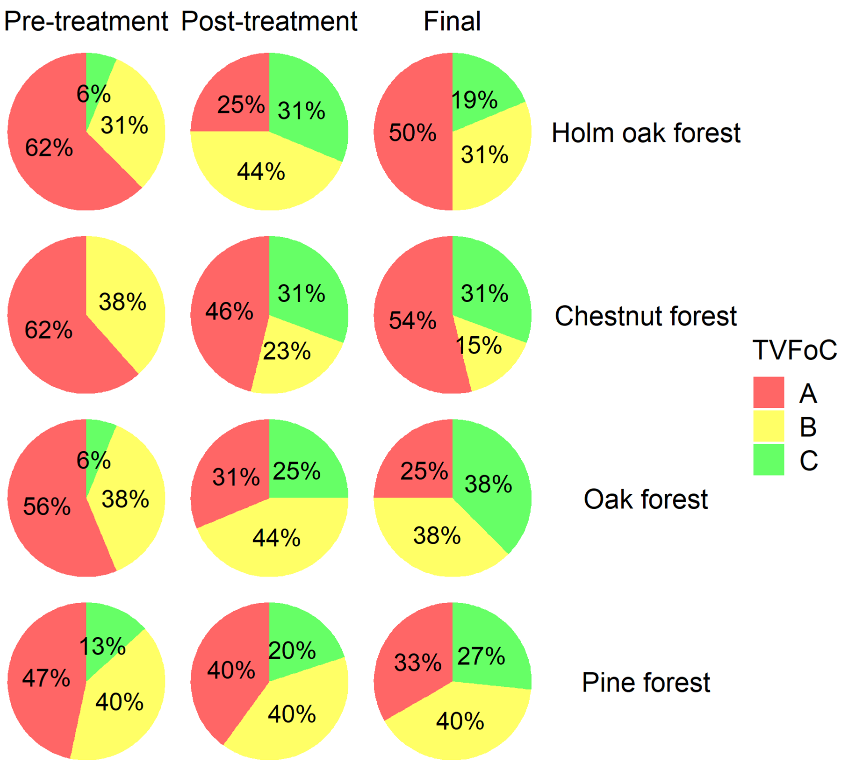



*Figure 24. Evolution of structural vulnerability to crown fires (TVFoC; Piqué et al., 2011) with the application of MixForChange silviculture. The percentage of area classified into each vulnerability category is shown for each forest formation: high (A), moderate (B) and low (C). "Pre-intervention": inventory before the intervention, "post-intervention": inventory just after the intervention and "final": inventory 2 or 3 vegetative periods after the intervention.*

*Figure 25. Examples of stands with high (left), moderate (centre) and low (right) structural vulnerability to crown fires.*

> ***The interventions have succeeded in generating structures with less vulnerability to crown fires in most cases. However, the evolution of this indicator after 2 or 3 vegetative periods varies according to the formation: in holm oak and chestnut stands, the improvement gained is largely lost, whereas in pine and oak stands, vulnerability continues to fall spontaneously.***

## 10.4. Effect on the water balance

Water availability is the main limiting factor for primary production in the Mediterranean, and the prevision of decreasing availability in the future gives the water balance an essential role to consider in forest ecosystems management. The effect of MixForChange silviculture on the water balance in 9 monitoring plots, representative of the project's 4 forest formations, has been studied. For this reason, the *Medfate* model (De Cáceres *et al.*, 2021), which simulates the eco-physiological functioning of the vegetation in given edaphic and climatic conditions, has been employed. *Medfate* makes it possible to calculate various parameters, including plant transpiration and relative runoff or blue water percentage (that is, the proportion of precipitation which is not transpired by the vegetation and reaches surface or subterranean water courses. This model is based on the characteristics of the soil (depth and texture), vegetation (density, species, heights and diameters of the tree layer; species, height and cover of shrub layer) and the daily meteorology of the area of work.

Figure 26 shows, for the 2002-2021 period, the annual transpiration and relative blue water which would result from the forest structure in its initial state (pre-intervention) and 2 or 3 vegetative periods after the application of MixForChange silviculture (final). It is observed how the silviculture applied significantly reduces the annual transpiration in pine stands (87 mm on average), and in a less evident way in chestnut stands (8 mm on average), with intermediate values in holm oak and oak stands (29 and 25 mm on average, respectively). In the case of relative blue water, the silviculture applied is seen to produce a beneficial effect, especially in pine stands (+17% on average) and, to a lesser extent, in oak and holm oak stands (+6% in both cases). In chestnut stands the effect is little significant (+2%).

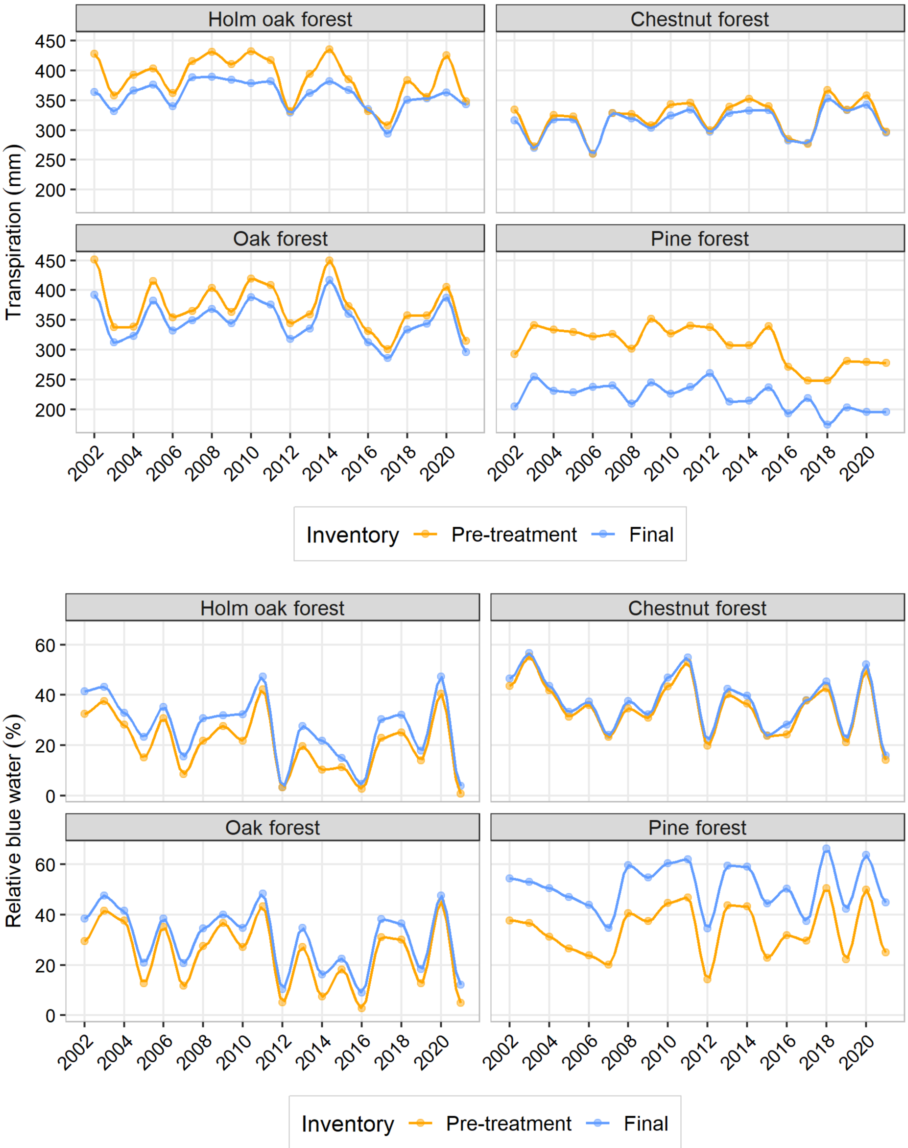



*Figure 26. Annual transpiration and relative blue water, simulated with the Medfate model (De Cáceres et al., 2021) for the 2002-2021 period, considering the project's demonstrative stands in their initial state (pre-intervention) and 2 or 3 vegetative periods after the application of MixForChange silviculture (final).*

> ***The MixForChange silvicultural approach improves the water balance of forest systems, reducing transpiration and augmenting blue water.***

## 10.5. Carbon balance

A forest's capacity to mitigate climate change is associated, in large part, with its carbon balance. This factor has been studied for the tree layer of the MixForChange forests, based on two variables: total fixed carbon and annual fixation rate. The calculation has been done on the individual tree level, in accordance with MITECO (2019). The variables considered for the calculation of the total fixed carbon include: volume of wood with bark, increment in aerial biomass, wood density and the relationship between aerial and subterranean biomass. The annual carbon fixation rate incorporates, moreover, the annual increase in the volume of wood with bark.

The calculations have been done for four of the project's demonstrative plots, one per forest typology, in three different moments: initial, just after the intervention and after 2 or 3 vegetative periods (Figure 27).

The silviculture causes, as was expected, an initial reduction in both fixed carbon and the fixation rate, due to the reduction in tree density. However, both factors show a rapid recovery in the short term, especially in the case of oak stand.

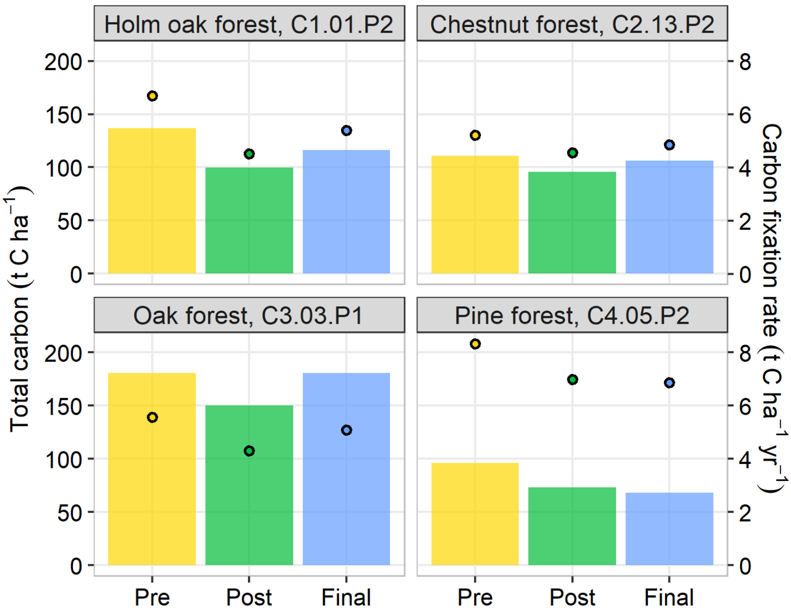



*Figure 27. Total fixed carbon (bars) and carbon fixation rate (dots) in four MixForChange demonstrative plots, before the intervention ("pre"); just after the intervention ("post") and after 2 or 3 vegetative periods ("final").*

It must be added that the carbon extracted in the interventions is allocated to the manufacturing of bioeconomy products (wood for packages, energy uses, furniture, construction...), with a much more favourable carbon balance than that of their nonrenewable alternatives (plastic, fossil fuels, metal, concrete...). In addition, the innovative silvicultural approach aims to increment the diversity of products obtained, and especially to augment, in the medium term, the proportion of trees which give rise to wood products of high added value and long service life (furniture, beams, barrel making...). By especially promoting the trees which would give rise to these kinds of products, the proportion of carbon retained during decades or centuries is augmented even further.

Finally, the reduction in vulnerability to forest fires also has a very relevant impact on the capacity of these stands to mitigate climate change, as the probability of high-intensity fires and their associated $CO_2$ emissions is reduced.

***Like any other treatment, MixForChange silviculture has led to an immediate reduction in the total accumulated carbon and in the fixation rate, although there is evidence of a short-term reaction which makes it possible to recover, in large part, the initial values. This silviculture aims to foster the trees which will result in wood products of high added value and long service life, and it also helps reduce the structural vulnerability to fires, which altogether favourably affects the capacity to mitigate climate change***

# 11. Economic balance of MixForChange silvicultureе

## 11.1. Methodology of study

The economic balance of the innovative forest management applied in the project (from here on, IFM; described in Block II) and of the theoretical application of a conventional forest management (from here on, CFM), has been studied. CFM is defined as the silvicultural approach which would have been applied in the demonstrative stands following the usual principles in the area of work. The main difference between the two forms of silviculture is that CFM is based on greater intensity fellings, focused on obtaining a single product, without considering the application of mixed-stand or single-tree silvicultural criteria (promoting individuals of high economic or ecological value), nor shoot selection or partial and selective clearings.

The economic balance consists in analysing the costs and returns of each of these management alternatives, referring to an area of 1 ha. The costs are itemised in execution (personnel, machinery and other costs) and planning and follow-up (marking and supervision of work). The returns are defined by the products obtained, assessed on a quantitative (product volume) and qualitative (types of products) level. The sale price and transport cost to the destination industry is considered for each product.

The basic tool employed for conducting this analysis has been 93 surveys given to the forest work crews, technical staff responsible for forest operation monitoring and supervision, transporters and forest industry. The surveys of the professionals involved in the execution and monitoring of the tasks were conducted through standard, replicable forms.

## 11.2. Results of the economic balance

In general terms, neither IFM nor CFM are economically sustainable, with average economic balances (difference between costs and return) of between -600 and -1,800 €/ha depending on the area of study and forest typology (Figure 28). The initial state of the stand and the type of timber resources play a more decisive role than the type of silviculture applied in the overall economic balance, with more favourable results obtained in the most developed and capitalised stands.

Overall, CFM is more economically favourable than IFM, especially in stands with low or intermediate capitalisation and in which there are hardly any products of certain value. However, in capitalised stands the economic balance of the two alternatives is similar.

*Well-formed, high-value tree*

The cost analysis shows how IFM tends to result in higher values (4% to 37% more) than CFM, especially for technical monitoring costs (marking and workers' capacitation), which represent 5-25% of the total costs in IFM and only 1-16% in CFM. The cost of clearing also rises in IFM, as it is applied using selective criteria, while in CFM clearing is total or is not applied. The smaller volume of wood extracted in IFM (on average, 16% less than in CFM, ranging between 2% in holm oak woods and 29% in pine stands) proportionally reduces the costs of the forest works. This item is the main cost in both approaches: 72 - 85% in IFM and 72 - 89% in CFM. The total costs fall between 1,850 and 4,200 €/ha in IFM and 860 and 4,270 €/ha in CFM, the lower values of each range corresponding to the less capitalised stands, in which the costs of IFM double those of CFM.

As for the returns, CFM leads to higher returns (4 to 33% greater) than IFM, thanks to the extraction of a higher volume of wood, which compensates its predominantly lower added value. IFM gives rise to a lower, but more diverse, quantity of products. The profit ranges of the two approaches are very similar, varying between 325 and 3,020 €/ha in IFM and between 325 and 3,140 €/ha in CFM, with the lowest values in the least capitalised stands. The most favourable results of IFM are obtained in the stands from which broadleaf or pine pieces of certain quality are extracted. These products of higher added value represent a small portion of the wood lots: 13% in chestnut stands, 16% in oak stands of Montnegre-Corredor and 6% in pine stands of Bellmunt-Collsacabra. In CFM, these products are not separated from the main lots, which are sent for pallets, firewood or shredding.


*Figure 28. Costs and returns of the application of IFM or CFM for each forest formation, grouped by stand type (A, B, C...), that is, stands which show analogous silvicultural characteristics and type of intervention. The dot inside each bar indicates the balance: positive (green), negative between 0 and –2,000€/ha (yellow) and negative below –2,000€/ha (red).*

It must be remembered that this balance has been applied in stands traditionally managed following a CFM system, which is why their structure is especially favourable to this form of management. In a first application of IFM, the economic results were not expected to have gone more favourably than those of CFM, which seeks, in large part, to achieve the maximum economic sustainability of each intervention. The result of the reiterated application of IFM in these stands is yet to be assessed; it should make it possible to progressively reduce costs (increasingly simple marking as the role of each individual in the stand becomes more evident, increasingly qualified crews in the application of the silvicultural criteria) and, especially, raise returns as the number of well-formed, valuable timber trees continues to increase. In CFM, this progressive improvement of the economic results would not be expected.

*Table 6. Chart summarising the main productive and economic differences between IFM (Innovative Forest Management) and CFM (Conventional Forest Management).*

| Types of costs and returns | IFM | CFM |
| --- | --- | --- |
| Obtained products | Diverse products<br>Low volumes | Homogeneous product, of low added value<br>High volumes |
| Potential to generate high-value products in the future | High | Low |
| Technical management costs | High (marking, workers training) | Low |
| Forest operations costs | Intermediate-low (high cost of selection and classification) | Intermediate-high (high cost of felling and hauling) |
| Clearing costs | Intermediate-high (selective and partial) | Intermediate-null (total or not applied) |

# IV. Tools and challenges to promote adaptive and close-to-nature forest management in the Mediterranean context

This Block explores various options available to local and regional administrations for promoting the application of sustainable, multipurpose forest management with close-to-nature and climate change adaptation criteria. The main challenges to face when promoting this form of silviculture in Mediterranean conditions are also presented.

## 12. The key role of local and regional administration in promoting forest management

In Spain, the regulation and administrative intervention of forest uses and services are the shared responsibility of national and regional governments. The main direct actions of the local administrations (municipalities, counties, provinces, metropolitan areas) on forest land are managing their own forests and the legal cataloguing of soil uses. In addition, there exist a wide range of measures which may be led by local administrations (each according to their capacities and responsibilities) to facilitate and promote sustainable and multipurpose forest management in their territorial sphere, including (Coello *et al.*, 2021):

**A) Facilitation measures**

- Actively facilitate the forest management of public and private properties, promoting collaboration between private owners, public-private alliances and joint forest planning on the municipal and inter-municipal level.
- Facilitate infrastructures for primary activities: sheds and other auxiliary infrastructures to promote extensive silvopastoral systems; logistics yards for forest products classification and distribution.
- Maintain and improve the basic network of forest roads.
- Apply the best practices available in managing its own agriculture, forest and livestock areas and lead the replication of this management in surrounding properties: promote good forest practices (marking, technical monitoring of the interventions), establish forest training spaces (demonstrative & training forests for specialised training on marking and other forest operations), facilitate lands for the incorporation of youth into the sector, for example, through grazing agreements.

**B) Regulatory and administrative measures**

- Avoid conceptual and terminological contradictions in regulations and planning. For example, avoid ambiguous concepts like “protection”, “preservation” or “conservation” which could be interpreted as an impediment to any form of management, even when geared toward promoting biodiversity (ex: recovery of open spaces) or preventing forest fires.
- Integrate potentially synergic planning tools in a coherent way: forest planning instruments, Sustainable Development Goals, climate change adaptation plans, forest fire prevention on the landscape scale, etc. This integration must be done with a consensus with the stakeholders of the territory.

- Ensure compliance with land use regulations (especially, on the theft of forest products) and forest access.
- Streamline the issuance of permits and licenses associated with sustainable land management, in terms of implementation as well as product logistics and processing.
- Establish a specific unit in the administration, responsible for coordinating and promoting forest actions.

**C) Improve the economic sustainability of forest management**

- Increase the demand for agrosilvopastoral products, preferably of local origin or with criteria of proximity, to supply municipal services and facilities. Ex: install biomass boilers in municipal facilities; encourage municipal facilities, infrastructures and public housing to be built and renovated using the maximum possible quantity of wood, as opposed to nonrenewable materials; promote local agrosilvopastoral products in public and private centres of collective consumption: nursing homes, school canteens, restaurants and hotels...
- Allocate a portion of municipal taxes (ex. traffic, waste collection, land value tax) to the improvement of peri-urban forests.
- Promote measures of corporate social responsibility associated with forest management and improvement by companies and entities present in the territory: direct investment, volunteer campaigns, rental of facilities, infrastructures and machinery, etc.

*Forest biomass is a source of renewable, emissions-neutral energy. Its local origin makes it possible to notably reduce dependence on alien sources of energy.*

**D) Communication and mediation**

- Communicate and transfer, internally (the entity's own personnel), to other administrations (and in collaboration with them) and to society in general, the implemented measures.
- Mediate between the multiple social demands toward forests (e.g. timber harvesting operations, livestock, hunting, public use, etc.) to coordinate them in a planned way, for example, through public-private working tables which incorporate all the local stakeholders.
- Foster agrosilvopastoral custodial agreements and volunteer activities to improve land use, above all in especially emblematic places.
- Promote workshops and sensibilisation activities about sustainable forest management in primary schools, secondary schools or institutions of continuing education.

**E) Qualification and transfer**

- Encourage the training of technical and political personnel in the sustainable management of natural resources.
- Lead the incorporation of new training modules associated with natural resource management in specialised training centres (vocational training, school-workshops).
- Promote and disseminate research studies and projects, citizen science and knowledge transfer, alliances with research centres and participation in projects with European funding.

> ***One local administration which has tried in recent years to promote measures to foster sustainable forest management is the city council of Mataró (Barcelona). Guitart and Busqué (2021) present a series of measures enacted by this local administration.***


*Modern wood engineering techniques, combined with this material's excellent thermal and physical properties, has transformed this renewable raw material into the best ally of sustainable building.*

# 13. Opportunities and challenges in the adoption of adaptive and close-to-nature forest management in the Mediterranean

Silviculture is a science with more than 300 years of history, which has never stopped evolving to respond to the diverse demands of societies and their socioeconomic contexts with respect to their forests. As mentioned in Block I, the Mediterranean forest is extraordinarily diverse as an ecosystem, and so, too, is the range of silvicultural methods and practices developed by the people who have managed it over the years. Always building on this cumulative experience, the following section presents the main opportunities and challenges identified which must be considered to advance in the incorporation of adaptive and close-to-nature criteria into Mediterranean silviculture. In spite of the existing difficulties, the opportunities which these approaches represent from the point of view of economic and environmental sustainability mean that failing to consider them may eventually prove more costly in terms of the loss of essential ecosystem services.

## 13.1. Opportunities of this silvicultural approach

**Multifunctionality and versatility**

The main advantage of this silvicultural approach is the <u>level of detail in its application</u>, which makes it possible to respond to multiple opportunities offered by forests (valorisation of micro-sites and individuals of greater potential) and, as a whole, to the multiple demands toward them. The principles applied may be moulded to practically any situation.

**Sustainability**

This form of silviculture combines:

· <u>Ecological sustainability</u>: it fosters the forests' capacity to adapt to the current and potential impacts of climate change and, thus, the long-term persistence of the services they provide, with a particular emphasis on biodiversity.

· <u>Economic sustainability</u>: promoting high-value timber products, in quantity and quality, is an investment bound to make the forest more valuable in the medium and long term. This factor is essential for involving private forest owners.

**Professionalisation and continuous improvement**

The application of this silvicultural approach is grounded in an adequate knowledge of the multiple factors which make up forest engineering: forest ecology and dynamics, disturbances and threats, wood technology, harvesting logistics... The application of this form of silviculture, based on selective interventions of low or moderate intensity, seeks to optimise the use of resources (staff, fuel) to make the interventions more ecologically, technically and economically efficient. It thereby aims for the continuous improvement in the qualification and professionalisation of the people and organisations involved in forest planning and management.

**Alignment with European policy**

The silvicultural approach proposed is clearly aligned with the European Green Deal and the strategies and policies developed in the sphere of environment and climate. In addition to the direct benefits from the point of view of adaptation (vitality, biodiversity, less vulnerability to droughts and fires, a better water balance), other derived benefits appear, such as the generation of local renewable products of high added value, a reduction in the dependence on external raw materials or a reduction in the emissions linked to forest fires.

## 13.2. Challenges for the adoption and promotion of this silvicultural approach

**The difficulty of changing the silvicultural model**

Mediterranean silviculture has developed or adapted a wide variety of management tools, although their practical application is often based on simplifying criteria (centred on a single product), based on custom and/or on optimising the economic results of the next intervention, externalising technical decisions to the logging companies. This situation especially occurs when the interventions' profit margin is very tight and when the owner (public or private) is unaware of silviculture's potential to generate investments in the medium term. These two situations are frequent in Mediterranean forests and may result in a type of short-term focused silviculture, without considering measures designed to progressively improve the stand and, with them, the "capital" (the forest). The principles of close-to-nature silviculture highlight the need to pursue economic sustainability, taking into account, also on a detailed scale, the assets (costs and returns) and the liabilities: stand capitalisation, site productive capacity and stocks (investments) in the form of high-value trees (Beltrán *et al.*, 2020).

The incorporation of new silvicultural criteria is also limited by the inertia and structure of the forest stands themselves. Today's forests are the result of the use made of them during centuries, and above all in the last few decades, including the generalised decline of agrosilvopastoral activities. Thus, the current structure of the stands is particularly modelled on certain silvicultural principles which, if modified, would necessarily imply going through a phase of transition. During this phase, which may be lengthened over the course of diverse interventions (especially with interventions of low or moderate intensity), the stand will gradually adapt to the desired structure but, as explained in Block III, the economic results are unlikely to surpass those of maintaining the previous form of silviculture. Nonetheless, once the target structure has been achieved, and is maintained with successive interventions in the same vein, the forest will become more economically and ecologically valuable, more resilient and multifunctional.

Finally, it is fundamental to remember that a change in the management model toward an adaptive, close-to-nature form of silviculture also implies a detailed assessment which allows forest management professionals to gather valuable knowledge and continuously improve the criteria and processes which underpin the successive interventions, as the stand keeps evolving toward the target structures.

> ***Example of support tool for the change of silvicultural model developed in LIFE MixForChange: the Catalogue of uses of valuable broadleaves timber in Catalonia. (Coello et al., 2020b) demonstrates the existence of an unsatisfied demand for valuable and local wood in Catalonia, currently compensated with imports. A local product of high added value, obtained in sufficient quantity and quality, may serve as a motor of this silviculture system's economic sustainability, without detriment to all other forest uses and products.***

**Transfer, training and qualification**

Any change in the management model must be accompanied by an effort to communicate and transfer the goals and results, adapted to a wide range of audiences: from forest owners (public or private, and their associations), the advisory companies and experts, other companies throughout the value chain (from harvesting to final manufactured product) and policy makers to society as a whole, especially the people living close to peri-urban forests.

The silvicultural approach proposed will entail investing fewer human and material resources in forest operations, but of a higher quality, that is, focused on tasks which require greater knowledge of forest ecology, silviculture (marking and control), hauling, classification, etc. which is why professional training and qualification is essential. In this sense, one limiting factor of this form of silviculture is the high component of subjectivity in the principles proposed, which are not based on strict rules or quantitative indicators but rather on experience and an observant attitude, with decisions founded in details, which makes it essential for the training and capacitation activities to be conducted in-situ. This implies logistical difficulties for training on all levels (pre-university, university, practitioners, owners), made worse by the scarcity of personnel qualified to impart this type of training and of suitable demonstrative forests. The lack of capacitation is especially serious in the majority of forest crews, due to the prevailing precariousness of their working conditions. It is also common for forest operations companies to possess the machinery and work methods designed for the specific silvicultural tasks they most typically perform, which are not always optimal for the interventions proposed with this innovative silvicultural approach.

Just as in the previous challenge, training and capacitation in the principles of this silviculture exert a cumulative effect, as they will favourably influence its application, assessment on the terrain and continuous learning.

> ***Example of capacitation tool developed in LIFE MixForChange: the "Protocol for standing timber quality assessment of valuable broadleaves" (Coello et al., 2020a) aims to facilitate decision-making in the application of close-to-nature, single-tree silviculture by simplifying the identification and promotion of the trees with the most potential or current economic interest.***

**Logistics**

The silviculture proposed is based on interventions of greater frequency and less intensity than the kind typically applied in our context. Moreover, in each intervention a wide variety of wood products are generated in terms of species, qualities and sizes. This approach represents a challenge when it comes to planning, executing and monitoring (as it forces interventions to be made regularly; any lengthy abandonment of the management would make it difficult to accomplish its objectives) and to the logistics of these products' extraction, transport and sale. Therefore, it is necessary to have infrastructures such as storage areas and logistics yards to valorise and provide an adequate commercial outlet for the products with the highest added value, which will be, at least during the first interventions, relatively scarce.

All links in the timber value chain, from forest owners (especially if they can conduct joint management) and logging companies to primary and secondary processing industries, timber wholesalers and end consumers, have their own role to play to generate a supply of local timber in sufficient quantity and quality to consolidate its demand.

As in the previous cases, increasing the area managed under the principles proposed will facilitate the development of this wood's logistics and value chain, especially in the context of fostering the bioeconomy based on local renewable resources.

> ***Example of support tool for product logistics developed in LIFE MixForChange: the Pilot System for Logistics and Marketing of Forest Products from Sub-Humid Mediterranean Mixed Forests (Guitart and Rosell, 2022) aims to facilitate the logistics associated with the application of the silviculture method proposed. This system presents the technical and legal conditions affecting the logistics, marketing and valorisation of wood products to identify the most advantageous marketing alternatives.***

**Administrative and economic factors**

Many administrations have instructions or precise procedures for the writing, reviewing and tendering of forest planning projects, on both public and private land, which augments the coherence and facilitates the supervision of a territory's forest management. Nonetheless, a form of silviculture like the one proposed, with a significant portion of decisions taken on the field, may require adapting these procedures to make them more flexible. At the same time, it is fundamental for these procedures to incorporate the importance of tree marking and work supervision.

The logistical challenges presented in the previous point make it difficult to apply this form of silviculture in forest properties with small areas. Thus, measures must be implemented to facilitate joint planning and management instruments, applicable on the municipal or inter-municipal level, which facilitate the products' logistics and sale. These measures must be partly technical but primarily administrative in nature in order to efficiently develop and implement the planning tools.

In zones where private property predominates, another technical and administrative challenge is to identify and involve absent or uninformed forest owners and, if this is not accomplished, to determine which options may be proposed to implement measures in the service of the common good (for example, wildfire prevention).

Subsidy policy plays a fundamental role in making many silvicultural interventions economically viable. An aid policy which prioritises interventions with high added value in terms of ecosystem services and whose economic balance does not allow self-financing, as occurs in the first applications of the proposed silvicultural approach, could be a way to promote this form of silviculture. One example is the time-consuming marking process in these interventions, a necessary practice whose application could serve as a criterion in the awarding of subsidies.

Finally, it is worth recalling the forestry sector's underfunding as a major challenge which must be tackled in a cross-cutting manner by society as a whole.

Example of tool used to adapt the regulations, developed in LIFE MixForChange: the "*Memorandum of regulatory aspects to be modified to facilitate adaptation to climate change in mixed sub-humid Mediterranean forests*" (CPF, 2021) compiles the main existing regulations and planning instruments in Catalonia associated with forest management and/or climate change adaptation. This compilation serves as the basis to identify 19 potential measures to include in 7 key regulatory and planning instruments.

***Example of tool used to adapt the regulations, developed in LIFE MixForChange: the "Memorandum of regulatory aspects to be modified to facilitate adaptation to climate change in mixed sub-humid Mediterranean forests" (CPF, 2021) compiles the main existing regulations and planning instruments in Catalonia associated with forest management and/or climate change adaptation. This compilation serves as the basis to identify 19 potential measures to include in 7 key regulatory and planning instruments.***

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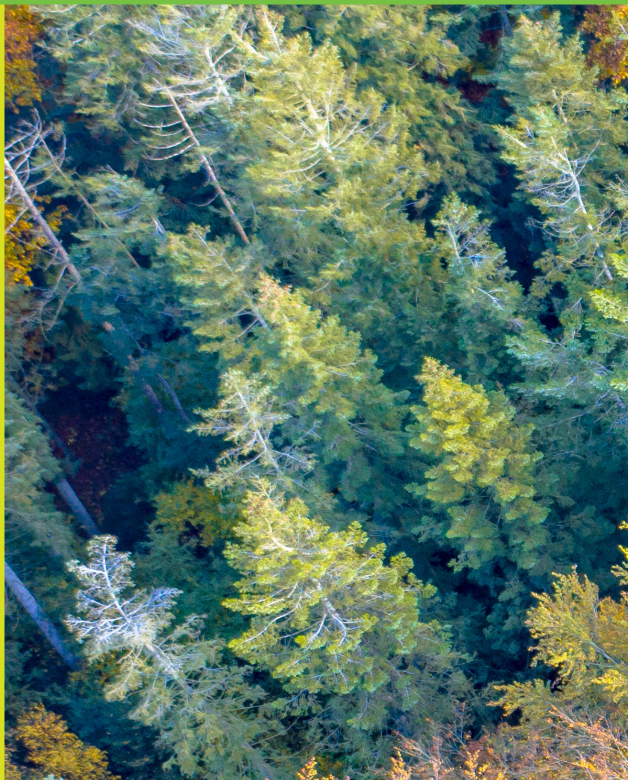

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