No. 4
2023

MIXED PLANTATION MANUAL

MIXED FOREST PLANTATIONS: FEEDBACKS AND GOOD PRACTICES

Planted Forest Report

iefc European Institute of Planted Forest

Interreg Sudoe COMFOR

TreeDivNet MixForChange

Publisher Institut Européen de la Forêt Cultivée

Editorial Office Institut Européen de la Forêt Cultivée
69 route d'Arcachon 33610 CESTAS
Email: contact@iefc.net
Phone: +33 5 35 38 52 74
www.plantedforests.org

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Author Benoît de Guerry (1), Camille Tourangin (2), Barry Gardiner (1), Susana Barreiro (3), Hervé Jactel (4), Christophe Orazio (1)

(1) Institut Européen de la Forêt Cultivée (IEFC)
(2) AgroParisTech (APT)
(3) Instituto Superior de Agronomia (ISA)
(4) Institut national de recherche pour l'agriculture, l'alimentation et l'environnement (INRAE)

Layout Suzanne Afanou

Disclaimer This publication has been produced by the Institut Européen de la Forêt Cultivée for the COMFOR-SUDOE project. IEFC is an independent, international, non-governmental association established in 1998. It promotes sustainable management and resilience of planted forests in Europe through improved co-operation in forestry research and development. For more information about IEFC and its activities visit www.plantedforests.org

Doi https://doi.org/10.57745/EE8Z78

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INTRODUCTION

Climate and global change require forest stakeholders to adapt their risk culture by facing more and more biotic and abiotic damage. Forest owners and managers must make management choices while paying more attention to these hazards, especially when it comes to the delicate step of reforestation. Mixed tree species plantations appear to be one solution to increase the resilence of forests and the sustainability of wood production. But despite the growing interest in this approach of forest management and the fact that the topic is now common in forestry debates, foresters familiar with monocultures are reluctant to engage in this new direction.

In fact, forest practitioners are facing several challenges in the establishment of mixed plantations, including technical issues, economic limitations and also physcological barriers due to perceptions around this topic. Furthermore, while scientific evidence describing the benefits of mixed forests are abundant in the literature, we are missing basic and practical knowledge on mixed species stands management and tree species behavior once placed in mixture with other species.

In Europe, 67% of the forest area is occupied by stands composed of two or more tree species (FOREST EUROPE, 2020: State of Europe's Forests 2020). However, most of this area is regenerated through natural processes (only 70M ha are plantations) and the stands are not necessarily actively managed. One of the challenges is, therefore, to promote a transition path in planted forests from single-species forestry to a more diversified system.

This document aims at bringing new perspectives to the issue of mixed forests plantations, with a strong focus on artificial establishment. Using a comprehensive approach, we tackle different aspects of the issues through the identification of the technical and psychological barriers to mixed plantations establishment, as well as a contribution to the empirical knowledge of successful mixture management. Some limitations in the quantitative data need particular attention from the reader and need to be addressed in future research work.

The partnering projects

The MixForChange project is an initiative of the global biodiversity experiment network TreeDivNet and is funded by the European BiodivERsA program. The project aims at identifying the main challenges and opportunities for the promotion of mixed-species forest plantations as a nature based solution for climate change mitigation and adaptation. An important part of the tasks are dedicated to the analysis of the huge TreeDivNet network database to better understand how the tree diversity, the species identity and the management type influence the stands carbon sequestration capacity and resilience towards biotic or abiotic threats.

The COMFOR SUDOE project is a South-West of Europe partnership to promote complex forests (either mixed-tree species plantations or irregular) as a more resilient and adaptive alternative. The projects aims to quantify and enhance complex forests' ecosystem services and to develop an intelligent management strategy for those forests. A common experimental network of mixed plantations has been created to better assess the tree species bahviour in mixtures and some best management practices. This network called FORMIX is also designed to join the TreeDivNet global network.

Both projects have the ambition to provide science-based recommendations and guidelines for forest owners, managers and policy makers.

MATERIAL & METHODS

Worldwide survey on mixed plantation experiments

The data acquisition started in June 2021 with the implementation of an online survey managed by IEFC in the framework of different projects (COMFOR, MixForChange, CORKNUT, FAO forest unit or IUFRO Task Force on resilient planted forests serving society & bioeconomy). The survey aimed at **collecting past and ongoing experiences in establishing and managing mixtures** based on practitioners' knowledge. Information is collected to record the type of mixture (tree species identity and location), the plantation design (initial stocking and proportion) and a subjective assessment of the level of success (objective of the management, success ranking, cause of failure).

We were able to gather the feedback from 60 practitioners describing 132 mixed species experiments. The survey will remain open to keep monitoring this field-based knowledge and help the forest and scientific communities: https://bdd.iefc.net/mixed-forest-plantations-survey/

National workshops with forest stakeholders

National workshops were organized in the three Sudoe countries : France (Bordeaux), Portugal (Coruche) and Spain (Bilbao) to gather local practitioner's knowledge in managing mixed plantations. Those meetings were an opportunity to present the results of the worlwide survey and to present some aggregated figures and discover the opinion of stakeholders.

Some sessions were facilitated to gather stakeholder feedback on several technical issues regarding mixed plantation establishment, e.g. plantation scheme and tree density, tree species choices, management challenges. Moreover, the workshops tried to investigate the challenges and/or opportunities for the establishment of mixed plantations, and whether these are economic, social or environmental issues. This practical knowledge is very important for illustrating and upscaling the survey outputs.

Interviews with stakeholders to identify the sociological and technical constraints

After gathering past experience and general feedback on the state-of the art concerning the implementation of mixed plantations, we wanted to investigate in more depth **the constraints and opportunities perceived by the stakeholders** on this topic. By doing so we hope to be able to understand the technical, economical and psychological barriers that are yet to be overcome concerning the establishment of mixed plantations, and the potential solutions that are emerging.
IEFC hosted an internship student to tackle this question applied to the Nouvelle-Aquitaine region case-study. The student conducted **semi-directive interviews with 19 forest stakeholders** (forest owners, managers, NGOs, R&D insitutes, policy makers) with experience on the topic of mixed plantations. Some qualitative results were made available from her masters thesis.

HOW TO DEFINE MIXED FORESTS?

We present here some concepts that help in characterizing mixed-species forests and some common typologies that will be refered to later in the document. This is because the definition of mixed forests appeared rather vague according to each interviewed stakeholder's views. We also take the opportunity of this introductory section to explore the margin of the commonly accepted definition and highlight the diversity of available options.

Species composition

Mixed plantations are primarily defined by the association of at least two different tree species in the same stand. We can define several **typologies of mixed-plantation according to the species composition**:

Broadleaved Mixture

Association of hardwood species, often with a high diversity of species

Conifer x broadleaf Mixture

Association of broadleaves and coniferous species which has a wide diversity of benefits

Coniferous Mixture

Association of softwood species, usually limited to two species

There is already a wealth of opportunities for tree species association, and more than that there is an infinite possibility for the relative importance of the species in the stand. We can group them in two categories:

- **Mixtures with equal distribution of the species** in terms of number of stems, e.g. 50%/50% for a two-species mixture or 33%/33%/33% for a three-species mixture
- **Mixtures with a dominant species**, but the proportion of the main species should not exceed **75%** of the canopy cover to still fit with the definition of a mixed forest.

Along with the chosen species comes the question of the **mixture's purpose**. Managing a mixed forest requires **maintaining the different species** until each stand reaches a mature age. But in practice, mixed plantations are also obtained by introducing low productivity accompanying species along with more productive ones, with the former often being harvested earlier, and the forest returning to a single-species forest.

At the margin of the definition

Some would advocate an expanded definition of mixed forests based on the **diversity of provenances** instead of tree species. For example, a Douglas fir plantation could associate the most productive provenances (*France, Washington 2*) with the provenance *California* that is more resistant to drought.
This is already higly recommended in Poplar cultivation with clonal diversification.

Forest mixture structures

Mixed forests are defined by their structure, the most classic of which are described below:

The horizontal mixture	The subordinate mixture	The vertical mixture
Tree species mixed side by side, in groups, lines or bands where all species have the same height	Planting or natural resprooting of a species under the cover of an existing monospecific stand. Typical of the coppice treatment within a forest where each component has a specific function (e.g. timber or fuelwood)	Typical of the irregular or the garden forest with a superposition of tree crowns
Attention point: high risk of competition between species	Attention point: requires a seperate management of each forest strata	Attention point: results in a staggered through time harvest
		

This document focuses on the establishment of mixed stands by plantation. This is why we will only detail the **horizontal mixture** type afterwards.

At the margin of the definition

Using **artificial seeding** can be an interesting alternative to planting when seeking to achieve an horizontal mixture. Although commonly used in the past, there is now a renewed interest for this technique with experimentation in several European countries. We mention some possibilities based on mixing the establishment techniques:

- Artificial seeding complemented by plantation
- Plantation complemented by natural or artificial seeding
- Monocultures complemented by artifical seeding to obtain a subordinate mixture (e.g. open lines in a chestnut coppice sown with pines)

These methods can be of interest for quick restoration, eliminating transplant shock, reducing costs, etc.

Plantation design

There are several ways to create an horizontal mixture depending on the spatial distribution of the plants and the plantation scale considered:

Intimate mixture	Alternating species plant by plant within the row. The species succession can be randomized or follow a predefined pattern.	
Per row(s)	Alternating rows of a single species to support more demanding species and to facilitate management and harvesting operations	
Per group(s)	Installation of islands of pure species with a surface area of less than 50 acres. This allows some adaptation to the topography of a stand	
Per block	Same principle as for the group plantation but with islands of geometric shape that are easier to manage and have a larger surface area.	

It is common to see **plantations using both an intimate and per row mixture** when establishing more than 2 tree species. For example, a main productive species planted in several pure rows and surrounded by two rows that alternate two or more secondary species inside the line. e.g. 2 pure rows of *Quercus petraea* and 1 row alternating valuable or fruit-bearing broadleaves in the following sequence: *Carpinus* / *Sorbus* / *Carpinus* / *Prunus* / *Carpinus...*

In the margin of the definition

The enrichment of an existing stand with a clump of another species. This practice involves introducing some diversity into a stand at any stage, either through artificial regeneration when you want to reorient the stands purpose, e.g. after a biotic outbreak, or in a natural regeneration in need of refill planting.

Hedgerows of broadleaves can be planted to surround a monospecific stand of productive species, allowing to get some of the mixed plantation benefits.

In the end, mixed plantations are a very subjective concept and will vary a lot from one person to another depending on the spatial and temporal scale considered. We could advocate a tree species mixture at the planting site level but some people are satisfied with different monospecific stands that bring diversity at the landscape level.

MIXED PLANTATION OPPORTUNITIES AND CHALLENGES

Advantages

- **Greater adaptability to climate change** through a greater adaptability to site conditions variations, an enhanced resilience to hazards, lateral protection against late frosts or droughts, ...
- **Reduced exposure to pests** which move less quickly in mixed stands due to a greater difficulty of access to their host and increased abundance of their natural enemies
- **Improvement of the biodiversity** due to a multi-stage canopy that provides more diffuse light, favouring flora and consequently fauna, and leads to a better biological activity within the soil
- **Optimizing subsurface occupancy** with some tree species developing a tracing root system following other species that find water and nutrients at depth in the soil
- **Management role** because mixtures containing accompanying species usually allow for an easy identification and confirmation of the final stems and improved natural pruning
- **Capital security** because the diversification of tree species makes it possible to adapt to changes in the price of timber and to take advantage of market opportunities
- **Social, legacy, landscape and wildlife assets** due to the fact that some forest owners are interested in the richness of the forest heritage, providing a large range of ecosystem services for recreational activities, aesthetic or even religious uses.

Plantation diversification, an asset for funders

In many reforestation aid schemes, mixed species plantations give access to an increased rate of public grants. It also became a mandatory criterion in the reforestation of stands above 10 hectares to benefit from the Covid recovery plan in France.

FRANCE RELANCE

It is expected that this criterion will be used in future EAFRD forestry funding measures as the European Commission is increasingly committed to the preservation of forests.

The European Agricultural Fund for Rural Development
Europe investing in rural areas

Afforestation projects with carbon offsetting also seek to prioritize the plantation of mixed stands. For example, the Reforest'Action company is supporting forestry projects in France and in the rest of the world by seeking funds from companies or citizens willing to minimize their carbon footprint. They set out the tree species mixture as a principle target when funding a reforestation project, regardless of the specifics or the forestry objectives.

Those financial incentives act as levers to remove the economic barriers faced by forest owners.

Challenges

- **Tree species compatibility** is too little taken into account when designing a plantation project. There is a need to associate species with similar growth or with different shade tolerance, compatible crown and root architecture, etc. And all of these considerations need to be adapted to each site with a background of the changing climatic conditions.

- **The diversification with broadleaved species** is a challenge when the forest sector is mainly optimized for conifer species. There is a risk of shortage of broadleaved plants in nurseries that might lead to more expansive plants, a higher vulnerability to game pressure or to drier climates, and limited market opportunities. Conversely, it is the exact opposite in Portugal where broadleaf use is the most developed part of the sector.

- **There are some technical and financial difficulties** in planting and maintaining a mixture. During the first stage, within the first years after planting, a lot of tending interventions are required, and after that in the following years much more technical support is required from the forest manager, which can be challenging if the forest workforce is already under pressure.

- **Some product harvesting and commercialization can be difficult** in view of the smaller volumes per species that can be made available, the possible lack of markets, and the requirement for diverse interventions depending on the species and the management objectives.

- **A minimum area of 6 to 8 hectares** is recommended for a mixed species plantation to be both economically and ecologically relevant (Moyses, 2021). Nevertheless, in regions suffering from land fragmentation, few forest owners have such contiguous areas available.

- There is a **possible negative visual impact on the landscape** due to the difference between the tree species leaf colours and timing of leaf emergence. This is especially an issue for stands mixing broadleaves and conifers, with a plantation design per row and located in hills or mountains.

In addition to these technical and economical barriers, the interviews identified **some psychological barriers** that key stakeholders can face when deciding to establish mixed species plantations. These barrier categories are often interconnected.

- **The uncertainty** is maybe the most important barrier to face for the forest owners. The uncertainty is not only applicable to the effect of climate change and the anticipation of the future climate but also to the effect of tree species association in mixture as there is very few examples of well documented successful mixed plantations. A lot of stakeholders interviewed lack feedback and are waiting for such a response.

- **The pressure caused by forest sector** demands can sometimes hinder innovation and the emergence of new practices.

- Changing **silvicultural habits** is always difficult, especially when the management of mono-species plantations is better documented, considered to be easier and remain very profitable.

The objective of this document is to gather and diffuse as much technical information and support as possible on the topic of mixed plantations and also to be transparent about existing uncertainties.

Focus on the mixture effect on forest productivity

The question around mixed forest productivity is clearly a hot topic that contributes to the stakeholder psychological barriers when considering this as a management option. Indeed, a lot of forest landowners fear that introducing a new tree species to diversify their monoculture will result in a loss of wood production and income. However, the answer is not straightforward and requires the discussion of productivity assessment and quantification in mixtures.

A global positive biodiversity-productivity relationship

Some metanalyses showed the consistent positive effect of tree species diversity on forest productivity worldwide (Figure 1) but is confounded by the site effect and the stand composition effect. The productivity is understood in these studies as the production of tree biomass regardless of the wood quality or relevance for industries.

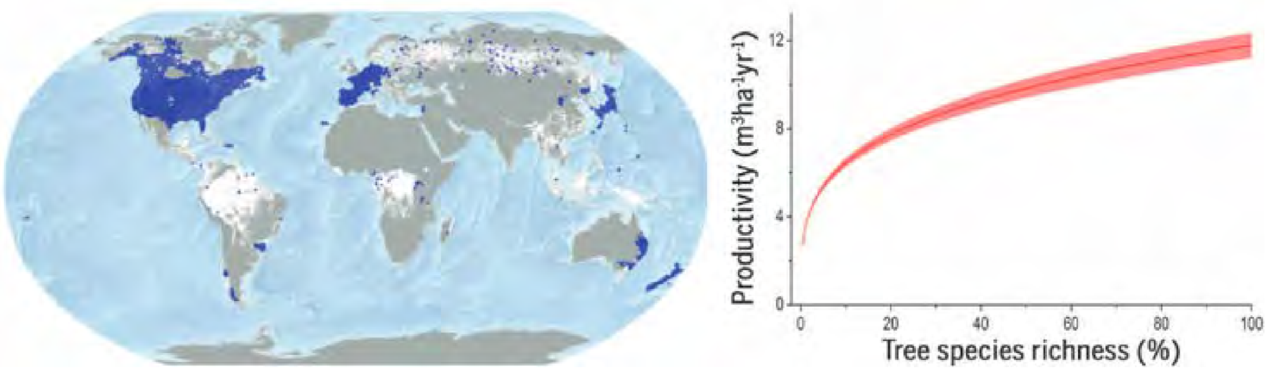


Figure 1: Global effect of tree species diversity on forest productivity (Liang et al., 2016)

The gain in productivity of a mixed forest is compared to the productivity of the monoculture of its constituent species. Having said that, we need to distinguish two types of gain in productivity:

- ## Overyielding = relative gain in productivity

An overyielding is observed in a tree species mixture when its productivity is above the mean productivity of the same species in monoculture (Figure 2).

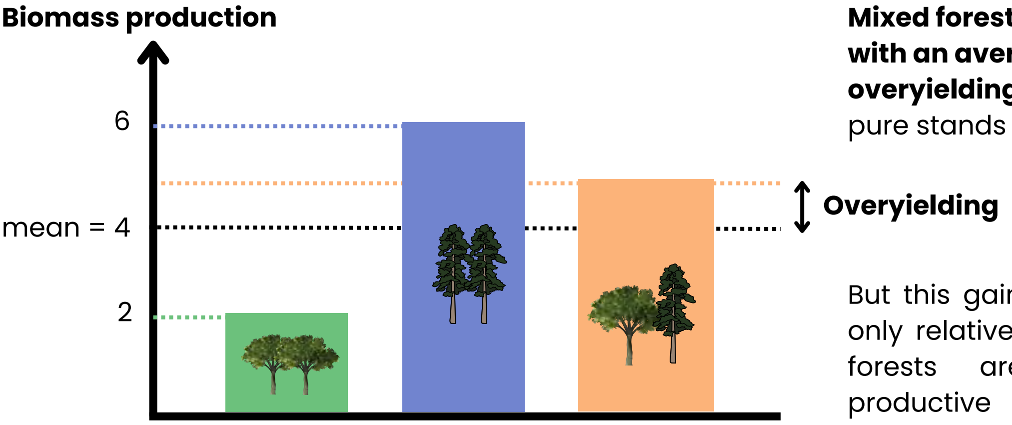


Figure 2 : Explanatory diagram of the overyielding concept

Mixed forests were observed with an average 15% overyielding compared to pure stands (Jactel et al., 2018)

But this gain of productivity is only relative and most mixed forests are actually less productive than the pure stands of the most productivee species present in the mixture

- ## Transgressive overyielding = absolute gain in productivity

Transgressive overyielding is observed when the productivity of the mixture is higher than the productivity observed for the most productive species when growing as a monoculture (Figure 3).

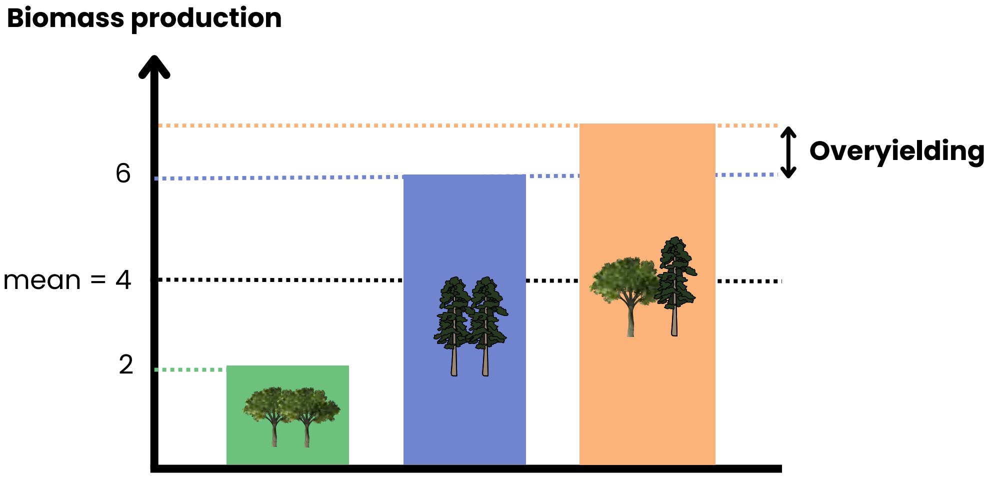


Figure 3 : Explanatory scheme of the transgressive overyielding concept

There are very few tree species mixtures that can provide an absolute gain in productivity compared to pure stands of the same species. However, there are some identified mixtures that have registered positive transgressive overyielding at some point in the development of the mixture:

- ***Pinus sylvestris - Picea sitchensis*** [Great Britain] (Mason et al., 2021)
- ***Pinus sylvestris - Picea abies*** [Great Britain] (Mason & Connolly, 2014)
- ***Pinus sylvestris - Alnus glutinosa*** [Great Britain] (Mason & Connolly, 2014)
- ***Pinus sylvestris - Fagus sylvatica*** [Spain] (García-Robredo F, 2018)
- ***Picea abies - Fagus sylvatica*** [Germany] (Pretzsch & Schütze, 2009)
- ***Picea abies - Betula pendula*** [Sweden] (Jonsson et al., 2019)
- ***Picea abies - Pinus sylvestris*** [Sweden] (Jonsson et al., 2019)
- ***Pinus sylvestris - Betula pendula*** [Sweden] (Jonsson et al., 2019)

PSYCHOLOGICAL LEVERS TO THE ESTABLISHMENT OF MIXED PLANTATIONS

Despite the numerous arguments supporting the benefits of mixed forests and despite their frequent mention in scientific publications, it is important to explain the individual motivations for landowners to try growing mixed species plantations. Based on the list of motivations raised by the practitioners interviewed, Figure 4 present the most important ones in a framework built on a two-axis distribution:

- the **general objective of the forest stand**, from a conservation to a productive approach
- the **scale of reflection**, from an intimate view to the consideration of global and external challenges (e.g. climate change, wood market)

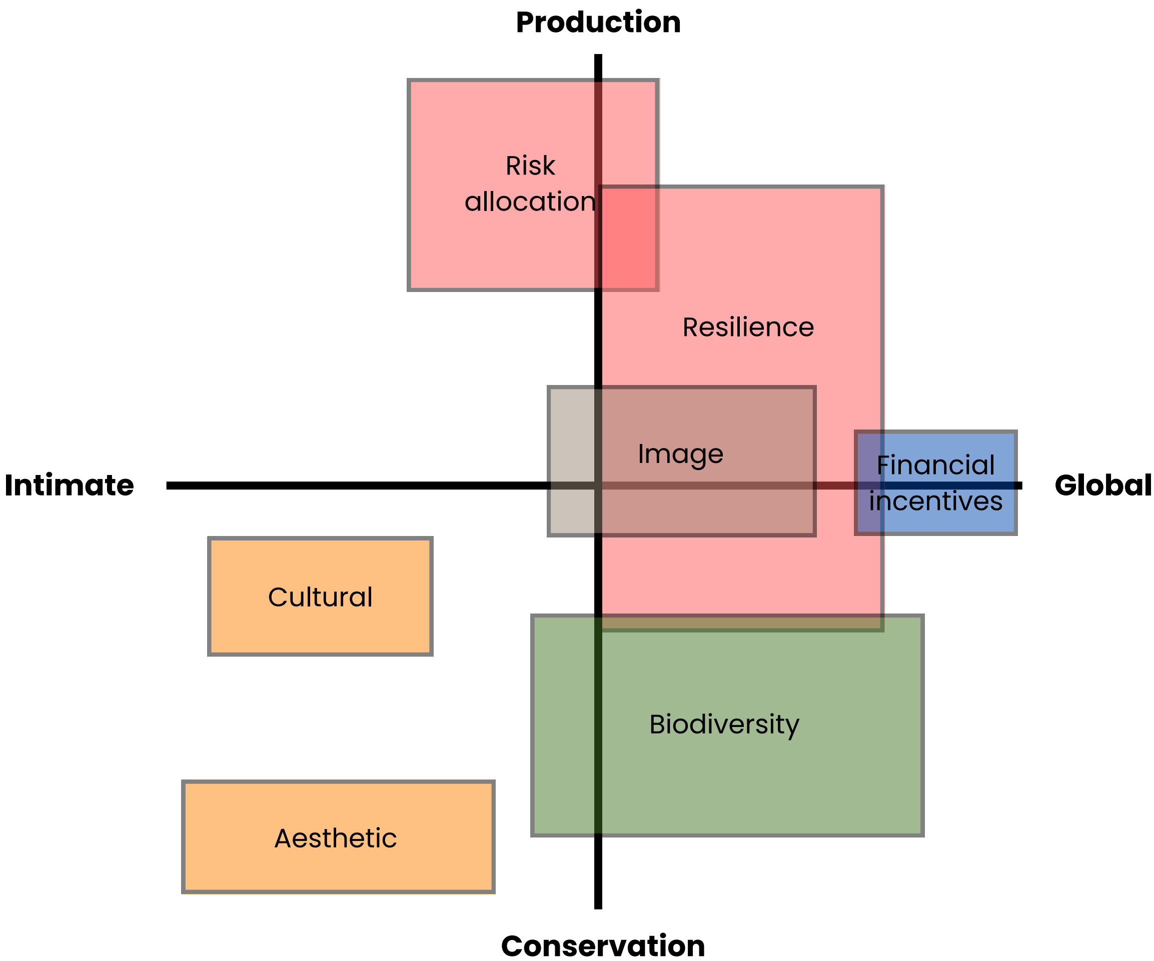


Figure 4: Framework of the stakeholders motivation categories distributed on a two axis basis. (Forest management approach / Scale of reflection)

Despite **the decision of the practitioners being based on a combination of complex and interconnected motivations**, we describe below some of the most quoted ones in descending order of importance:

Risk allocation: the plantation of a mixture of tree species is a way for landowners to diversify their resources when investing in the renewal of their stand. This diversification is presented as a means to guarantee the profitability and minimize the negative impacts of a given disturbance agent on at least one of the tree species in the mixture. The risks are mainly of two kinds: first the effect of climate change with the induced increasing biotic and abiotic disturbances, and second the possible volatility of the wood market.

Resilience: the practitioners interest is also to obtain less vulnerable ecosystems thanks to the greater adaptability of mixed forests to climate change and reduced exposure to pests and pathogens. This is of course one of the reasons behind the risk allocation motivation, except that the benefits on forest ecosystem health is more emphasized than the economical return.

These two motivations are driven by the idea of climate change adaptation applied in the context of a wood production management approach. They have been recognized **as the most important motivations** for practitioners to setting up mixed plantations.
However, It is interesting to note that the overyielding potential of mixed plantations over monocultures has never been mentioned by the respondants to the surveys. The economical purpose of the forest and the search for a consistent wood production is therefore indirect, through a reduction of the risk more than a direct improved productivity. We identify a clear need for additional effort in raising awareness and providing concrete demonstration of the overyielding effect in tree species mixtures.

Financial incentives: some landowners can plant mixtures by taking advantage of existing public or private financing aids. This can be a good lever to overcome extra costs in the establishment and help the landowners to take the step of mixed forest management. But they do not necessarily have additional motivations other than this external incentive, which is sometimes insufficient to maintain the mixture in the long-run.

Biodiversity: a motivation that can both support the creation of natural habitats to host more fauna and flora diversity and support the resilience capacity of the ecosystem.

Cultural: some landowners seek to improve the cultural value of their forest. The most important motivation is the provision of leisure activities (e.g. mushroom picking, hunting, non-timber forest products, ...). In rare cases, the management of mixed forest is a way to preserve family tradition and maintain know-how.

Aesthetic: some landowners also seek to improve the aesthetic value of their forest and to keep it pleasant and attractive. Sensory perception is considered expanded in mixed forests with more diverse leaf colors, more seasonal differences and complex structure and variation in patterns of light.

Image: some landowners are concerned about their image as foresters, especialy with the recent increasing societal expectations and media influence towards more diversity. In that case, the biodiversity improvement is more used as a marketing argument or to improve social perception of the forest sector as a whole.

FEEDBACK ON EXISTING MIXED PLANTATIONS

A lack of data

Each of the three data acquisition methods (worldwide survey, workshops and interviews) demonstrated **the lack of well recorded mixed plantations implementation and assessment**, which was quite surprising considering the importance of the topic among the forestry community. Most of the stakeholders interviewed were only initiating some trials, without any data to share yet, which is confirmed by the average young age of the plantations described in the survey.

In relation with this lack of data, this type of management is often less visible, the forest owners and managers being part of networks that would not necessarily promote mixtures. Therefore, this type of silviculture is **still seen at the stage of innovation**, and must be documented to become a normal part of the forestry systems.

Geographical distribution

The COMFOR-MIXFORCHANGE survey gathered 60 answers during the period between June 2021 to October 2022. The respondents described a **total number of 132 mixed plantations** located in 6 countries (Figure 5). These plantations are geographically distributed as follows:

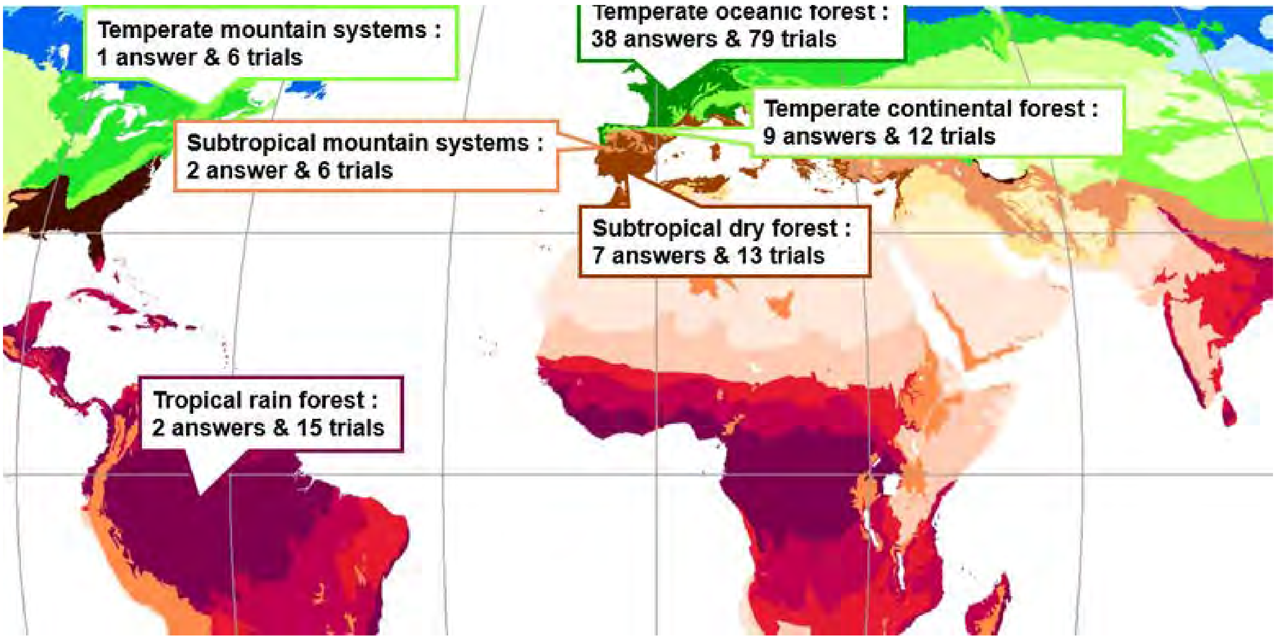


Figure 5: Distribution of the survey answers and associated number of described plantations according to the FAO Global Ecological Zones

Henceforth, only the **plantations in the European bioclimatic zones will be described** (80% of the total plantations recorded).

Quantitative results

Before analysing the success of the different tree species mixtures, it is important to provide some descriptive statistics of the plantations which can inform us of the data quality.

- **Age of the mixed plantations**

The survey asked for the plantation year which provides the age of the stands described. The pyramidal representation in 12 age classes shows **the relative young age of these plantations**, 40% of them being under 10 (Figure 6).

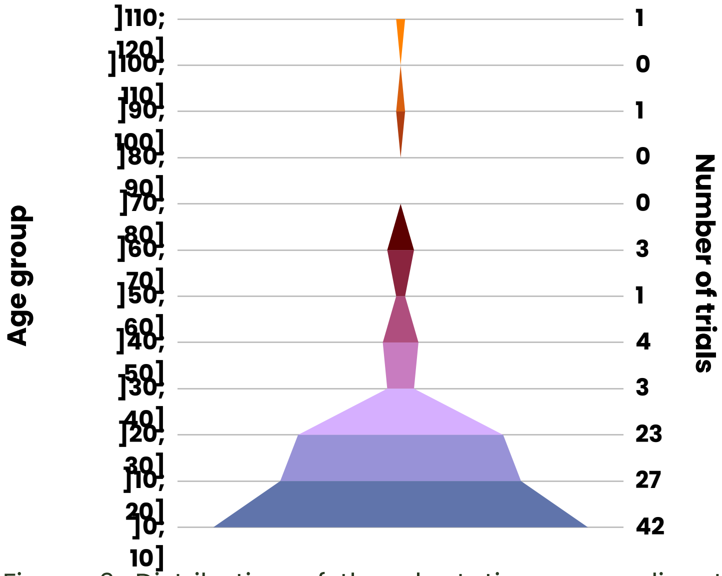


Figure 6: Distribution of the plantations according to their age group

On one hand, these results illustrate the **recent interest for tree-species mixture' plantations** and holds promise of interesting feedback in the years to come.

On the other hand, we can argue that these plantations are still too young to offer a real added value in the mixture success analysis. Indeed, it is likely that tree species under the age 10 are **unable to reflect a long term effect of the association**. The factors of failure described for these plantations refer only to abiotic pressure or game damages and not to any tree species competition.

- **Composition of the mixed plantations**

The survey described a wide range of mixture composition. If we look at the level of complexity of the mixtures, **60% are 2-species mixtures** while the other included three or more species. Most of the 2-species and 3-species mixtures present an equal species share (50% each and 33% each, respectively).

The Figure 7 below shows the distribution of the trials according to the species composition typologies. If we gather the trials associating conifers and broadleaves in various proportions, **the mixed mixtures are dominant** (52) compared to broadleaved mixtures (38) and coniferous mixtures (15). Half of the mixed mixtures have the same share of conifers and broadleaves (24).

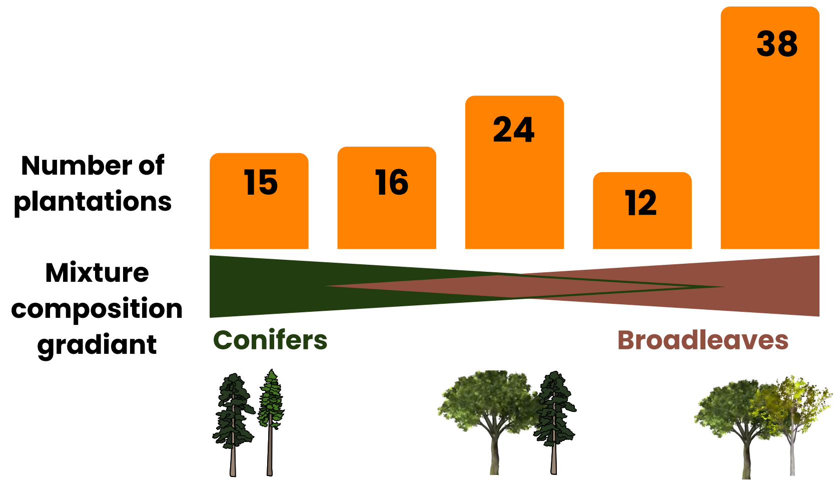
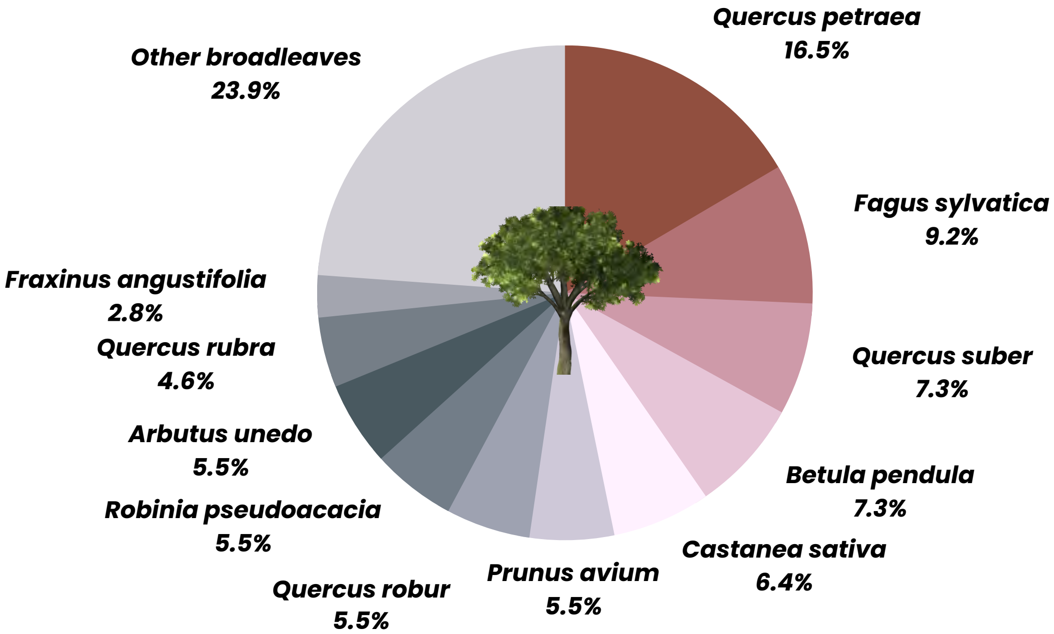


Figure 7: Number of plantations according to the proportion of conifers and broadleaves in the mixtures

- **Tree species identity**

To further explore the mixtures composition, we describe the diversity of tree species. If we only consider the tree species that are found in more than 33% of the planted stand, **the diversity of broadleaves choosen is incredibly rich**, approximately 3 times higher than the number of conifers.

Indeed, **three quarters of the mixed plantations with conifers are only using the following four species**: Douglas fir, Maritime pine, Norway spruce and Stone pine. The broadleaved category is richer in tree species and **the oak family is higly represented**. Overall, 68 different tree species were described in the survey.



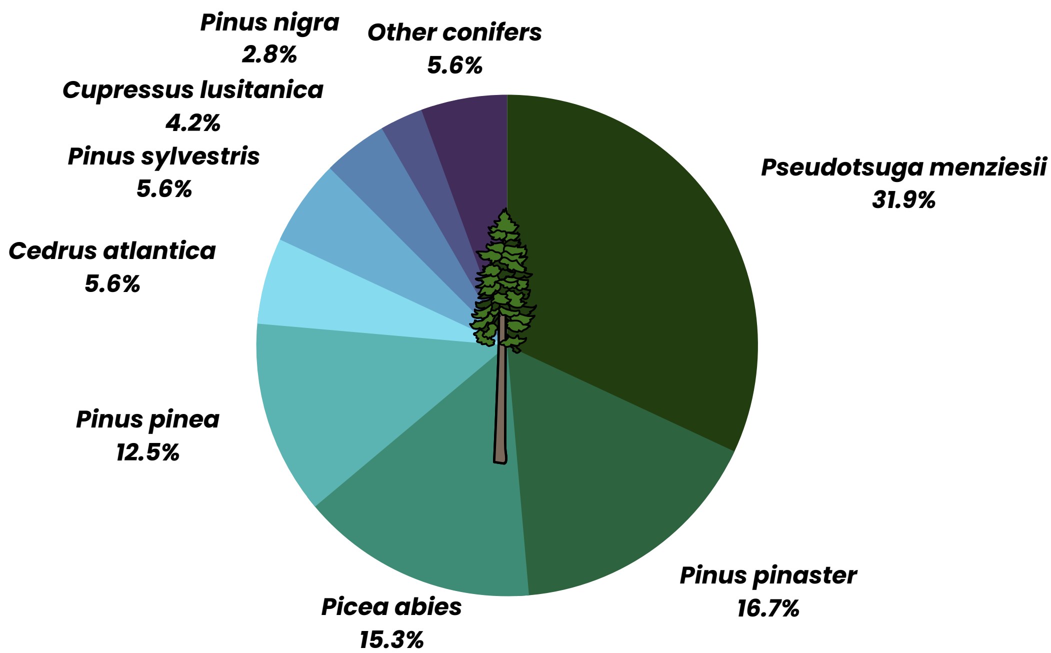


Figure 8: Percentage of occurence of the main tree species in the mixtures described, separating conifers and broadleaves

- **Mixed species plantation objectives**

It is important to define the objective of a forestation project to be able to assess its success, especially in mixed plantations where the different tree species can require individual management. The survey showed that the tree species diversification is not inconsistent with a wood production objective, in fact quite the opposite (Figure 9). The "Other" category comes second and is mainly made of scientific experiments.

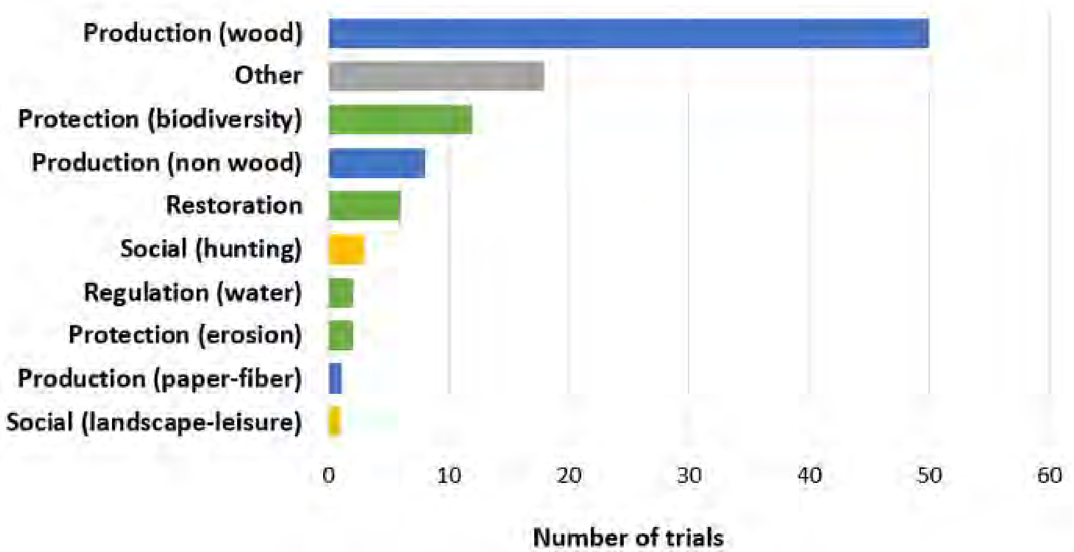


Figure 9: Main management objectives of the mixed plantations

Level of success of existing mixtures

The respondents were asked to assess the level of succes of their mixed plantations, on a four level scale (Figure 10). **This assessement excercise is very subjective**, and despite our guidelines in the definition of a successful or failed mixed plantation, we can identify some varying interpretations from the respondents that can affect the data homogeneity:

- Is a successful mixed-plantation one that has met its initial objective or one where the survival and growth of all species takes place?
- The mixed plantations can be exposed to external factors that can alter its success. The trees can be affected by biotic threats like pests and pathogens damages or abiotic events such as drought, frost or fire. Even a lack of management care at the early stages can affect the outcomes of the plantation. And since those reasons are not exclusive to mixtures, it is even more difficult to analyze the success ranking.

Another bias revealed by the graph below is that very **few respondents actually reported failing trials**. Therefore, our database is mainly giving us an indication on what is currently working. In addition, no statistical differences could be found between the level of succes and the mixture typology as defined in Figure 7.

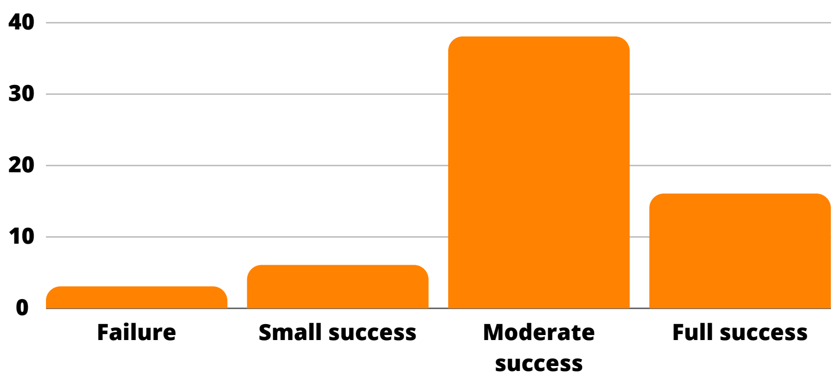
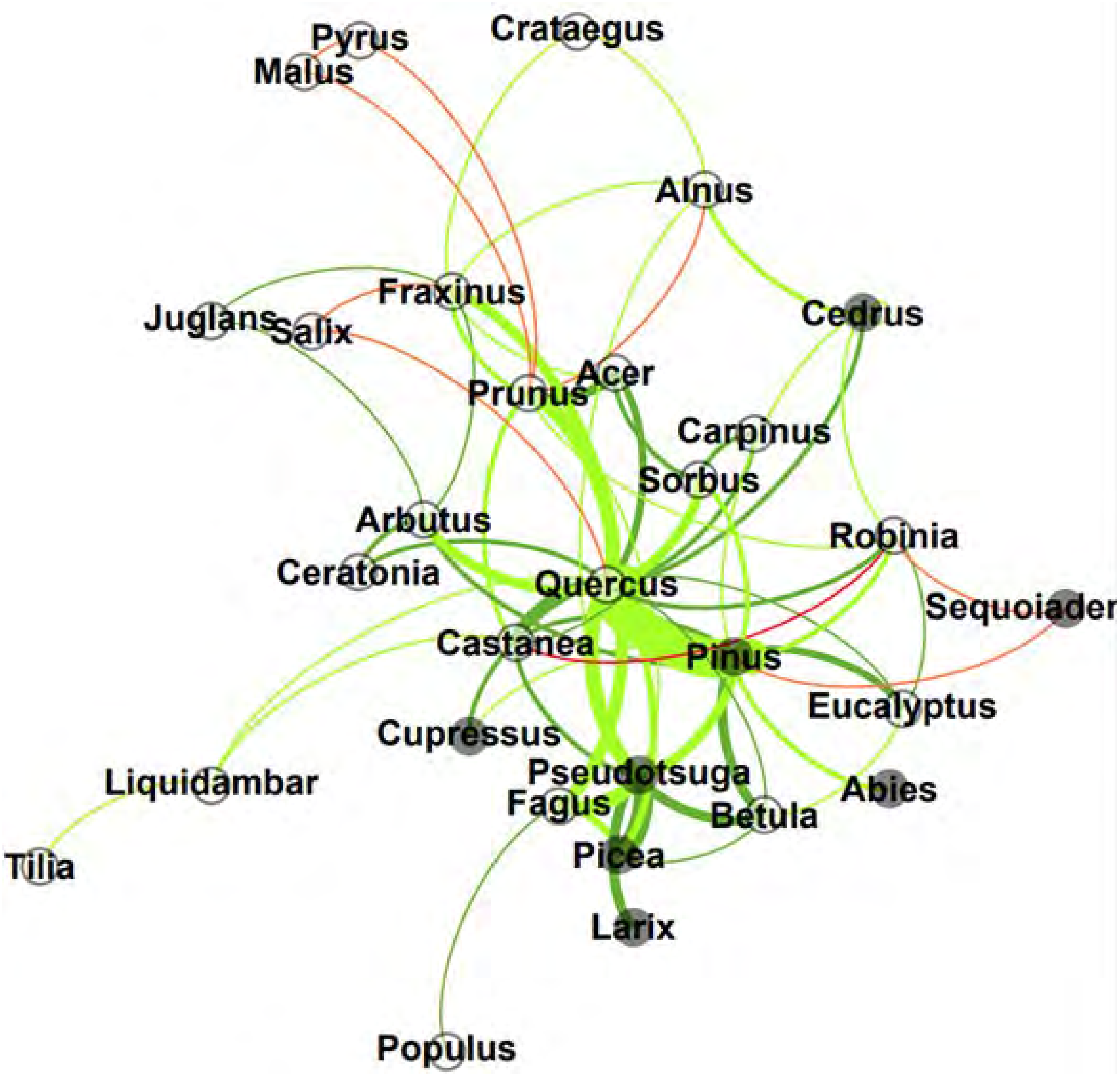


Figure 10: Level of success of the mixed plantations aged over 10 years

With all the necessary precautions mentioned above, we worked with the data to provide an **overview on the diversity of tree species associations** described in the answers to the survey. The tree species were gathered under their higher scientific classification, i.e. Genus. Figure 11 shows the combination betwen different genus with the arrow thickness indicating the occurence frequency, while the colors highlight the level of success of those associations in meeting the management objectives.



Spatialization using a repulsive algorithm Force Atlas

Nodes: tree species family

- Conifer
- Broadleaved

Links: species associated in a mixed plantation

Size of the link proportional to the number of plantations

Average level of success of the mixtures

- Full success
- Moderate success
- Small success
- Failure

Figure 11: Network of the tree species genus associations described in the COMFOR survey

The spacialization algorithm used resulted in a readable arrangement of the network based on the weight of the nodes and on their pairwise relations. Here are some lessons learnt from the graph and the underlying data:

Quercus x Pinus:

In the center of the network, ***Quercus* and *Pinus* appear as the most frequently used tree genera in mixed plantations** and are associated with a wide range of other tree species genera. Among the Quercus/Pinus mixtures, the red oak (*Quercus rubra*) is valued in mixture with maritime pine (*Pinus pinaster*) because of their similar important growth rate, or the combination of cork oak with stone pine so that pine can grow faster to shelter the oak. Sessile and pedonculate oaks (*Quercus petraea* and *Quercus robur*) also have a complementary behavior with Scots pine (*Pinus sylvestris*). Sessile oaks are also valued in mixture with Corsican pine. This kind of mixture has a great interest in protecting pines from the rot fungii (fomes and armillaria) and the oaks from powdery mildew.

Quercus x noble hardwoods:

In the upper part of the network, there is a strong interconnection between the ***Quercus* and a selection of noble hardwoods** (*Prunus, Acer, Sorbus, Fraxinus, Alnus, Juglans*). The Quercus species (often one among *Quercus petreae, Q. rubra, Q. robur*) are introduced in relatively high proportion (50-80%) compared to the other deciduous species. The other species have an accompanying role in the shaping of high quality oak timber (straight with natural pruning) and have value with the production of fruits for birds or flowers for insects. This type of mixture is especially recommended in the case of bare land (afforestation of agricultural land) or in the absence of natural woody recruits (former conifer clearings).

Pseudotsuga:

Douglas fir is a very important productive species that is commonly established in monoculture. The network above demonstrate several options to add more diversity and resilience in Douglas fir stands. Complementary species include conifers (*Picea abies*, *Larix decidua*, *Pinus sylvestris* or *Cedrus atlantica*) or broadleaves (*Betula pendula* or *Fagus sylvatica* in altitude). Among those, plantations mixing rows of Douglas fir and birch are showing the best level of success so far. This mixture can even be of interest in the case of young afforestations using conifers where damages from the *Hylobius abietis* pest can be minimized by a birch which naturally produces molecules with repellent properties.

Important safeguards:

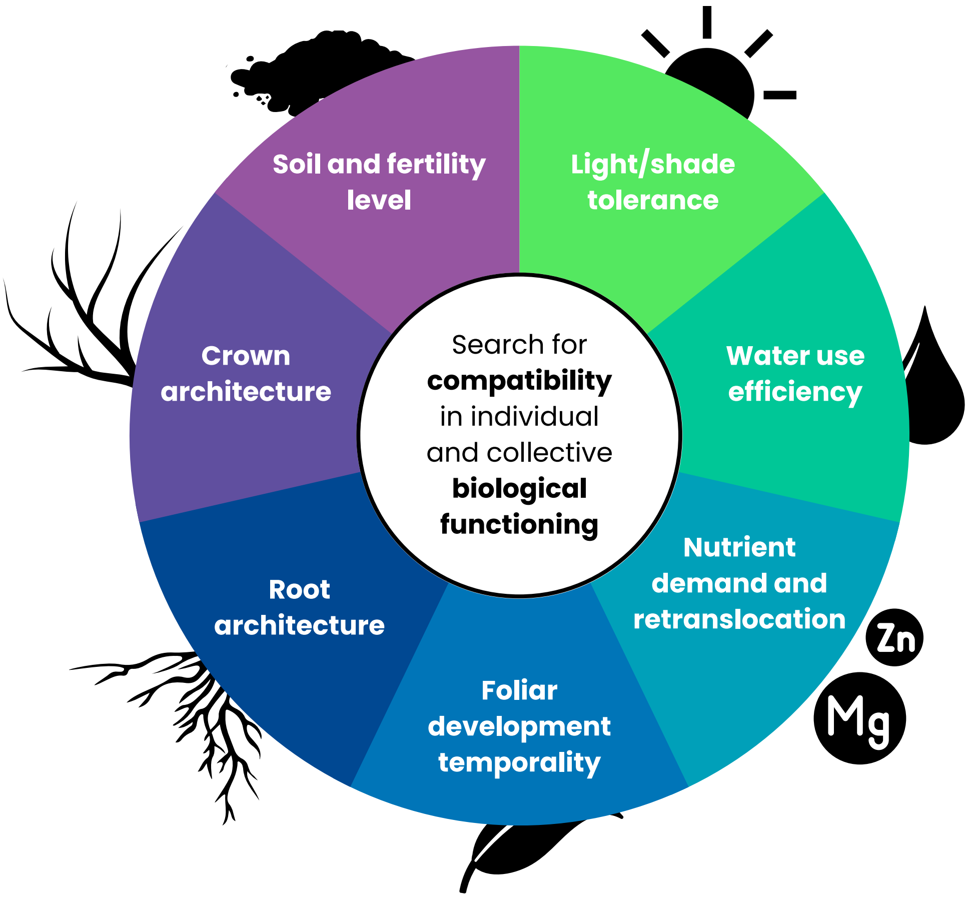
- **The sample tested is relatively small** and some of the tree species associations are not supported by more than one observation. The **level of success is not robust** in these cases.
- The level of success of the mixtures described in the survey and presented in the graph were **measured over the past decades**. **They are not necessarily recommended for future forestation due to the changing climate**. Therefore, it is really difficult to build recommendations on these past experiences.

RECOMMENDATIONS FOR CREATING A MIXED PLANTATION

Fundamental knowledge in the choice of species

The stationary identification:
The choice to move to mixed plantations should not be a substitute for addressing basic principles in forestry. The first principle is to choose the tree species according to the soil. Guides providing help in the identification of the stations are available in more and more natural regions. The CNPF even developed BioClimSol, a digital tool for sylvo-climate diagnosis and decision support at the scale of the forest plot: https://www.cnpf.fr/nos-actions-nos-outils/outils-et-techniques/bioclimsol

The autoecology of forest tree species:
Some plantation designs (i.e. intimate and per row mixture) can induce a strong interspecific competition if the autoecology of the tree species is too close. On the other hand, a facilitation effect can be reached when mixing complementary species, i.e. when species utilise resources in different ways resulting in niche partitioning. Here are some functioning traits that should be considered:



The search for compatibility in individual and collective biological functioning will be all the more effective in increasing productivity if they are contrasting, e.g. different levels of shade tolerance (protection against too much sun)

Decision support tool

To help choosing the best theoritical combination of species with complementary traits, we recommend to take a look at the **online platform named** **TRY** (https://www.try-db.org/TryWeb/Home.php). This database provides an unprecedented amount of information on more than 69,000 plants and their associated traits including growth, shape, dispersal, establishment, abiotic tolerance and more (Kattge et al, 2011). **This unified global database is an important support for research on community and functional ecology**.

Nevertheless, the online data portal allowing exploration and data requests is not of very practical use. Some time must be spent to select the desired species and traits and to review the heterogenous data compilation. We've put this portal into practice by requesting data on the biological functioning of some tree species commonly used in mixed plantations.

Table 1: Some forest tree species functional trait comparison using data extracted from the TRY platform

Tree species	Frost hardiness (leaf-buds) (°C)	Resistence to fire	Browsing sensitivity (1 -low; 5-high)	Tolerance to drought (0-low; 5-high)	Tolerance to shade (0-low; 5-high)
Betula pendula		No	1	1.85	2.03
Eucalyptus globulus		No		Low	Low
Fagus sylvatica			3	2.4	4.56
Larix decidua	-70	No	3	2.31	1.46
Picea abies	-25.83	No	2	1.75	4.45
Pinus sylvestris	-45.4	No	3	4.34	1.67
Pinus taeda	-25	Yes		4.5	1.99
Prunus avium				2.66	3.33
Pseudotsuga menziesii	-40	Yes			2.78
Quercus petraea			4	3.02	2.73
Quercus robur		Yes	4	2.95	2.45
Quercus rubra	-17.6	No		2.88	2.75
Robinia pseudoacacia	-5.1	No		4.11	1.72

This table is only a small selection of all the available traits and meta-data behind each field observation and measurement protocol. A pairwise comparative approach using such data could anticipate species behaviour when they are mixed together. Giving a special attention to traits like shade tolerance or browsing sensitivity could help the practitioners optimize tree species interactions. Other similar tools fcosuing on forest trees have been developped such as https://climessences.fr/ initiated by AFORCE network.

Some examples of mixed plantations found in France

Picture of an intimate mixture (*Prunus avium*, *Sorbus torminalis*, *Sorbus domestica*, *Acer campestre*) in the Vienne department ©Camille Tourangin

Picture of a per row mixture (1 line of *Quercus robur* between 2 lines of *Pinus nigra*) in the Dordogne department ©Camille Tourangin

CONCLUSION

Scientific experiments were successful in demonstrating the benefits of mixed forests over monocultures (drought resistance and water use, soil carbon storage, reduced exposure to pests, possible increased productivity and more). However, moving forward from plantations with a research focus to viewing mixed plantation forests as a commonly accepted solution for the forestry sector is a considerable challenge. In this document, we've tried to identify several obstacles to implementation and the levers or good practices obtained from several database analysis:

- Psychological barriers and the motivational drivers to overcome them
- Technical constraints and the overview of the most successful mixtures and associated design
- A lack of knoweldge on mixing effects in plantation and possible tools to search an optimal but theoritical combination of complementary traits

Some issues are still pending and we list below some challenges to address in the future.

Challenges to address

- **Tree species compatibility** is little known when designing a mixed plantation project. Whenever possible associate species with a similar growth, compatible crown and root architecture, etc. And all of these considerations need to be adapted to each unique site with changing climatic conditions. Given the limited knowledge it has been agreed that:
    - The survey on existing mixed plantations should remain open to collect additional information from practitioners
    - The plantations already described by practitioners should be included in a common framework to secure valuable results as decribed in the FORMIX protocol : https://formix.plantedforests.org
- The definition of mixed plantations is broad and all options for diversification in planted forest have to be explored and assessed.
- Relative and absolute overyielding is one of the main arguments to promote mixed plantations and all research efforts in this direction should be supported. FORMIX network will be part of the solution.
- The development of GIS-based tools can help managers and forest technicians to identify good potential areas for setting up mixed plantations and for better assisting their future management.
- The active management of additional tree species will require some adaptation from the forestry sector. Managing mixed plantations requires additional attention compared to monocultures, with the risk that less intensive management might lead plantations towards becoming mono-specific stands. The wood processing industry should be associated with these silviculture explorations that may lead to more diversified tree species with lower homgoeneity and in lesser quantities.

Acknowledgment

A special thank to all partners involved in the review of this document:
Many thanks to all stakeholders and forest practitioners who joined the regional meetings or who accepted to be interviewed.

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COMFOR SUDOE seeks to promote complex forests (mixed and irregular) and multi-species plantations as a resilient adaptive strategy in response to climate change and declining biodiversity. The project was launched to strengthen the synergistic and networked functioning of research and innovation at a transnational level in specific sectors of SUDOE based on smart and sustainable growth, by promoting research, development and transfer of technology and innovation

This project has received funding from the Interreg SUDOE programme project Integrated and Intelligent management of complex forests and mixed-species plantations in South-West Europe

The **MixForChange** project is funded by the BiodivERsA program, under the Horizon 2020 ERA-NET COFUND scheme.

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